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Multidirectional speed in basketball players: new approaches to assessment and training

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MULTIDIRECTIONAL SPEED IN BASKETBALL PLAYERS:

New approaches to assess and training

INTERNATIONAL DOCTORAL THESIS

Francisco José Barrera Domínguez

Doctorate Program in Sport and Physical Activity

2025

Supervised by:
Dr. Jorge Molina López
Dr. Bartolomé J. Almagro Torres

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Research in the Teaching and Learning of Experimental Sciences, Social, Mathematics and Sport and Physical Activity.

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MULTIDIRECTIONAL SPEED IN BASKETBALL PLAYER: NEW APPROACHES TO ASSESS AND TRAINING.

DOCTORAL THESIS

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Research in the Teaching and Learning of Experimental Sciences, Social, Mathematics and Sport and Physical Activity.

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Doctoral candidate D. Francisco José Barrera Domínguez has undertaken the present International Doctoral Thesis as a beneficiary of a contract under the *'Formación de Profesorado Universitario'* programme (FPU22/01057) of the Spanish Ministry of Universities, as per the resolution of the General Secretariat of Universities on December 14, 2023.

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"Some people want it to happen,
some wish it would happen,
others make it happen."

Michael Jordan –

Sí, lo sé, la presente tesis doctoral está en inglés. Perdonadme los lectores anglosajones, pero por suerte o por desgracia las personas que más quiero que lean esta sección la van a entender mejor en castellano, por lo que voy a permitirme el lujo de escribir los agradecimientos para ellos, en nuestro idioma.

Hace bien poco escuché que *"lo más importante en la vida no es lo que hagas o hasta dónde llegues, sino a quién elijas para que te acompañe en el camino y disfrutar de él"* – aunque no recuerdo bien quien lo dijo, no puedo estar más de acuerdo con esta frase. Si hoy he llegado hasta aquí es gracias a ello y a todas las personas que he elegido o no para que me acompañen en esta gran aventura. Además, soy tan afortunado que las personas que me han tocado sin elección, mi familia, son las primeras que me apoyan y me acompañan en todas las aventuras en las que me adentro. Para todas esas personas, que de una manera u otra han influido en el desarrollo de esta tesis doctoral, van las siguientes líneas.

"Tú no te preocupes de nada y mantente estudiando hasta los 30 años que es la mejor forma de crecer y evolucionar como persona" – Isabel Domínguez y Francisco J.

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y un largo etcétera de fuegos que han ido apagando para que esta tesis doctoral pueda desarrollarse de forma correcta. Ni queriéndolo hubiera podido dar con unos directores de tesis más implicados, con gran capacidad de trabajo y dedicación en el proyecto de los que he tenido, muchas gracias por aguantarme estos años.

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OUTLINE OF THE THESIS

The present doctoral thesis, titled *"Multidirectional Speed in Basketball Players: New Approaches to Assessment and Training"* comprises 11 scientific studies. As of the thesis submission date, nine of these studies have been published in high-impact scientific journals ***(Table 1)***, while the remaining two are currently under peer review. These publications fall within a unified research framework and are part of a project aimed at enhancing the scientific and practical understanding of key performance indicators influencing multidirectional speed actions in basketball players. Given the broad scope of this topic, the thesis has been structured into the following chapters to ensure a clear and systematic presentation ***(Figure 1)***.

Chapter 1. Decisive factors for a greater performance in changes of direction.

The first essential step in improving the performance of any physical capacity is to understand its biomechanical and neuromuscular demands. Secondly, it is crucial to analyse the external factors influencing its performance. This approach allows for directly addressing the specific demands of the targeted skill, while also training the different physical capacities that indirectly contribute to its performance. Although extensive scientific literature exists on this topic, ongoing controversy persists so far. This doctoral project aims to provide further clarity in this regard. This chapter includes five scientific publications ***(Figure 1)***.

Chapter 2. New tools and standardization to assess change of direction.

'What cannot be measured, cannot be improved'. Based on this well-known statement, the present doctoral thesis focuses on standardising the assessment of multidirectional speed tests in sport. Simultaneously, it aims to develop an assessment tool that minimises the limitations of currently available tools, making speed assessments more accessible across all sporting contexts. Given that, *'not everything that can be measured matters, nor everything that matters can be measured'*, this research seeks to

standardise what really matters for assessing change of direction actions, ensuring that these evaluations are really quick, simple and accessible. Furthermore, as *'no data is better than bad data'*, the development of a new measurement tool will be based on the principle that it must be both validated and reliable tool for use. This chapter includes two scientific publications ***(Figure 1)***.

Chapter 3. New approach to individualised change of direction training.

At this stage, the most crucial aspect and the primary motivation behind this doctoral thesis remains: the implementation and development of new individualised training approaches to improve performance in multidirectional speed actions. Unfortunately, scientific research does not always lead to practical applications. However, this thesis project has made every effort to contribute to the daily practice of strength and conditioning coaches in basketball and any other sport involving multidirectional movements. Quoting Dr. Jean-Benoit Morin, a leading world scientist in the field of sports performance, *'From the field to the lab, to the field again'*. It is now time to 'return to the field' and apply the scientific knowledge generated to improve athlete's performance and well-being. This chapter includes four scientific publications ***(Figure 1)***.

Finally, it is important to highlight that this doctoral thesis would not have been possible without the support of —in addition to the two supervisors who have contributed daily to the project— the 12 co-authors from six different universities, two of them international (*University of Salford* – Manchester, United Kingdom; and *La Trobe University* – Melbourne, Australia) who have collaborated in the different scientific publications.

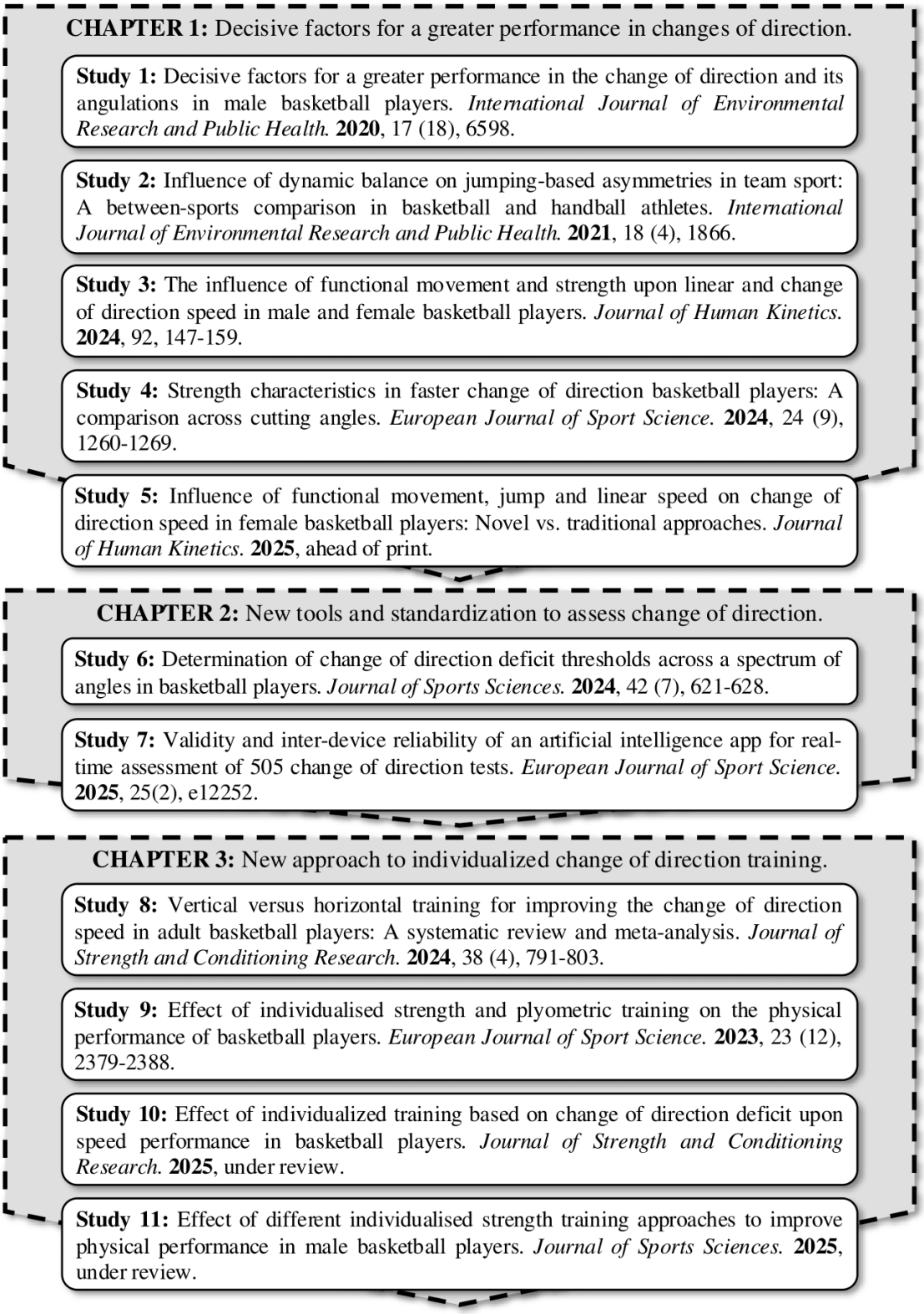

Figure 1. Thesis structure.

IMPACT FACTOR OF INCLUDED STUDIES

Table 1 presents the different quality indices of the journals in which each of the studies included in this doctoral thesis entitled 'Multidirectional speed in basketball players: New approaches to assess and training' has been published or is currently under review.

Table 1. Impact factor of the studies included in the thesis.

Study	Journal (Year)	IF year	SJR (Quartile)	JCR (Quartile)
1	Int. J. Environ. Res. Public Health (2020)	2020	0.75 (Q2)	3.39 (Q1)
2	Int. J. Environ. Res. Public Health (2021)	2021	0.81 (Q2)	4.61 (Q1)
3	J. Hum. Kinet. (2024)	2023	0.81 (Q1)	1.90 (Q2)
4	Eur. J. Sport Sci. (2024)	2023	1.08 (Q1)	2.40 (Q2)
5	J. Hum. Kinet. (2025)	2023	0.81 (Q1)	1.90 (Q2)
6	J. Sports Sci. (2024)	2023	1.12 (Q1)	2.30 (Q2)
7	Eur. J. Sport Sci. (2025)	2023	1.08 (Q1)	2.40 (Q2)
8	J. Strength Cond. Res. (2024)	2023	1.14 (Q1)	2.50 (Q2)
9	Eur. J. Sport Sci. (2023)	2023	1.08 (Q1)	2.40 (Q2)
10	(Under review)	–	–	–
11	(Under review)	–	–	–

Abbreviations: IF, Impact Factor; SJR, SCImago Journal Rank; JCR, Journal Citation reports.

ABBREVIATIONS

Table 2 collects all abbreviations used in this doctoral thesis.

Table 2. Abbreviations.

Abbreviations	Meaning
1RM	One-repetition maximum
AI	Artificial intelligence
BM	Body Mass
BMI	Body Mass Index
CI	Confidence Interval
COD	Change of direction
CODD	Change of Direction Deficit
CMAS	Cutting Movement Assessment Score
CV	Coefficient of Variation
e.g.	For example (*"exempli gratia"* from Latin)
ES	Effect Size
ETG	Electronic Time Gates
ICC	Intraclass Correlation Coefficient
i.e.	That is (*"id est"* from Latin)
IF	Impact Factor
LPS	Local Positioning System
$m \cdot s^{-1}$	Metres / Seconds (Velocity)
$m \cdot s^{-2}$	Metres / Seconds^2 (Acceleration)
MD	Mean Difference
SEBT	Start Excursion Balance Test
SD	Standard Deviation
SSC	Stretch-Shortening Cycle
SSG	Small Side Games
WB-DT	Weight-Bearing Dorsiflexion Test
YBT	Y-Balance Test

Abstract

"From the field to the lab,
to the field again."

– Jean-Benoît, Morin –

Multidirectional Speed in Basketball Players: New Approaches to Assess and Training

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Abstract

Changes of direction (COD) are high-intensity actions most frequently performed during real situations in basketball games, regardless of playing position or gender. Therefore, these actions should be considered a key performance indicator in basketball players. This doctoral thesis aims to explore this athletic skill through a comprehensive review of the most current literature on the topic and to advance scientific knowledge with the inclusion of eleven scientific studies. The information has been organised into three fundamental chapters, each with specific objectives, to facilitate a better understanding of COD.

Chapter 1 addresses the decisive factors for optimising COD performance. COD actions are complex multidirectional movements in which a multitude of technical and physical skills interact to achieve peak performance. In this regard, current scientific literature still exhibits controversy regarding the factors that most significantly influence performance in these actions, due to the use of different tests or assessment tools, and the characteristics of the samples analysed. Therefore, it was considered necessary to analyse the effect of different anthropometric characteristics, functional movement, linear speed and lower limb strength on COD performance in basketball players according to the cutting angle and gender. As a result, five scientific studies have been included in this section, highlighting the lower limb muscular strength as the most decisive factor in COD performance regardless of the cutting angle and gender. Furthermore, further knowledge, it was observed that velocity-oriented COD actions (i.e., cutting angles <90°) were more influenced by concentric strength; whereas force-oriented COD (i.e., cutting angles >90°) showed a stronger relationship with isometric and eccentric strength. With respect to gender, differences were also identified in COD performance between male and female basketball players. A short stretch-shortening cycle with a horizontal force orientation was the variable that showed the strongest relationship with COD performance in male basketball players; whereas a long stretch-shortening cycle with a vertical force orientation mainly affected COD performance in female athletes. Based on these findings, it is recommended to consider gender and athlete-specific characteristics when attempting to establish a relationship between different physical capacities and COD actions at different angles.

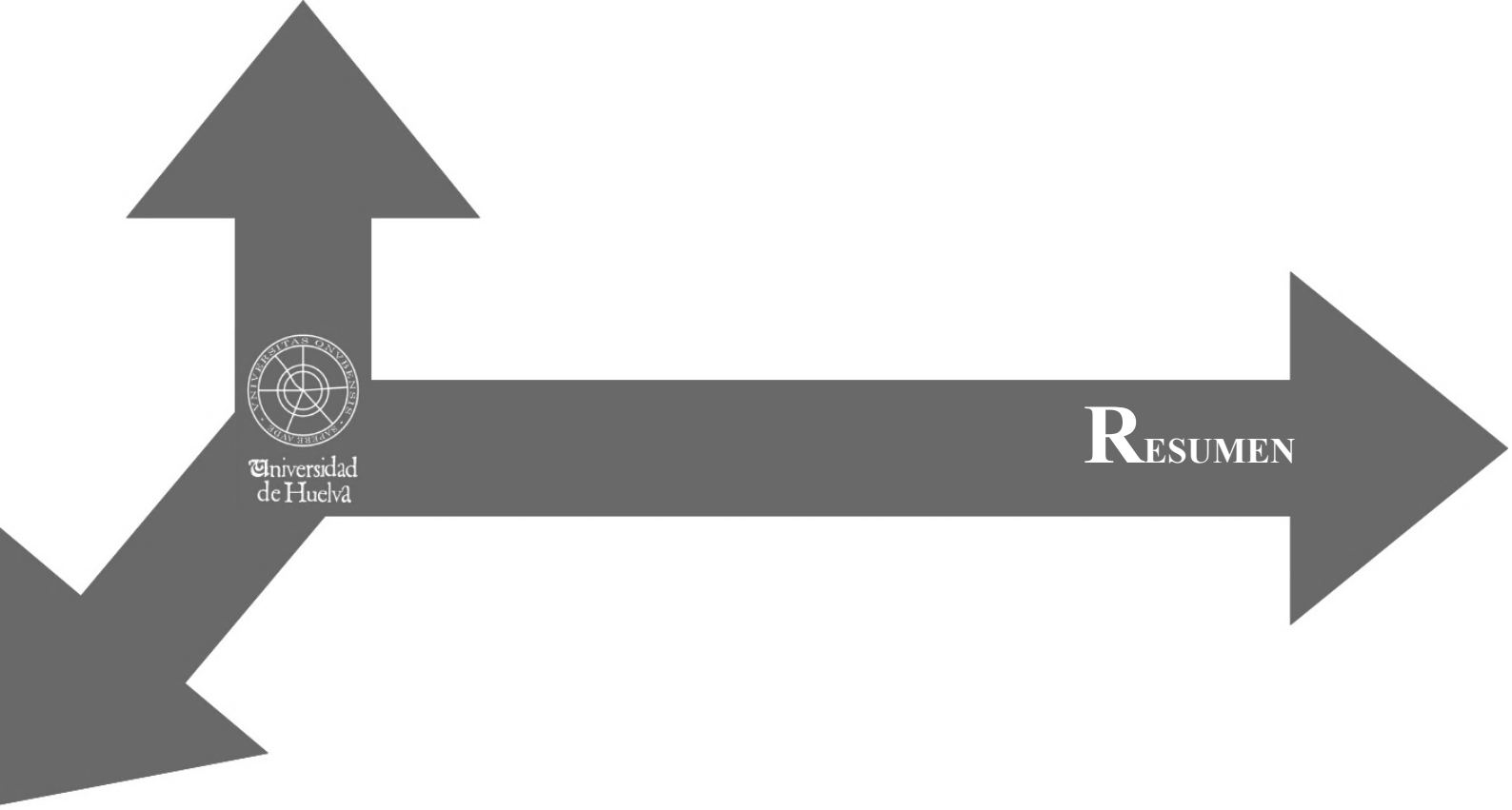
Continued

Chapter 2 aimed to standardise COD assessment and validate a novel evaluation tool based on execution time. Two scientific studies were included in the thesis to address these objectives. Firstly, the results demonstrated that Asstrapp is a valid and reliable tool —cost-effective, portable, providing real-time feedback, and easy to use— which makes speed assessment more accessible to all coaches. Furthermore, it was recommended to implement a short-duration testing protocol with a single cut at various angles, using both execution time and COD deficit as evaluation metrics. This approach provides sports professionals with a more comprehensive understanding of the performance and efficiency of their athletes in multidirectional actions.

Finally, chapter 3 aimed to examine the effect of different individualised training approaches on physical performance in basketball players. In response to this objective, four scientific studies were included in this section. The results underscored the importance of specific and individualised training stimuli according to the needs of each athlete to maximise performance improvements. Specifically, training programs oriented towards specific force demands and methodologies focused on addressing the athlete's physical weaknesses appear to be the most effective strategies for optimising sports performance. Therefore, strength and conditioning coaches are strongly encouraged to design individualised training programs based on COD deficit to enhance multidirectional performance, or by targeting any other physical variable according to the specific needs of each athlete.

Keywords

Change of Direction, Deceleration, Validation, Performance, Team Sport.



Resumen

"La ciencia debe enfocarse
desde el terreno de juego al laboratorio,
para volver al terreno de juego de nuevo."

Jean-Benoît, Morin –

Velocidad Multidireccional en Jugadores de Baloncesto: Nuevas Perspectivas de Evaluación y Entrenamiento

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Resumen

Los cambios de dirección (COD) son las acciones de alta intensidad que se realizan con mayor frecuencia en situaciones reales de juego en baloncesto, independientemente de la posición de juego o el género. Por ello, estas acciones deben considerarse un factor clave en el rendimiento de los jugadores de baloncesto. La presente tesis doctoral pretende desgranar esta habilidad deportiva a través de una revisión de la literatura más actual y avanzar en el conocimiento acerca del tópico con once estudios científicos incluidos, los cuales se han divididos en tres capítulos para una mejor comprensión de los COD.

El capítulo 1, aborda los factores decisivos para optimizar el rendimiento del COD. Los COD son acciones multidireccionales complejas en las que interactúan multitud de habilidades técnicas y físicas para alcanzar el máximo rendimiento. La literatura científica actual aún muestra controversia acerca de los factores que afectan mayormente al rendimiento en estas, debido al uso de diferentes pruebas o instrumentos de evaluación y a las características de la muestra analizada. Por ello, se consideró necesario analizar el efecto de diferentes características antropométricas, de movimiento funcional, velocidad lineal y fuerza en los miembros inferiores sobre el rendimiento de los COD en jugadores de baloncesto en función del ángulo de corte y del género. Como resultado, cinco estudios científicos han sido incluidos en esta sección, resaltando la fuerza muscular de los miembros inferiores como el factor más determinante en el rendimiento de los COD, independientemente del ángulo de corte y del género. Además, se observó que las acciones de COD orientadas a la velocidad (i.e., <90º) estaban más influida por la fuerza concéntrica; mientras que los COD orientados a la fuerza (i.e., >90º) mostraron una mayor relación con la fuerza isométrica y excéntrica. Con relación al género, también se encontraron diferencias entre los jugadores masculinos y las jugadoras femeninas en el rendimiento del COD. Siendo un ciclo de estiramiento-acortamiento corto con una orientación horizontal la variable que mayor relación mostró con el rendimiento del COD en jugadores de baloncesto masculinos; mientras que un ciclo de estiramiento-acortamiento largo con una orientación de la fuerza vertical afectó principalmente al rendimiento en acciones de COD en deportistas femeninas. Tras estos hallazgos, se recomienda prestar atención al

Continuación

género y a las características específicas de cada deportista cuando se pretenda buscar cierta relación entre diferentes capacidades físicas y las acciones de COD a diferentes angulaciones.

En el capítulo 2 se pretendió estandarizar la evaluación de los COD y validar una novedosa herramienta de evaluación basada en el tiempo de ejecución. Dos estudios científicos fueron incluidos en la tesis para dar respuesta a estos objetivos. En primer lugar, los resultados mostraron que Asstrapp es una herramienta valida y fiable, económica, portable, con feedback en tiempo real y fácil de usar; lo que hace más accesible la evaluación de la velocidad a todos los entrenadores. Además, se recomendó implementar un protocolo de pruebas de corta duración con un solo corte a diferentes angulaciones; usando como medidas de evaluación tanto el tiempo de ejecución en la prueba, como el COD déficit. Ya que esto permite al profesional del deporte tener una visión mucho más amplia acerca del rendimiento y eficiencia en acciones multidireccionales de sus deportistas.

Finalmente, en el capítulo 3 se trató de analizar el efecto de diferentes aproximaciones de entrenamiento individualizado sobre el rendimiento físico en jugadores de baloncesto. Como respuesta a este objetivo se incluyó cuatro estudios científicos en esta sección. Los resultados resaltaron la importancia de estímulos de entrenamiento específicos e individualizados acorde a las necesidades de cada deportista, para maximizar las ganancias en el rendimiento. Concretamente, un trabajo con la orientación de la fuerza específica y el uso de una metodología de entrenamiento focalizada en el desarrollo de las debilidades físicas del deportista, parece ser la mejor estrategia para optimizar el rendimiento deportivo. Por lo que se anima encarecidamente a los preparadores físicos que planteen programas de entrenamientos individualizados en base al COD Déficit para la mejora del rendimiento multidireccional o usando cualquier otra variable física según la necesidad de cada deportista.

PALABRAS CLAVES

Cambios de Dirección, Deceleración, Validación, Rendimiento, Deportes de Equipo.

INTRODUCTION

RELEVANCE OF CHANGE OF DIRECTION ACTIONS IN BASKETBALL

Basketball is a multidirectional team sport with an intermittent nature (Abdelkrim et al., 2010), characterised by alternating high-intensity actions with periods of low intensity and rest. The estimated work:rest ratio ranges from 1:3.5 to 1:4.3 (Delextrat et al., 2017). Basketball players perform over 1050 physical actions during a game, 11.5% of which are executed at maximum intensity (Abdelkrim et al., 2010). These high-intensity actions last between two to five seconds, resulting in an average work:rest ratio of 1:10 when considering only maximal effort actions (Abdelkrim et al., 2010).

Basketball matches are divided into four periods of 10 or 12 minutes, depending on the competition. During each quarter, players cover over 1500 metres in multiple directions (Scanlan et al., 2015), reaching peak speeds of up to 6.6 $m \cdot s^{-1}$ in Spanish sub-elite basketball competitions (Puente et al., 2017), and even higher speeds of up to 8.09 $m \cdot s^{-1}$ in elite players competing in the North-American Basketball League (Caparrós et al., 2018). The technical and tactical demands of basketball require players to perform a significant number of repeated high-intensity movements, including accelerations and decelerations, changes of direction (COD), high-intensity sprints, jumps and landings (Scanlan et al., 2011), both with and without the ball (Stojanović et al., 2018). In previous studies with male basketball players, Svilar et al. (2018) identified COD as the most frequently executed high-intensity action during a match, with players performing an average of 324.1 COD per game, 15.1% of which were executed at maximal intensity (>3.5 $m \cdot s^{-2}$). This finding has been corroborated by other studies and applies regardless of playing position (Salazar et al., 2020) or gender (Power et al., 2022). Therefore, the correct execution and performance improvement in these actions may be considered critical for success in decisive moments of the game, such as scoring, gaining an advantage over the opponent in offensive situations, blocking the opponent's space, or intercepting the ball in defensive actions (Bourgeois et al., 2017; Delextrat et al., 2017).

Specifically, basketball is an indoor court sport played on a relatively small court size. This explains the large number of accelerations, decelerations and the importance of COD in this sport. Regarding these actions, it was observed that female basketball players performed, on average, more accelerations than decelerations during matches, with a total of 370 accelerations and 273 decelerations (Portes et al., 2020). When analysed by playing position, Portes et al. (2020) showed that interior female players performed a greater number of these actions during the match. These total values reflect the volume of these actions throughout the game. However, when acceleration and deceleration in basketball was analysed by intensity zones, it was observed that while the number of moderate accelerations (<3 $m \cdot s^{-2}$) was higher than moderate decelerations, the opposite occurred when the intensity of these actions was high (>3 $m \cdot s^{-2}$) (Vázquez-Guerrero et al., 2018). Specifically, the number of maximal decelerations exceeds that of maximal accelerations across all playing positions, with a significantly lower high-intensity acceleration:deceleration ratio (>3 $m \cdot s^{-2}$) in perimeter players (1:4.87 ratio) compared to interior players (1:2.57 ratio) (Vázquez-Guerrero et al., 2018). This highlights the critical role of braking actions, particularly for perimeter players.

However, a recent meta-analysis (Petway et al., 2020) concluded that further research is still needed to gain a clear understanding of the acceleration and deceleration demands in basketball training and competition. Additionally, it highlighted the necessity of accurately and systematically assessing competition demands to develop appropriate training strategies that closely replicate match play. In this regard, the development of Local Positioning System (LPS) technology, has significantly enhanced the study of sport-specific physical demands. Over the coming years, this technology may contribute to a deeper understanding of this topic. LPS can collect and store thousands of data on specific game actions, enabling the analysis not only of the demands of basketball, but also the most demanding scenarios over different continuous time periods of a match. In this context, a preliminary study revealed that basketball players experience significantly higher workloads (in arbitrary units per minute) during 15-second time periods compared to longer time intervals ranging from 30 to 90 seconds (Salazar & Castellano, 2019). In this regard, other scientific studies have been published (Fox, Conte, et al., 2021; Vázquez-Guerrero et al., 2020) to reach a better understanding of the most demanding scenarios in basketball and, thus, to develop more effective and sport-specific training approaches. For instance, during a 60-second time period, basketball players perform 6.9 accelerations and 6.4 decelerations at high intensity, covering a total of 120.4 metres (Vázquez-Guerrero et al., 2020). Although these findings may help professional basketball design more specific and individualised training programmes, it is important to highlight that the most demanding scenarios vary depending on the individual and the playing position (García et al., 2022). They also depend on the team's playing style and competition level (Ujaković et al., 2024); moreover, external intensity peaks decrease throughout the match due to sport-induced fatigue (Salazar et al., 2024). Therefore, it may be useful to consider the generic data published in the scientific literature, but it would be recommended to assess the needs of each athlete according to their specific context.

These previously detailed characteristics and external demands of sport lead players to experience high peaks of internal load. Regarding perceived internal load, elite players reach, on average, 150 beats per minute, with peaks of up to 190 beats per minute during matches (López-Laval et al., 2016). In contrast, amateur and junior players experiment an even higher internal load, with an average of 168 beats per minute per match, with maximum values of up to 199 beats per minute. Additionally, basketball is an intermittent sport dominated by endurance and anaerobic metabolism, which is reflected in players reaching blood lactate concentrations of 5.49 mmol/l on average during the game (Abdelkrim et al., 2009). Returning to the external demands of the sport, the high metabolic demand of basketball matches also impacts on players' physical performance during the course of the game. In this regard, total player load decreased quarter by quarter during a basketball match (Fox, Salazar, et al., 2021), with the most significant decrease in performance occurring in the final quarter. Therefore, it is crucial for strength and conditioning coaches to focus on metabolic training, exposing players to high intensity accelerations, decelerations and COD actions under maximum demand and fatigue conditions during training sessions.

Given the increased intensity and external loads of modern basketball (Sugiyama et al., 2021), the importance of high-intensity, multidirectional movements under fatigued conditions during game actions becomes evident for players to achieve optimal athletic performance. Therefore, coaches are encouraged to focus on developing fast, efficient and robust players capable of executing fast accelerations, decelerations and COD in any direction (McBurnie & Dos'Santos, 2022) through: (1) analysing the key determinants of COD actions, (2) properly assessing and monitoring COD loads using appropriate tools that allow frequent evaluation and training adjustment, and (3) implementing precise and effective training programmes tailored to each player's individual needs.

CHANGE OF DIRECTION AND ITS KEY PERFORMANCE INDICATORS

COD actions, which are vital in basketball, require precise body control, high muscle activation and high peak force production (Spiteri et al., 2015). This is a multidirectional skill involving planned deceleration and acceleration in different directions (Nimphius et al., 2016). Specifically, COD is defined as the ability to accelerate, decelerate and reaccelerate in a planned direction (Nimphius et al., 2018). It is important to highlight that COD ability is complementary to but independent from agility (Young et al., 2015), which involves perception, processing and reaction to a stimulus. To clarify the various concepts used in the scientific literature around the topic of COD, ***Table 3*** presents all relevant terms that might be used throughout this dissertation alongside their definitions.

Table 3. Definitions and key terms related to changes of direction reported in the scientific literature. Adapted from Jones & Dos'Santos (2023).

Term	Definition
Multidirectional Speed	'Competency and capacity to accelerate, decelerate, change direction, and ultimately maintain speed in multiple directions and movements, within the context of sports-specific scenarios' (McBurnie, Dos'Santos, et al., 2021)
Agility	'A rapid and accurate whole-body movement with change of velocity, direction or movement pattern in response to a stimulus' (Jones & Nimphius, 2018)
Game Speed	'The ability to exploit the qualities of speed and agility within the context of a sport' (Jeffreys, 2010)
Change of Direction Ability	'The skills and abilities needed to change movement direction, velocity, or modes. Describes the physical event of changing direction' (DeWeese & Nimphius, 2016)
Manoeuvrability	'The ability to maintain velocity during a change of direction, when performed without a clear "plant" step (i.e. a curvilinear path of movement); or the ability to perform or change mode of travel to and from "transitional" movements (i.e. side shuffle or back pedal)' (DeWeese & Nimphius, 2016)
Change of Direction Speed	'The ability to decelerate, reverse or change movement direction and accelerate again' (Jones et al., 2009) 'The ability to change initial direction to a predetermined location and space on a field or court' – applicable to specific situations in open skilled sports. (Nimphius, 2014)
Change of Direction	'A reorientation and change in the path of travel of the whole-body centre of mass towards a new intended direction' (McBurnie, Dos'Santos, et al., 2021)
Curved Sprinting	'The upright running portion of the sprint completed with the presence of some degree of curvature' (Caldbeck, 2019)
Deceleration	The action of reducing horizontal momentum (negative acceleration) during a locomotor task across a series of foot contacts as an isolated agility action or prior to change of direction manoeuvre (Dos'Santos & Jones, 2022a) or the ability to proficiently reduce whole body momentum, within the constraints, and in accordance with the specific objectives of the task (i.e. braking force control), whilst skilfully attenuating and distributing the forces associated with braking (i.e. braking force attenuation).
Attacking agility	In the context of invasion team sports (i.e. court-and field-based sports with the objective to score goals/points), defined as 'distinct, sharp, change of directions or decelerations performed for attacking purposes (i.e. team in possession) while being actively defended by an opponent(s)' (Fox et al., 2014)
Sprinting	Running at maximal or near-maximal speeds. (Mcmillan & Pfaff, 2018)

Furthermore, for facilitating understanding, ***Figure 2*** —extracted and adapted from Young et al. (2002)— illustrates the classical model of the key determinants of (A) agility and its distinction from (B) COD. Considering this, although COD actions in real game situations typically occur in response to external stimuli (e.g., player or ball movements on the court), it is not possible to replicate game-specific stimuli in an isolated context (Young et al., 2021). Therefore, the mechanics of planned COD actions are considered the best approach for understanding the biomechanical and physiological basis of COD performance in response to real-game situations (i.e., agility).

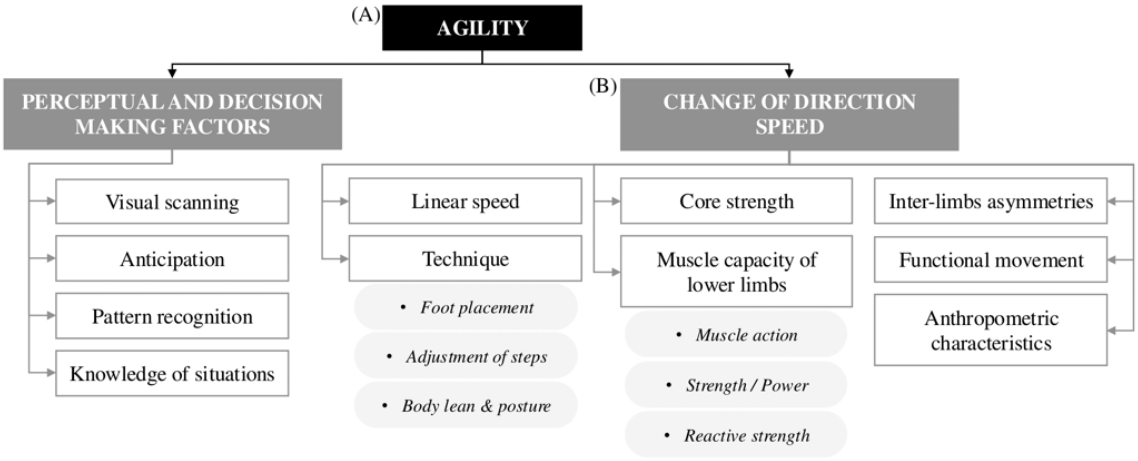


Figure 2. Classical model indicating the main key factors determining (A) Agility, and (B) change of direction speed. Extracted and adapted from Young et al. (2002).
Agility: *running speed with at least one change of direction performed in a competitive game. This may include being in possession of a ball or piece of equipment;* ***visual scanning:*** *ability to process visual information in competitive game;* ***anticipation:*** *prediction of an event in a game that influences the movements of a player in a game;* ***pattern recognition:*** *the ability to recognise patterns of play by an opposing team or player;* ***knowledge of situations****: knowledge of the probable movements of other players, based on previous experience of the game.*

The primary objective of COD actions is simply to reorient and redirect the whole-body centre of mass trajectory towards a new preplanned direction (David et al., 2017; Wyatt et al., 2019). This often involves a stop in the running cycle and some manipulation of the base of support relative to the centre of mass to generate a perpendicular impulse that redirects and accelerates the centre of mass towards the intended direction of movement (Dos'Santos & Jones, 2022b; McBurnie & Dos'Santos, 2022). To achieve this, basketball players perform a wide range of manoeuvres, including side-step cuts, crossover cuts, split-step cuts, shuffle-step cuts, spin manoeuvres, turn or decelerations ***(Table 4)*** (Dos'Santos & Jones, 2022b). Each of these movement mechanics has different physical and biomechanical demands, so it should be considered when analysing COD actions. Additionally, ***Figure 3*** outlines the advantages and disadvantages of using the main movement mechanics mentioned above.

Table 4. Classification and description of the different movement mechanics used in change of direction and agility actions (which involve a change of direction). Adapted from Jones & Dos'Santos (2023).

Mechanics	Description
Side-step	Athlete plants their foot laterally opposite to the direction of travel to create a propulsive impulse into the new intended direction.
Shuffle-Step	Athlete performs a series of lateral side-steps (often double/triple) with the final movement similar to the side-step action, sometimes known as double/ triple step or stutter step.
Crossover cut	Athlete positions the planted foot on the same side (ipsilateral) of the new direction (or sometimes medially across the pelvic midline) and then crossing the opposite leg (contralateral) in front of the body for the new step in the new direction, accelerating in the same direction of the push-off leg.
Split-step	Athlete performs a small jump (amplitude jump) prior to push-off, landing with both feet greater than or equal to shoulder width apart, and then, upon landing, the contralateral limb is used for push-off into the intended direction of travel.

Table 4 (continued).

Mechanics	Description
Spin	Athlete plants the foot and pivots/ rotates the foot and whole body using a 'blind turn' / spinning movement, generally rotating the whole body at ≥270°.
Turn	This is a unilateral or bilateral turning strategy where one foot rotates and remains in contact with the ground and redirects centre of mass (typically for directional changes ≥110°).

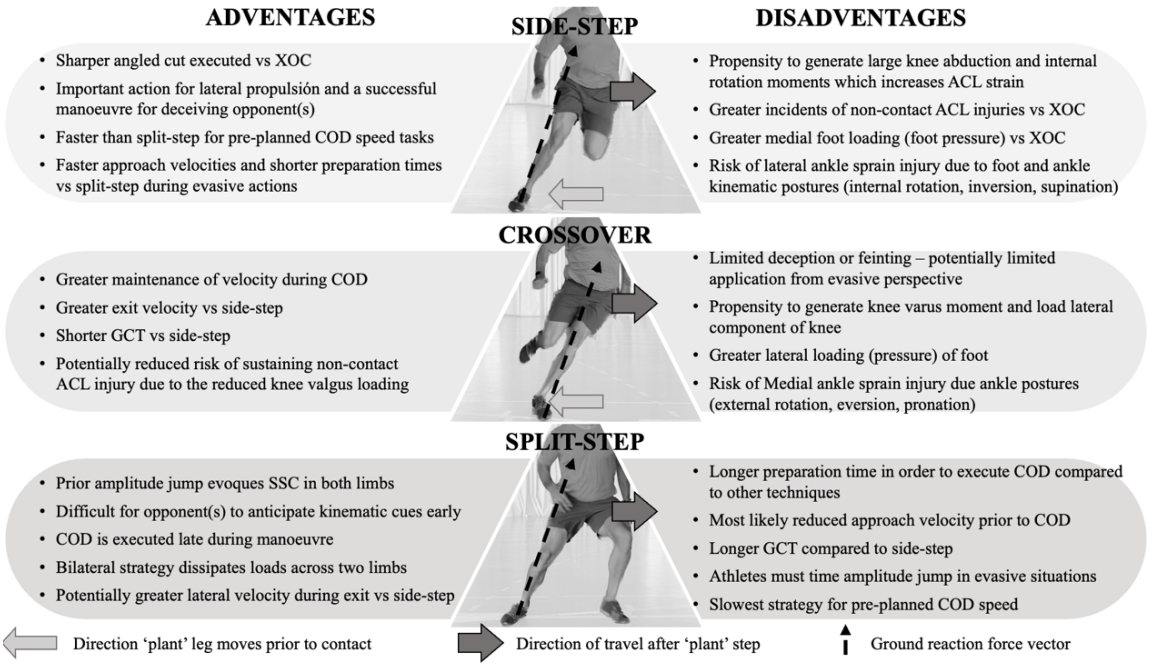


Figure 3. Characteristics, advantages and disadvantages of the main movement mechanics performed during change of direction manoeuvres. Extracted and adapted from Dos'Santos et al. (2019).
Abbreviations: COD, Change of Direction; XOC, Crossover Cut; SSC, Stretch-Shortening Cycle; GCT, Ground Contact Times; ACL, Anterior Cruciate Ligament.

Despite the existence of different movement mechanics for executing COD, these actions can generally be divided into four phases (McBurnie & Dos'Santos, 2022): (1) initial acceleration, which involves linear, curvilinear or lateral movement primarily characterised by concentric action aimed at acceleration and largely determined by the distance prior to the COD itself; (2) preliminary deceleration, which consists of steps preceding the COD, where eccentric force predominates, producing preliminary deceleration actions and generating postural adjustments for optimal COD execution; (3) COD foot plant, the main phase of the COD, where isometric force predominates and the whole body must reorganise towards the exit direction; and (4) re-acceleration, the final phase towards the new direction of movement. These four COD phases are mutually dependent and are influenced by the athlete's approach speed and inertia, physical capacities of the player, cutting angle and agility demands specific to the sport context (McBurnie & Dos'Santos, 2022).

Basketball players perform hundreds of COD during training and games, across a wide range of intensities, approach velocities, and cutting angles (Gonzalo-Skok & Bishop, 2023). In this regard, scientific literature has examined COD actions across a broad spectrum of approach velocities (3–7 $m \cdot s^{-1}$) and cutting angles (30–180º) (Donelon

et al., 2020); determining that these COD actions are mainly influenced by the approach velocity and cutting angle (Dos'Santos, Comfort, et al., 2018). These variables regulate the intensity, and define the physical and biomechanical demands of COD ***(Figure 4)***. For instance, in COD with shear angulations (<45º), high braking forces are not required, so the main objective is the maintenance of maximal velocity. Consequently, these COD are considered velocity-oriented and are more closely associated with dynamic concentric force characteristics and fast stretch-shortening cycles (SSC) (Bourgeois et al., 2017). Nevertheless, COD with sharper cutting angles (>90º), are considered force-oriented COD as braking force requirements increase substantially to reduce horizontal momentum; and ground contact times are significantly longer to lower centre of mass, facilitate momentum redirection, and enhance subsequent propulsive impulse (Dos'Santos, Comfort, et al., 2018). As a result, sharper COD are more dependent on dynamic eccentric force production; that is, muscle action in which the muscle-tendon unit is elongated, increasing tendon demands, and involving a slow SSC (Bourgeois et al., 2017). Given that both approach velocity and cutting angle regulate intensity in these actions (Dos'Santos, Comfort, et al., 2018), proper management of these two variables would be recommended to modulate intensity and ensure a controlled progression in training, particularly when working with beginners or athletes recovering from injury.

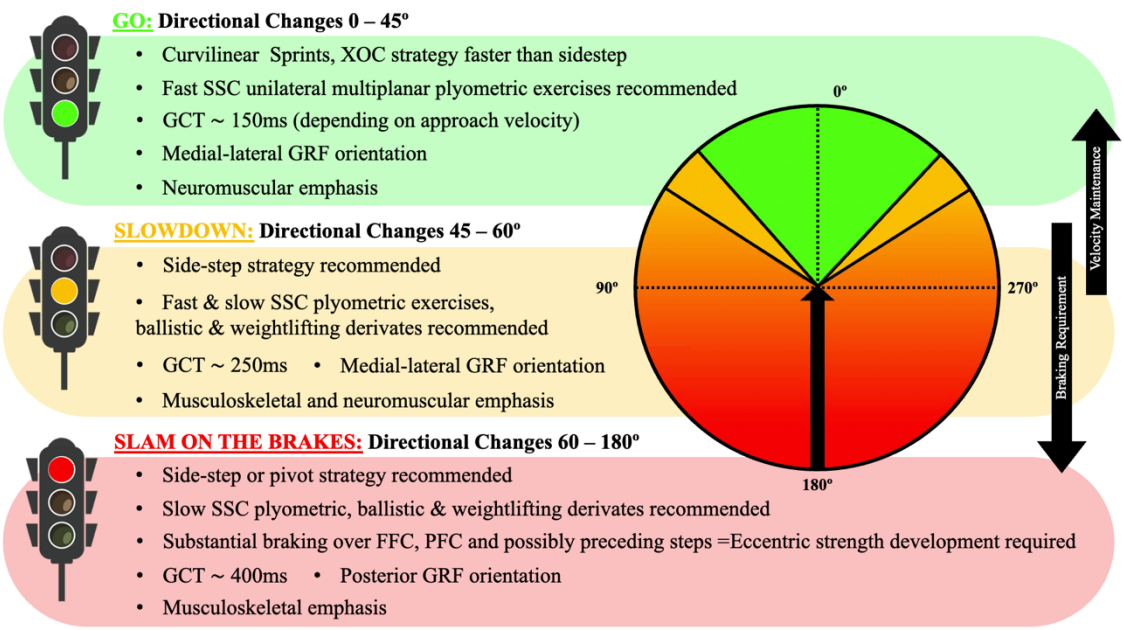


Figure 4. Relationship between cutting angle and approach speed during change of direction actions. Extracted and adapted from Dos'Santos, Comfort, et al. (2018).
Abbreviations: XOC, Crossover Cut; SSC, Stretch-Shortening Cycle; GRF, Ground Reaction Forces; GCT, Ground Contact Times; FFC, Final Foot Contact; PFC, Penultimate Foor Contact.

Due to the plethora of manoeuvres available for executing cutting actions and the infinite COD intensities resulting from the combination of different approach velocities and cutting angles, these multidirectional actions are highly complex to analyse. Nevertheless, previous literature (Chaouachi et al., 2009; Hewit et al., 2013; Pereira et al., 2018) has analysed the key performance indicators in COD actions ***(Figure 2B)***.

Although there is no consensus about them, the most critical factors influencing COD performance according to the current literature were outlined below.

Linear speed

Traditionally, linear speed has been considered a physical ability closely related to COD actions (Sheppard & Young, 2006; Young et al., 2015), particularly when assessed over short distances (<20 metres) (Michael et al., 2021). This is because COD actions often involve linear displacement both before and after the cutting action itself (McBurnie & Dos'Santos, 2022).

This relationship between both abilities may be attributed to the commonly used assessment method: the execution time of the test (Nimphius et al., 2018). However, the final outcome of a COD test based solely on execution time may not accurately represent the athlete's actual COD ability. According to previous studies (Nimphius et al., 2016), the time exclusively dedicated to the COD is less than 30% of the total test duration. Consequently, measuring COD performance using alone may mask deficiencies in COD ability (Nimphius et al., 2018). Furthermore, this assessment may be biased towards faster athletes (Sayers, 2015), as athletes with high linear sprinting ability may compensate for possible COD deficiencies. To address this limitation, the scientific literature has introduced advanced assessment techniques, such as laser speed guns (Hader et al., 2015), three-dimensional motion cameras (Jones et al., 2022) or the Change of Direction Deficit (CODD) (Nimphius et al., 2016). These methods allow for a more comprehensive understanding of the athletes' COD ability by isolating the cutting action itself during the COD tests and thus obtaining a more holistic view of the athletes' COD ability. Notably, when COD is assessed in isolation using CODD, the relationship between linear speed and COD performance disappears (Nimphius et al., 2016). Therefore, it would be recommended to consider these two actions as distinct physical abilities (Young et al., 2015).

To delve deeper into this topic, it has previously been explained how COD performance is directly influenced by the cutting angle. The angle of COD appears to be a key variable when analysing the impact of linear speed on COD performance. In this regard, the ability to maintain velocity during COD will be influenced by the intended cutting angle, the approach distance and the athlete's physical capacity; as sharper COD angles require greater braking forces. Consequently, greater net horizontal impulse and deceleration will be required (Jones et al., 2016). At shear angles (45° and 90°), Hader et al. (2015) demonstrated that the minimum horizontal velocity reached during the test was a key determinant of COD performance, while maximum acceleration and velocity also contributed. Additionally, Jones et al. (2022) found that minimum horizontal velocity and approach speed during a 70–90° cut could explain 82% (79% adjusted) of the variation in COD time. Therefore, the ability to maintain speed or minimise speed decrease before and during 45–90° cuts seems advantageous for higher COD performance (Dos'Santos, Comfort, et al., 2018). However, contrary to shear cuts where the speed can be ~2–5 m/s during the execution phase (Dos'Santos et al., 2021), in sharper COD athletes must reduce their horizontal velocity to zero or near zero to execute the turn at angles >90º (Ken-ichi

et al., 2019). Therefore, to effectively overcome inertia and deflect the centre of mass, athletes with higher approach velocities will have greater acceleration impulse (mass · velocity) and, will require greater braking impulse to effectively decelerate before turning (Dos'Santos et al., 2021; Jones et al., 2017; Ken-ichi et al., 2019). As a result, these sharper cutting angles could be found to be more closely associated with force-related variables. This aligns with previous studies (Bourgeois et al., 2017) specifying that COD with shear angles (<90º cut) are more related to linear speed actions, whereas COD with sharp angles (>90º cut) are primarily associated with lower-limb muscle capacity.

Technique (performance-injury conflict)

Like all sport actions, technique is one of the main factors influencing COD performance. In this regard, the key technical, kinetic, and kinematic factors for greater COD performance using side-step mechanics include: greater ankle power, higher ankle plantarflexion moments, greater torso inclination and rotation, greater hip power and extensor moments, rapid knee and hip extension, wider lateral foot placement, reduced hip and knee flexion, and proper lowering of the centre of mass (David et al., 2017, 2018; Dos'Santos, & Jones, 2021a). Proper lowering of the athlete's centre of mass during the COD execution phase increases stability and improves postural adjustment, allowing for a wider lateral foot placement, which is essential for generating perpendicular impulse (Havens & Sigward, 2015; Jones et al., 2015). Furthermore, during this COD execution phase —which involves high braking forces coupled with elevated propulsive forces— a rapid transition from weight acceptance to a powerful simultaneous triple extension of the ankle, knee and hip, together with reduced hip and knee flexion (i.e., a 'stiffer' strategy), allows for a rapid transition from braking to impulsion. This strategy helps to achieve shorter ground contact times and greater SSC utilisation, enhancing force generation efficiency, especially as sharper cutting angles (Dos'Santos et al., 2021). Additionally, dynamic trunk control is also essential for COD performance, as reducing lateral trunk flexion and promoting medial trunk inclination shifts the centre of mass closer to the intended direction of movement. This minimises unnecessary displacement and results in a more efficient movement (Dos'Santos et al., 2021; King et al., 2018; Marshall et al., 2014).

However, when performing high-intensity actions such as COD in chaotic and often unpredictable sporting environments, there may be an inherent risk of injury associated with cutting actions. COD, particularly those executed using side-step mechanics, are a common trigger for non-contact lower limb injuries, including anterior cruciate ligament injuries (Brown et al., 2014; Montgomery et al., 2018), hamstring strains (Kerin et al., 2022), adductor injuries (Serner et al., 2019), and medial or lateral ankle sprains (Wade et al., 2018). This risk is particularly relevant in multidirectional sports such as basketball. In this context, a paradox arises between optimising COD performance and mitigating injury risk (Dos'Santos et al., 2021); as the current literature suggests that the technical and mechanical factors associated with higher approach and exit speeds during COD may conflict with safer movement patterns (i.e., minimising mechanical loads on the involved joints) (Dos'Santos, McBurnie, Comfort, et al., 2019; Fox, 2018; McBurnie, Dos'Santos,

et al., 2021). For example, some kinetic adjustments such as reducing the lateral distance between the support foot and the centre of mass, increasing hip and knee flexion, controlling foot and pelvis rotation prior to cutting, and minimising ground reaction forces; may reduce potentially hazardous loads on the knee joint. However, these kinetic modifications are also likely to come at the detriment of COD performance (Dos'Santos et al., 2021; McBurnie, Dos'Santos, et al., 2021).

Despite this, certain technical and mechanical variables are linked to both improved COD performance and reduced multiplanar joint loading, thereby lowering the potential risk of injury. Additionally, ***table 5*** showed some variables could be modified to minimise the risk of injury without negatively impacting COD performance (Jones & Dos'Santos, 2023). For example, knee valgus is a primary mechanical risk factor for anterior cruciate ligament injury, yet it provides no performance benefits (Dos'Santos, & Jones, 2021a; McBurnie, Dos'Santos, et al., 2021). Conversely, medial trunk inclination is associated with reduced knee joint loading while also being linked to enhanced COD performance (Dos'Santos, & Jones, 2021a; McBurnie, Dos'Santos, et al., 2021). Furthermore, an effective braking strategy —characterised by greater decelerative force during the penultimate step before COD, particularly in sharper cuts— has been shown to simultaneously enhance performance and reduce potential knee joint loading (Dos'Santos & Jones, 2021a; Dos'Santos et al., 2019; Jones et al., 2016). This approach is also considered safer, as braking predominantly occurs in the sagittal plane with increased knee flexion, thereby distributing forces more effectively.

Table 5. Checklist of side-step technique regarding the performance-injury conflict. Extracted from Jones & Dos'Santos (2023).

Determinant	Rationale	Recommendation
Approach velocity and COD angle	Athletes are unlikely to sprint slower and avoid sharper CODs, and velocity is key determinant of performance.	Optimise technique and develop physical capacity to tolerate knee joint loads. Encourage PFC to brake during sharper COD and postural adjustment prior to COD to facilitate effective weight acceptance during execution of foot contact.
Lateral trunk flexion/rotation	Medial trunk lean is associated with faster performance and lower knee joint loads. However, during unplanned COD, athletes may laterally flex trunk (drop shoulder) to deceive (feint) opponents.	Coach upright/medial trunk lean during pre-planned COD. Coach upright trunk position for unplanned COD
Wide lateral foot plant	Although a wide lateral foot plant increases moment arm and KAM, it is necessary to generate ML GRF and perpendicular force to accelerate into the intended direction. Athletes are unlikely to adopt narrower foot plants at the expense of a slower performance.	If coaching a wide lateral foot plant, ensure that athletes avoid initial valgus postures with lateral trunk flexion. An amalgamation of several high-risk postures is worse than just lateral foot plant. Ensure high levels of muscular support before and during ground contact to support ligament unloading.

Abbreviations: GRF, ground reaction force; COD, change of direction; PFC, penultimate foot contact; FFC, final foot contact; KAM, knee abduction moment; GCT, ground contact time.

Table 5 (continued).

Determinant	Rationale	Recommendation
Knee valgus and hip rotation	Knee valgus and internal hip rotation are linked to greater KAMs but offer no associated performance benefits.	Encourage strong frontal plane alignment of the hip, knee, and ankle.
Knee and hip flexion	Increasing knee flexion can reduce the impact of GRFs, KAMs, and anterior tibial shear, but increased flexion is also associated with longer GCTs and reduced exit velocity. Similar observations have been observed for hip flexion.	Encourage ankle, knee, and hip rapid co-flexion with rapid transition to forceful triple extension. Encourage active touchdown (initial flexed postures) with high muscular pre- and co-activation.
Foot position	Excessive internally and externally rotated postures can increase KAMs and tibial rotation, respectively. Neutral foot position is the safest strategy without any detrimental impacts for performance.	Encourage neutral position during COD.
Impact GRF	High GRFs increase KAMs and are a by-product of running faster and reduced knee flexion. High-impact GRFs are needed to facilitate greater braking forces to reduce momentum.	Encourage braking during earlier foot contacts, such as PFC.
PFC braking	PFC braking, particularly for sharper COD, is associated with faster performance and lower knee joint loads and is considered a safer strategy because braking generally occurs in the sagittal plane and through greater knee flexion. This, in turn, lowers knee joint loads during FFC and permits the FFC to focus on propulsion and redirection rather than braking.	Encourage PFC dominant braking strategies for sharper COD. Ensure optimal PFC placement for effective weight acceptance during shallower CODs.

Abbreviations: GRF, ground reaction force; COD, change of direction; PFC, penultimate foot contact; FFC, final foot contact; KAM, knee abduction moment; GCT, ground contact time.

To address this performance-injury 'conflict' and assess key technical and mechanical aspects of COD actions in basketball players, a validated observational tool, the Cutting Movement Assessment Score (CMAS), has been developed (Jones et al., 2017). CMAS is a qualitative COD assessment tool consisting of nine items ***(Table 6)*** that assesses the braking strategy during the penultimate step prior to the COD, as well as trunk, hip, knee and foot positioning and movements during the final step of a side-step cutting manoeuvre. Athletes who fail to meet the criteria for each item during COD execution (Dos'Santos et al., 2021) receive a score according to CMAS guidelines ***(Table 6)***. Higher scores typically indicate suboptimal technique and greater peak knee abduction moments, which leads to reduced performance and increased risk of injury during COD actions (Dos'Santos, McBurnie, Donelon, et al., 2019; Jones et al., 2017).

Table 6. Cutting Movement Assessment Score Tool (CMAS). Extracted from Jones et al. (2017).

Recommended camera		Variable	Observation	Score
		Penultimate contact		
Side/20–45º	**1.**	**Clear PFC braking strategy**	**Y/N**	**Y = 0/N = 1**
		Final contact		
Front/20–45º	**2.**	**Lateral leg plant distance** (at initial contact)	**Wide, Moderate, Narrow**	**Wide = 2, Moderate = 1, Narrow = 0**
Front/20–45º	**3.**	**Hip in an initial internally rotated position** (at initial contact)	**Y/N**	**Y = 1/N = 0**
Front/20–45º	**4.**	**Initial knee 'valgus' position** (at initial contact)	**Y/N**	**Y = 1/N = 0**
All 3	**5.**	**Foot not in neutral foot position** (at initial contact)	**Y/N**	**Y = 1/N = 0**
Front/20–45º	**6.**	**Frontal/transverse plane trunk position relative to intended direction of travel** (at initial contact and during WA)	**L/TR, U, M**	**L/TR = 2, U = 1, M = 0**
Side/20–45º	**7.**	**Trunk upright or leaning back throughout contact** (at initial contact and during WA)	**Y/N**	**Y = 1/N = 0**
Side/20–45º	**8.**	**Limited knee flexion during final contact ≤ 30º** (during WA)	**Y/N**	**Y = 1/N = 0**
Front/20–45º	**9.**	**Excessive knee 'valgus' motion** (during WA)	**Y/N**	**Y = 1/N = 0**
Low CMAS ≤ 3		**Moderate CMAS 4–6** **High CMAS ≥ 7**	**Score**	**/11**

Abbreviations: PFC, Penultimate foot contact; WA, Weight acceptance; L, Lateral; TR, Trunk rotation; U, Upright; M, Medial; Y, Yes; N, No.

Finally, based on the technical deficiencies in COD actions identified using CMAS, targeted intervention programmes have been developed to develop more efficient and technically robust athletes in these movements, improve COD performance and reduce injury risk ***(Figure 5)*** (Dos'Santos et al., 2021). Previous intervention studies (Dos'Santos et al., 2021; Dos'Santos, McBurnie, Comfort, et al., 2019) have demonstrated that a six-week training programme focused on improving COD speed and modifying key technical factors may improve COD performance (Dos'santos et al., 2022), while reducing knee loads during cuts (Dos'Santos et al., 2021). On the one hand, the positive improvements in COD performance were mainly attributed to increased speed at key moments of the action, enhanced propulsive force production with shorter ground contact times and reduced knee flexion range (Dos'santos et al., 2022). On the other hand, improving COD performance and modifying technique did not appear to be sufficient to reduce knee loads and the risk of injury in COD actions. However, subjects who initially exhibited high multiplanar knee joint loads —and were therefore considered at potentially high risk— responded positively, showing reductions in knee joint loads (Dos'Santos et al., 2021). This highlights the importance of an individualised training approach based on CMAS ***(Figure 5)*** to design training that not only optimise performance but also minimise injury risk.

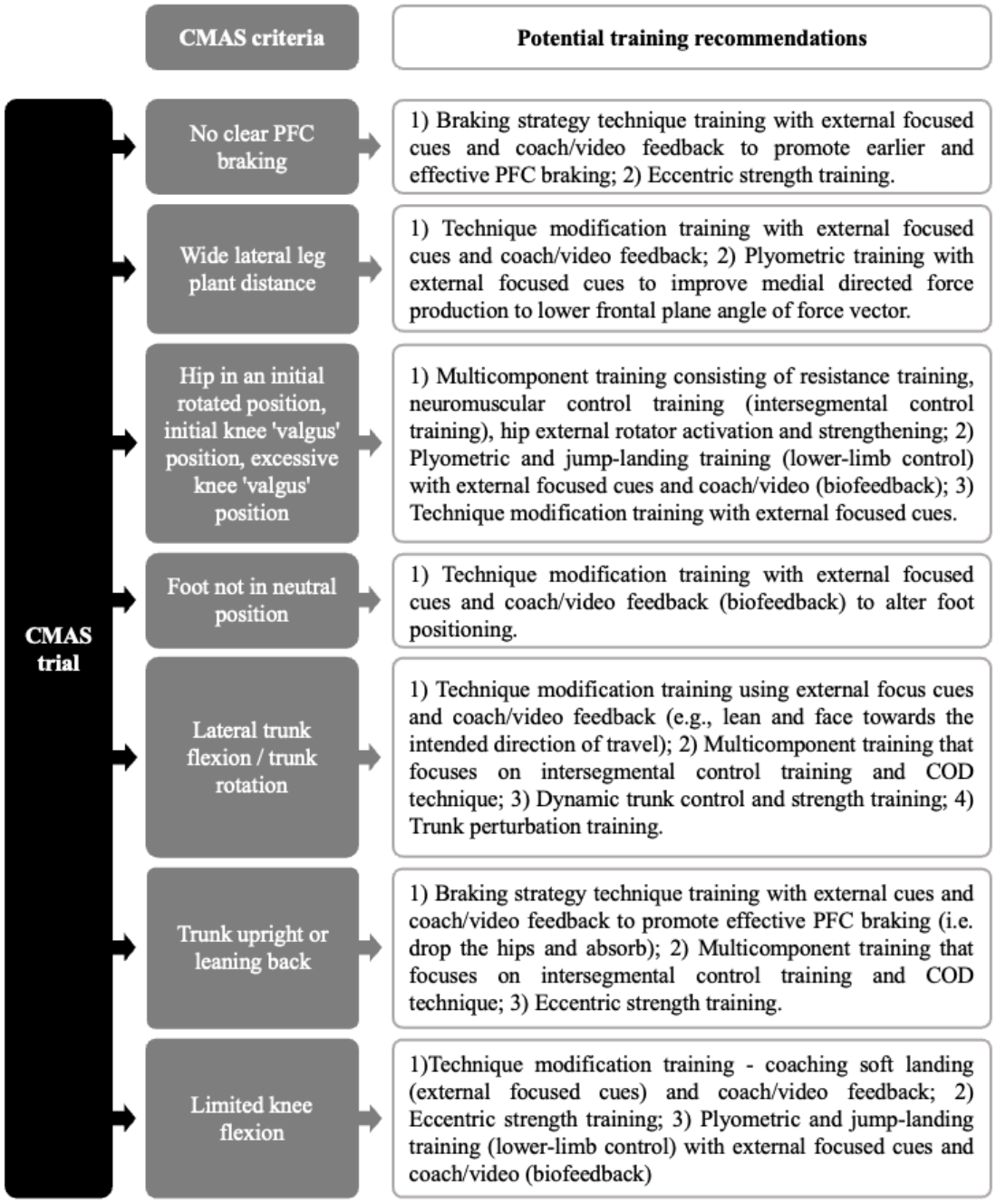


Figure 5. Decision tree for training recommendations based on CMAS, adapted from Dos'Santos et al. (2021).
Abbreviations: CMAS, Cutting Movement Assessment Score; PFC, Penultimate Foot Contact; COD, Change of Direction.

Core strength

As highlighted in the previous section on key technical factors in COD actions, trunk control in space is crucial for executing COD efficiently and safely. During the final foot contact in a COD action, maintaining an upright trunk, and ideally tilting and rotating the trunk and pelvis towards the intended direction of movement, is associated with improved COD performance (Dos'Santos, Comfort, et al., 2018; Marshall et al., 2014). At the same time, minimising lateral trunk flexion during the final foot contact reduces

knee joint loads, thereby decreasing the risk of injury (Dempsey et al., 2007, 2009; Havens & Sigward, 2015). Consequently, proper control and strength of the entire trunk and pelvic musculature may enhance athletes' multidirectional performance while mitigating the biomechanical risk factors inherent to these actions (Horníková & Zemková, 2024).

Recent meta-analysis studies (Dong et al., 2023) demonstrated that core-specific training has a significant positive effect on overall athletic performance, particularly in tests assessing trunk muscle endurance and dynamic balance. However, this type of training showed limited effect on sport-specific action and COD performance. These findings may be explained by the nature of the core exercises conducted during the interventions, as they often focus on developing endurance strength in the core musculature (Dong et al., 2023). In this context, the ability to generate high peak forces in the trunk and pelvic muscles within a short period of time is more important in COD performance than core muscle endurance (Horníková & Zemková, 2024). Therefore, general core training programmes focused on muscular endurance may be beneficial for improving performance in adolescent athletes or those with lower baseline performance (Horníková & Zemková, 2024). However, core training programmes for semi-professional or professional athletes should include more functional and sport-specific core exercises in closed kinetic chain to enhance COD performance. These exercises should prioritise rapid pre-activation of the core musculature to efficiently transmit forces and orientate the trunk in multiple directions (Horníková & Zemková, 2024). For this reason, an initial assessment is crucial to individualise training and to choose the appropriate core exercises based on the athlete's level and specific needs.

Muscle capacity of lower limbs

The ability to approach the cutting point as quickly as possible, decelerate in the shortest time and distance prior to the COD, and generate a greater braking impulse, are critical for COD performance. Although the performance of these actions is multifactorial and depends on a wide range of skills (Young et al., 2002), there is consensus in the scientific literature that stronger athletes demonstrate a higher rate of force development and superior external mechanical power, making them faster in multidirectional movements (Chen et al., 2023; Harper et al., 2022; Jones et al., 2022; Suchomel et al., 2016). Moreover, these athletes tend to have a lower risk of injury.

However, although numerous strength-related variables have been analysed in relation to COD performance, there is still no consensus on which specific strength qualities are the most important determinants in these actions (Chen et al., 2023). This lack of agreement poses a challenge for sports professionals seeking to optimise their players' performance, and could be explained by several reasons. Firstly, multidirectional movements are highly complex due to the diverse phases involved (McBurnie & Dos'Santos, 2022), and the wide variety of assessment tests available (Sugiyama et al., 2021). Secondly, there are multiple types of muscle actions (i.e., concentric, eccentric and isometric) and a broad range of conditions under which strength can be expressed, depending on the external load and the time available for force application (James et al.,

2023). This results in a range of independent strength qualities (i.e., maximal isometric strength, explosive strength, reactive strength, heavy dynamic strength, etc.). Depending on the authors taken as a reference, these strength-related concepts and the tests used to assess them may vary or even contradict each other (James et al., 2023); making it difficult to establish a consensus that provides strength and conditioning coaches with clear guidelines on the most important strength qualities required for COD performance. Therefore, to advance scientific understanding in this topic, it would be necessary to standardise the assessments of different independent strength qualities, as well as linear and multidirectional speed. ***Figure 6*** illustrates the standardised use of terms related to muscle actions, their interaction and the different independent strength qualities as outline in this doctoral thesis, following the framework of Badillo & Ayestarán (2002) and James et al. (2023).

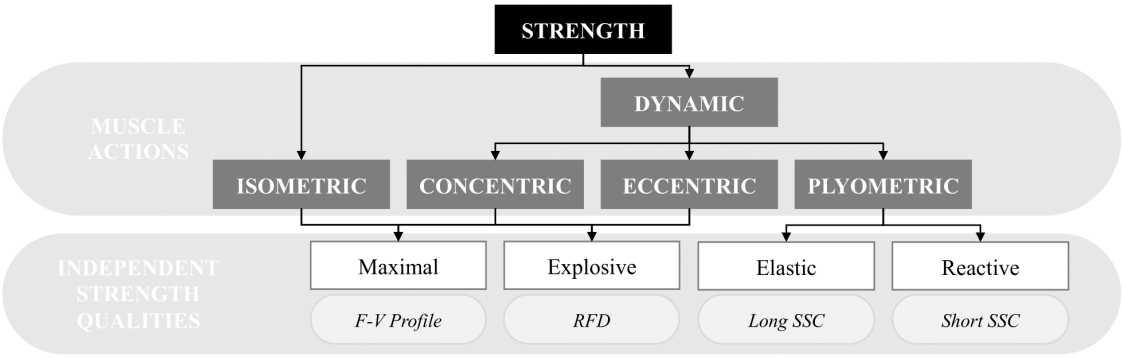


Figure 6. Classification scheme of different muscle actions illustrating their interaction and the different independent strength qualities.
Abbreviations: F-V, Force-Velocity; RFD, Rate of Force Development; SSC, Stretch-Shortening Cycle.

- ***Muscle actions***

COD are high-intensity ballistic actions that can be broken down into four phases: acceleration, deceleration, COD foot plant and re-acceleration (McBurnie & Dos'Santos, 2022). When changing direction, athletes must quickly and efficiently coordinate force application and impulse during the braking phase (i.e., eccentric), the COD foot plant phase (i.e., isometric) and the propulsion phase (i.e., concentric) of the movement (McBurnie & Dos'Santos, 2022). Although these phases can be analysed individually, COD should be considered as complete and indivisible movements, as all cutting phases are interrelated and mutually dependent. As a result, clear relationships may not be observed between isolated strength measures when the movement requires the simultaneous involvement of multiple strength components (Spiteri et al., 2014). Supporting this idea, previous studies suggested that all muscle actions equally influence on COD performance (Spiteri et al., 2015). However, these conclusions remain very superficial, highlighting the need for a deeper and more holistic approach to analyse the effect of different muscle actions and independent strength qualities on performance in each COD phase and their interactions. The relationship between each muscle action and COD performance was analysed below.

Eccentric. It was previously suggested that players with higher approach speed prior to the cut were less efficient at changing direction (Freitas et al., 2018), due to the higher body momentum they must decelerate within short periods of time to execute the COD efficiently. Consequently, in sports with multidirectional speed demands, deceleration capacity is considered a critical component for achieving effective performance (Winter et al., 2016). Deceleration, according to Harper et al. (2022), refers to an athlete's ability to proficiently reduce whole-body momentum, within the constraints, and in accordance with the specific objectives of the task (i.e. braking force control), whilst skilfully attenuating and distributing the forces associated with braking (i.e. braking force attenuation). However, this ability not only entails the rapid reduction of momentum but also requires the athlete to skilfully absorb and distribute high-impact forces through the muscle-tendon structures of the lower limb. This process may necessitate certain muscles to operate primarily through eccentric muscle action (Harper & Kiely, 2018; McBurnie, Harper, et al., 2021).

In multidirectional tasks requiring significant deceleration (i.e., COD >90º), the average rate of velocity change is 70–75% higher during the deceleration phase (ranging from –4.43 to –6.82 $m \cdot s^{-2}$) compared to the acceleration phase (from 2.55 to 4 $m \cdot s^{-2}$), due to the shorter times in which velocity changes typically occur during rapid decelerations (Zamparo et al., 2019). As a result, deceleration actions generate high peak of ground reaction forces, which may reach up to six times body mass (BM) (Nedergaard et al., 2014; Verheul et al., 2021). These forces may be up to 2.7 times greater in magnitude during maximal deceleration compared to acceleration of equal intensity ***(Figure 7A)***. The biomechanical forces observed in rapid decelerations are likely associated with an initial heel strike, an anterior foot placement, and very high peak segmental accelerations of the braking foot, tibia, and thigh (Chen et al., 2025; Nedergaard et al., 2014; Verheul et al., 2019).

On the other hand, depending on the distance and approaching velocity to the cut, a significant portion of the movement will be spent reducing speed prior to the COD; that is, decelerating ***(Figure 7B)*** (Graham-Smith et al., 2018). This is why a proper deceleration during the steps preceding the cutting action itself would be decisive in the COD performance and efficiency. In this regard, previous studies (Dos'Santos, & Jones, 2021a; Nedergaard et al., 2014) highlighted the importance of the ante-penultimate and penultimate steps prior to cutting ***(Figure 7C)***, with contact times of 200 and 235 ms, respectively. Specifically, Dos'Santos, & Jones (2021a) found that faster players in the 505 COD test exhibited higher braking forces in the ante-penultimate step, a higher horizontal force orientation in both the ante-penultimate and final step, and a higher horizontal:vertical force ratio in the final three steps. Interestingly, Jordan et al. (2021) reported plantar flexion velocities ranging from 307–484º/s and knee flexion velocities between 325–469º/s, with these velocities increasing as deceleration demands intensified.

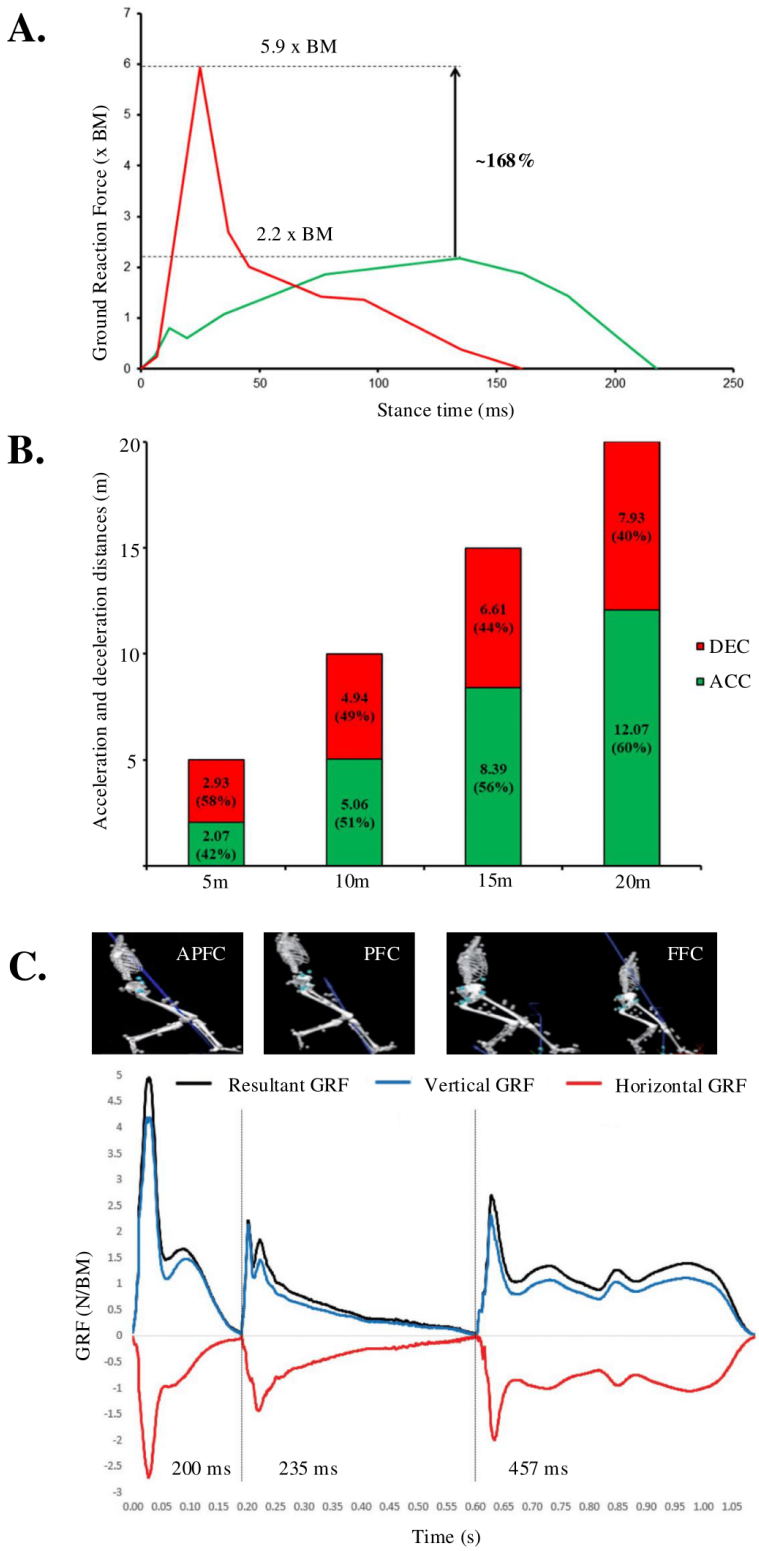


Figure 7. Different deceleration characteristics in change of direction actions. (A) Comparison of ground reaction forces during maximal deceleration (red line) and maximal acceleration (green line). Extracted and adapted from Harper et al. (2022) and Verheul et al. (2021). (B) Distance covered accelerating and decelerating from different approach distances in sprint-to-stop tests (percentage of time shown in parentheses). Extracted and adapted from Graham-Smith et al. (2018) and Harper et al. (2022). (C) Mechanical photo sequence and ground reaction force characteristics of the ante-penultimate, penultimate, and final foot contact during a traditional COD 505 test. Extracted and adapted from Dos'Santos & Jones (2021a) and Harper et al. (2022).

Abbreviations: BM, Body Mass; DEC, Deceleration; ACC, Acceleration; APFC, Ante-Penultimate Foot Contact; PFC, Penultimate Foot Contact; FFC, Final Foot Contact; GRF, Ground Reaction Forces.

Given the necessity to decelerate in COD actions —generating high peak forces (i.e., up to six times body weight), at very short ground contact times (i.e., <250 ms), and exhibiting high angular velocities of plantar and knee flexion— it would be crucial that the muscles involved in the control of the lower limb joints are capable of producing high internal extensor moments through eccentric actions to resist and control the joint flexion imposed by abrupt braking. Therefore, optimal execution of these deceleration actions involves reducing braking impulse and minimising body momentum through the interaction of multiple neuromuscular and biomechanical factors, including the need for high levels of technical skill and eccentric strength ***(Figure 8)*** (Harper et al., 2022).

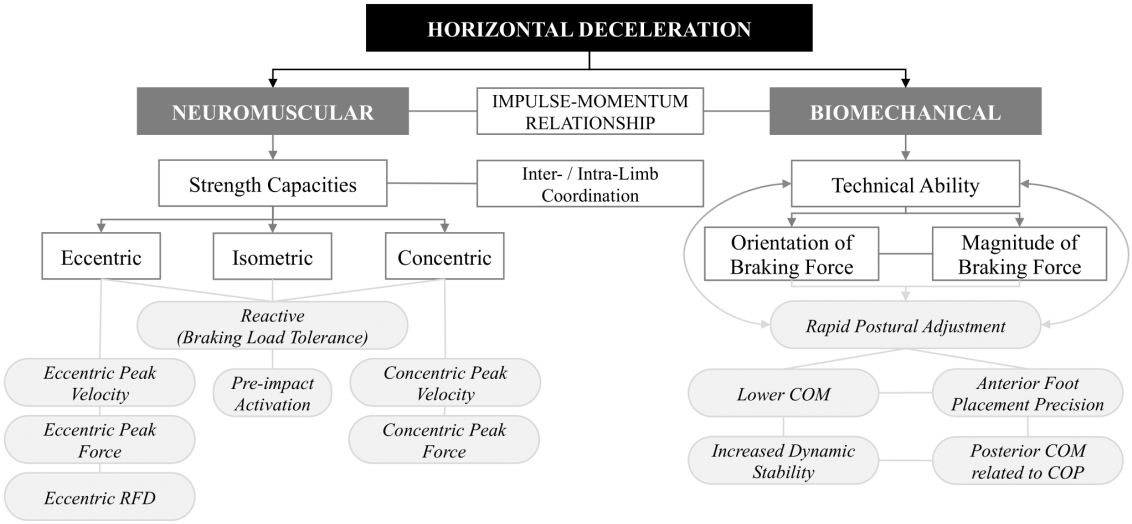


Figure 8. Biomechanical and neuromuscular determinants of horizontal deceleration ability. Extracted and adapted from Harper et al. (2022).
Abbreviations: RFD, Rate of Force Development; COM, Centre of Mass; COP, Centre of Pressure.

Due to the previously mentioned characteristics specific to deceleration actions and their critical role in COD performance ***(Figure 7)***, eccentric strength is considered a key performance factor in these actions. In particular, unilateral eccentric strength of the knee extensors (i.e., quadriceps) has demonstrated to be particularly important for horizontal deceleration ability (Harper et al., 2021; Jones et al., 2017; Zhang et al., 2021). When comparing female football players with high and low quadriceps eccentric strength, those with a greater ability to apply eccentric force during the braking phase of COD achieved higher approach velocities, shorter braking times before COD, and consequently, better overall COD performance (Jones et al., 2017). Given the high angular velocities reached in the lower limb joints in very short periods of time, rapid unilateral eccentric torque (from 0–100 ms) of the quadriceps may also be important for generating greater rapid force, power and impulse during horizontal deceleration (Zhang et al., 2021). This enhanced capacity could allow for a greater contribution of passive elastic tissue structures to force generation and attenuation during abrupt braking. Smajla et al. (2022) also found that, in a large sample of basketball and tennis players, eccentric strength alone explained 25.1% and 37.4% of performance in 90º and 180º cutting actions, respectively. The peak force variables and the rate of eccentric force development during a countermovement jump showed the greatest relationship with and impact on COD

performance. At this point, there appears to be a clear consensus in the current scientific literature highlighting the importance of both maximal and rapid eccentric strength in COD actions for efficient deceleration.

Isometric. Isometric strength involves the absence of external movement; therefore, it may be the least specific to most high-intensity ballistic actions performed in basketball compared to dynamic strength (Suchomel et al., 2016). Even so, a recent meta-analysis found a significant relationship (r =–0.41 [95% Confidence Interval (CI): –0.62 to –0.15]) between maximal isometric strength and COD actions (Chen et al., 2023). Specifically, the isometric mid-thigh pull exercise —although performed with knee (120º–150º) and hip (124º–175º) flexion angulations that are non-specific to COD (Comfort et al., 2019; Dos'Santos, & Jones, 2021b)— has shown significant relationships with performance on 505 COD tests in female basketball players (r =–0.85, p <0.01) (Spiteri et al., 2014) and male collegiate athletes (r =–0.57, p <0.05) (Thomas et al., 2015).

Findings from other studies, which evaluated isometric strength in the unilateral squat exercise at 140º of knee and hip flexion, in female basketball players (Spiteri et al., 2015) and male and female amateur athletes (Spiteri et al., 2013), demonstrated how players with higher isometric strength were able to exit faster after the cut (effect size [ES] =0.67, p =0.01) and, therefore, obtain a higher overall COD performance. After analysing the findings, the current scientific literature suggests that relative isometric strength may be a critical component of COD performance. Although it seems that isolated isometric strength training programmes do not improve multidirectional speed performance in team sports (Bimson et al., 2017). Still, it would be recommended to include isometric exercises in combination with other strength stimuli, as they increase neuromuscular adaptations in specific joint positions without increasing fatigue (Lum & Barbosa, 2019).

Concentric. Reaching high acceleration peaks pre- and post-cutting action is key for COD performance. Although the acceleration phase is influenced by multiple factors ***(Figure 9)*** (Bishop & Girard, 2013; Ross et al., 2001), the scientific literature highlights ground contact time and time to peak force production during stance as the key variables for optimising acceleration performance in team sports such as basketball (Lockie et al., 2011). While stride frequency may have some relevance (Hewit et al., 2013), these two variables are considered fundamental.

The theoretical model of the horizontal force-velocity profile, developed by Samozino et al. (2016), has provided valuable insight into the importance of maximal horizontal force application in acceleration actions. This model was supported by subsequent practical research (Buchheit et al., 2014), which concluded that the ability to apply horizontal force concentrically during the acceleration phase is a key determinant of individual performance in highly trained football players. These findings have been corroborated in other sports, such as futsal (Baena-Raya, García-Ortega, et al., 2021) and basketball (Baena-Raya et al., 2020). These studies indicate a strong relationship between linear acceleration and COD performance, emphasising the importance of maximal

horizontal force application for increased performance in these actions. For instance, in a case study involving three athletes, Baena-Raya, Rodríguez-Pérez, et al. (2021) observed that, despite all athletes displaying similar performance in the 20-metre linear speed test, the fastest player in COD actions was the one who exhibited a higher capacity to apply maximal horizontal force during the first steps of acceleration. This result highlights the relevance of both the magnitude and orientation of force in COD performance.

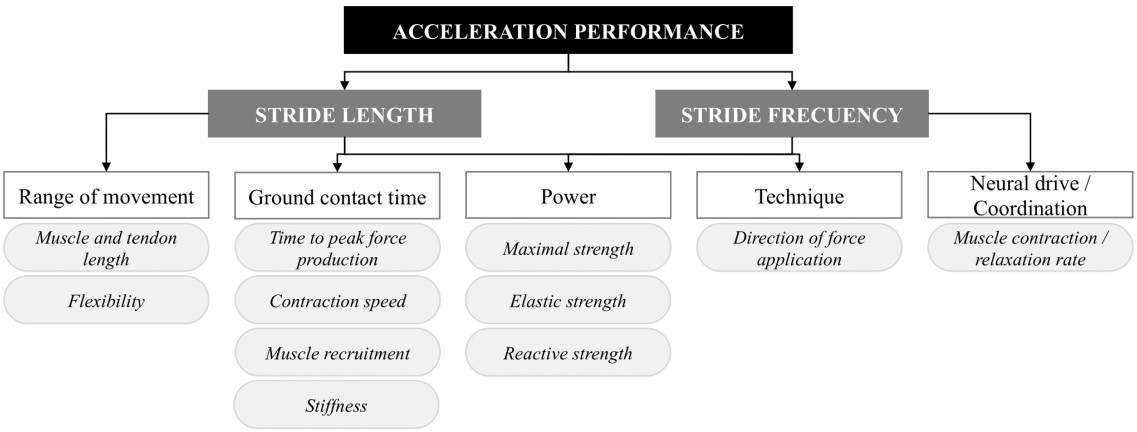


Figure 9. Components of acceleration performance. Adapted from Bishop & Girard (2013) and Ross et al. (2001)

Concentric maximal strength, traditionally assessed by 1-repetition maximum (1RM) in the squat exercise, has been significantly related to COD performance in female basketball players (r =–0.79, p <0.01) (Spiteri et al., 2014), in female softball players (r =–0.75, p <0.05) (Nimphius et al., 2010), and in female football and handball players (Falch et al., 2021); for both force-oriented (r =–0.48, p <0.05), and velocity-oriented (r =–0.50, p <0.05) COD. According to these results, female team sport athletes with a relative strength of less than 1.5 BM in the bilateral squat, or less than 1 BM in the unilateral quarter squat, could improve COD performance by increasing their concentric relative strength in these exercises. However, such significant relationships between lower-limb concentric maximal strength (i.e., 1RM) and COD at different cutting angles were not found in male athletes (Falch, Rædergård, & van den Tillaar, 2020a).

These discrepancies might be due to a multitude of factors such as: (1) the tests used to determine concentric maximal strength, as they only assess concentric maximal strength through high loads with very low velocities of displacement (i.e. 1RM) without taking into account the rest of the load-velocity profile; (2) the basal relative strength levels of each gender, as males tend to have higher initial relative strength levels than females, which could influence on COD performance; (3) the variability in methodologies, as each study uses different tests and variables to describe the samples, which would hinder the results' comparison. Currently, to the best of the author's knowledge, there are no studies that systematically analyse the relationship between different strength variables and COD performance considering the effect of gender with homogeneous methodologies. Therefore, it would be recommended to develop future studies investigating the effect of gender on the relationship between different strength variables and COD performance.

Plyometric. Plyometric actions involve, similar to COD, a SSC. This could be either short (<250 ms; velocity-oriented COD, <90º) or long (>250 ms; force-oriented COD, >90º) (Turner & Jeffreys, 2010). The SSC comprises a muscle action that includes an eccentric or stretch phase, followed by a transitional isometric period, culminating in an explosive concentric action with increased energy output. The incorporation of these muscular actions has been shown to improve sports performance by 20–30% compared to performing the action without a SSC (Bosco et al., 1987). These enhancements may be attributed to increased elastic energy storage and tension (Bojsen-Møller et al., 2005), increased activation of the central nervous system (Bosco et al., 1987), greater active range of motion (Bobbert et al., 1996), muscle length-tension characteristics (Finni et al., 2001), muscle pre-activation (Kyrölänen et al., 1991) or improved intra- and inter-muscular coordination (Bobbert et al., 1996) inherent to the SSC.

The role of elastic and reactive plyometric actions in COD actions is evident in the initial acceleration and re-acceleration phases, as well as during the COD foot plant itself, which requires the immediate release of stored elastic energy for propulsion and re-acceleration (Jarvis et al., 2022). Consequently, previous studies found significant correlations (r ≤–0.57) between both skills, plyometric strength and COD performance (Chen et al., 2023; Falch, Rædergård, & van den Tillaar, 2020a; Jarvis et al., 2022; Jones et al., 2009; Smajla et al., 2022). Additionally, Jarvis et al. (2022) suggested that force-oriented COD (i.e., with sharper cutting angles) are more closely associated with elastic plyometric strength variables, whereas velocity-oriented COD (i.e., with more shear angles) are linked to reactive plyometric strength. Force-oriented COD involve longer ground contact times (>400 ms) (McBurnie & Dos'Santos, 2022); which is why they may be more related to a long SSC. Conversely, velocity-oriented COD exhibit shorter ground contact times (<250 ms) (McBurnie & Dos'Santos, 2022), similar to those of a short SSC. In this regard, Jones et al. (2009) found a significant correlation between a long SSC and force-oriented COD actions (r =–0.50; p <0.01), while this relationship disappeared with a short SSC. These findings were confirmed in subsequent studies with highly trained male football players, Falch, Rædergård, & van den Tillaar (2020a) found large significant relationships (r =–0.61; p <0.05) between a long SSC (i.e., unilateral countermovement jump) and force-oriented COD actions (i.e., COD180º); whereas a short SSC (i.e., drop jump) only demonstrated significant relationships (r =–0.54; p <0.05) with velocity-oriented COD actions (i.e., COD45º).

The current scientific literature highlights the great importance of plyometric strength on COD performance in male players of different sports, such as football (Falch, Rædergård, & van den Tillaar, 2020a), Australian football (Young et al., 2015) or rugby (Delaney et al., 2015). Nevertheless, when the samples are composed of female athletes in basketball (Spiteri et al., 2014), softball (Nimphius et al., 2010), handball and football (Falch et al., 2021), the variables of elastic, reactive or power strength extracted from plyometric actions did not show any significant relationship with COD performance. Conversely, other strength variables, related to higher loads and lower velocities within the load-velocity profile, demonstrated a stronger relationship with COD actions in females. These differences between genders could be explained by the different methods

used to assess plyometric strength, the different COD tests used in the assessments or the lower levels of basal strength generally reported by the female gender (Lazić et al., 2022). Thus, no clear consensus has been reached on the relationship between plyometric strength and COD performance from previous scientific evidence so far.

Another important variable when analysing the effect of plyometric strength on COD actions is the force orientation, as these actions are multidirectional and involve multiple force vectors interacting with the athlete during COD execution. However, the literature so far has primarily analysed plyometric and reactive strength with a vertical orientation. Some authors, such as Peterson et al. (2006), found high correlations between the T-test and single horizontal jumps with long ground contact times in young male ($r = –0.61$, $p < 0.01$) and female athletes ($r = –0.79$, $p < 0.01$). Similarly, Chaouachi et al. (2009) also reported high correlations ($r = –0.61$, $p = 0.02$) between the T-test and the five alternating reactive horizontal jump test in elite male basketball players. However, in another study with elite male football players (Chaouachi et al., 2012), the relationship between these same tests was marginal. As can be observed, the specific characteristics of the sample might influence the outcome of the association between these variables. Nevertheless, the existing literature on the effect of horizontal plyometric actions on COD performance remains limited and contradictory, preventing clear conclusions. Therefore, future scientific studies should investigate this topic by comparing gender differences, using plyometric tests involving different force orientations, and implementing a standardised COD assessment to ensure comparability of data across studies.

- ***Musculature involved in COD actions***

In addition to the relationship between COD performance, the different muscle actions and strength qualities, another important aspect to analyse is the musculature involved in these actions and the peak of activation they reach. The complexity and multidirectional nature of COD make them unique actions in the sporting context, with peaks of muscular activity very different from other athletic skills, such as jumps or strength exercises in different planes of movement (Falch, Rædergård, & Van den Tillaar, 2020a; Falch, Rædergård, & van den Tillaar, 2020c).

Specifically, jumping actions and vertical strength exercises showed greater muscle activations in musculature primarily responsible for controlling movement within a single plane of motion (Falch, Rædergård, & van den Tillaar, 2020a). For example, the rectus femoris, which is responsible for knee flexion-extension in the sagittal plane. However, COD actions demonstrated higher activation peaks in muscles that generate substantial horizontal force and contribute to control the knee and hip stability in multiple directions, while ensuring proper trunk orientation during multidirectional movements. These muscles include the adductor longus, gastrocnemius, semitendinosus and biceps femoris (Falch, Rædergård, & van den Tillaar, 2020b). The muscle activation patterns observed during COD actions in these specific muscle groups are not similar to any other athletic skill. Consequently, it would be recommended that strength training target these muscles both in isolation and through sport-specific exercises to optimise COD performance

(Falch, Rædergård, & Van den Tillaar, 2020a; Falch, Rædergård, & van den Tillaar, 2020c).

However, it is important to interpret electromyographic activation results during COD actions with caution, as peak force levels are reached during the deceleration phase through eccentric muscle activation (Harper et al., 2022). Previous studies suggest that such force peaks during the deceleration phase in COD (i.e., eccentric muscle action) are not related to electromyographic activity (Chaabene et al., 2018). This may be because eccentric muscle actions exhibit lower electromyographic activity compared to concentric muscle actions (Bigland-Ritchie & Woods, 1976), mainly due to a reduced number of actively recruited motor units and lower discharge rates during eccentric actions (Duchateau & Enoka, 2016). Additionally, there is evidence of a selective recruitment of fast twitch motor units during maximal eccentric muscle actions (Nardone et al., 1989), a strategy also observed during high intensity COD actions (ter Haar Romeny et al., 1982).

Finally, previous studies demonstrated that players with greater knee and ankle strength produced superior horizontal deceleration and COD performance (Chen et al., 2025). Interestingly, deceleration performance with different sprint distances may have different demands on the knee and ankle strength. Specifically, ankle plantarflexion strength was more crucial when decelerating from slower sprint velocities, whereas knee extensor strength may be key in deceleration actions involving higher movement speeds and longer sprint distances. For all these reasons, it would be recommended to consider the specific muscular demands of COD actions to optimise performance in basketball players.

Inter-limb asymmetries

Although basketball is a sport that involves a wide variety of predominantly unilateral movements and jumps, any asymmetries that may arise during the natural movement of the sport are often compensated for by subsequent actions (Ibáñez et al., 2023). For this reason, basketball could be considered a symmetrical sport, where inter-limb differences observed in athletes may not be directly attributed to training, competition, specific tasks, game situations or player positions (Ibáñez et al., 2023). However, some players may develop asymmetries in specific cases, which are probably not caused by basketball practice. Despite this, it would be recommended that the coaching staff identify any asymmetries as soon as possible and apply corrective training to minimise or make them disappear (Ibáñez et al., 2023).

Scientific literature has shown a growing interest in analysing the relationship between inter-limb asymmetry and its impact on both injury risk and athletic performance (Guan et al., 2022). Regarding injury risk, previous studies indicate that athletes with inter-limb asymmetries greater than 10–15% exhibit a higher incidence of injury compared to those athletes who do not reach these thresholds (Grindem et al., 2011; Kyritsis et al., 2016). Such asymmetry could increase the risk of injury in both limbs: the stronger leg might be overstressed due to increased reliance and loading, whereas the weaker leg might not be able to withstand even low loads (Ford et al., 2003). Additionally,

inter-limb asymmetries have been linked to a greater risk of sports injuries, by generating uneven force absorption or a loss of stability in the frontal plane (Paterno et al., 2010), which is particularly critical for managing the impact forces inherent to basketball.

On the other hand, the role of inter-limb asymmetry in sports performance remains unclear and contradictory (Bishop, Turner, et al., 2018; Fox Id et al., 2023). Some studies have found that inter-limb asymmetry close to ∼10% leads to reduced performance in jump actions (Bell et al., 2014) and slower COD movements (Hoffman et al., 2007; Kozinc & Šarabon, 2020). Furthermore, a recent meta-analysis (Fox Id et al., 2023) suggested that inter-limb asymmetries, assessed through unilateral jumps tests, negatively impacted performance in both linear speed and COD actions. Conversely, other studies have reported conflicting results (Bishop, Turner, et al., 2018; Dos'Santos, Jones, et al., 2018; Işln et al., 2022; Lockie, Callaghan, et al., 2014; Raya-González et al., 2020), arguing that the presence of inter-limb asymmetries may be justified in sport actions where limb dominance is evident (Schiltz et al., 2009).

The existing controversy in the current scientific literature regarding the impact of inter-limb asymmetries on athletic performance may be explained by several factors. Firstly, (1) the methodology used to calculate inter-limb asymmetry significantly influences the results obtained (Bishop et al., 2016). In this regard, the literature has documented more than ten different formulas for calculating asymmetry across different scientific studies (Bishop et al., 2016). Since the choice of formula directly affects the outcome, these data are not completely comparable and may even lead to contradictory conclusions. Furthermore, the methods used to determine the athlete's dominant limb may also impact the results (McFadden et al., 2022). Until appropriate standards for classifying limbs during testing are established, the standardisation of normative values for asymmetries should be considered with caution.

Another critical aspect is (2) the control motor difficulty associated with many unilateral tests used to assess inter-limb asymmetries. This difficulty can lead to inconsistent results, with high coefficients of variation (CV), particularly if athletes are unfamiliar with the test or lack proper motor control over the test (Bishop, 2020). If a test or metric presents a CV above 10%, its reliability is questionable (Atkinson & Nevill, 1998). For instance, if a metric reflects a high asymmetry value (e.g. 25%) but with a CV of 20%, the result may lack relevance due to the low measurement reliability (Bishop, 2020). This suggests that not all observed inter-limb asymmetries are necessarily relevant to performance.

Precisely due to these previous points, (3) the use of standard thresholds to determine an athlete's asymmetry, regardless of the test used, constitutes another common error found in many scientific publications (Bishop, 2020). In most cases, previous studies that use standard thresholds to classify athletes as asymmetric often use thresholds of 10–15%, based on previous research findings rather than their own empirical data (Bishop, 2020). Given that inter-limb asymmetries are highly dependent on the type of test applied (Read et al., 2020), the use of generic thresholds represents a simplistic approach that fails to capture the complexity of these differences.

Finally, (4) the asymmetry direction (i.e., the dominant limb in the test) is another factor that requires caution (Fílter et al., 2021). The dominant limb is not always the same across different tests, even when assessing the same ability through different tests (Ujaković & Šarabon, 2021). For example, the asymmetry direction was different when assessing multidirectional speed using curvilinear sprint and COD test in football players (Fílter et al., 2021) or across different cutting angles in basketball players (Gonzalo-Skok & Bishop, 2023). Therefore, assessing an athlete's asymmetry with a single test may not provide a comprehensive picture.

Due to the current limitations in measuring and calculating asymmetry, determining its accurate impact on athletic performance remains challenging. Consequently, recent studies have suggested a paradigm shift in how asymmetry should be approached in sport performance (Afonso, Peña, et al., 2022; Maloney, 2019). A critical review proposes considering asymmetry, rather than as a negative factor, as a 'window of opportunity' (Maloney, 2019). From this perspective, in scenarios of high asymmetry, the weaker limb is underdeveloped, while the stronger limb may experience greater stress during sports training. Over time, this would imply a higher training load for the stronger side and a greater potential for improvement in the weaker side (Maloney, 2019). This approach is based on the principle of decreasing performance (Peterson et al., 2005), which states that the capacity to generate positive performance adaptations decreases as an athlete's performance is close to their maximum potential. In this regard, the dominant limb, being closer to its maximum performance potential, will have more limited margin for improvement. In contrast, the non-dominant limb will have a greater potential for adaptation, presenting an opportunity to enhance its development and, consequently, the athlete's overall performance (Maloney, 2019). This new paradigm suggests focusing training on the weaker link rather than merely reducing asymmetry. This approach may help explain the findings of certain training interventions that successfully reduced asymmetry while simultaneously improving athletic performance (Brown et al., 2017; Bazyler et al., 2014; Gonzalo-Skok, Tous-Fajardo, Suarez-Arrones, et al., 2017).

In conclusion, asymmetry in sports persist regardless of age, gender or competitive level; it can even be observed in sports traditionally considered symmetrical, such as running (Girard et al., 2017; Virgile & Bishop, 2021), rowing (Fohanno et al., 2015), cycling (Carpes et al., 2010), or even basketball (Ibáñez et al., 2023). However, asymmetry should be accepted as an inherent phenomenon of sport rather than a cause for concern or a direct risk factor for injury. Most studies assessing bilateral asymmetries are not longitudinal, limiting their capacity to establish causal relationships with injuries, as they do not directly track injury occurrence (Bahr, 2016; Opar et al., 2022; Ruddy et al., 2019). Indeed, it is widely accepted that injuries may lead to increased inter-limb asymmetries (Bishop, Read, et al., 2018; Kotsifaki et al., 2022), whereas there is no conclusive evidence to suggest that pre-existing asymmetries increase injury risk. Therefore, just as cranio-caudal or dorso-ventral asymmetries in the human body are accepted, it is advisable to recognise inter-limb asymmetry as a natural —and even beneficial— characteristic of human structure and athletic performance (Afonso, Peña, et al., 2022; Maloney, 2019). Furthermore, it is crucial to consider that asymmetry

assessments are highly dependent on test, metric, individual and sport-specific characteristics. These asymmetries fluctuate considerably over time, both in magnitude and, more notably, in direction (Afonso, Peña, et al., 2022). This variability complicates their analysis, as asymmetry-related variables tend to show weak correlations with each other and with measures of athletic performance (Afonso, Peña, et al., 2022).

Functional movement

Multidirectional actions in a sport context challenge many of the athlete's capacities. Among them, efficient execution of a COD requires an optimal balance between mobility and stability across all body structures, particularly the lower limbs, to ensure effective force transmission during the acceleration, deceleration, and re-acceleration phases of COD (Gonzalo-Skok & Tous, 2015). To assess functional movement and its relationship with COD actions, previous literature has employed ankle mobility tests, such as the Weight-Bearing Dorsiflexion Test (WB-DF), and dynamic balance tests, such as the Star Excursion Balance Test (SEBT) or its shortened version, the Y-Balance Test (YBT) (Gonzalo-Skok et al., 2015). These tests are commonly used in the scientific literature to assess lower limb stability and mobility (Chisholm et al., 2012; Overmoyer & Reiser, 2013), monitor rehabilitation processes (O'Driscoll et al., 2011), or identify potential injury risks in athletes (Sman et al., 2014).

On the one hand, limited ankle mobility may lead to increased valgus and medial knee displacement, as well as reduced quadriceps activation (Dill et al., 2014). These may alter the biomechanics of multidirectional actions resulting in a greater knee abduction moment and increasing the risk of anterior cruciate ligament injury (Dos'Santos, McBurnie, Donelon, et al., 2019; Jones et al., 2017). However, previous studies have found no relationship between ankle mobility and performance in either linear or multidirectional speed actions (Gonzalo-Skok et al., 2015).

On the other hand, the SEBT requires high levels of neuromuscular coordination, strength, flexibility and range of motion, especially at the hip, making it a valuable indicator of dynamic postural control (Gribble et al., 2012). Additionally, Endo & Sakamoto (2014) demonstrated that the posterolateral and posteromedial directions of the SEBT were positively correlated with limited hip internal rotation and hamstring stiffness in basketball players. The anterior and posterolateral direction of the SEBT were also related with hip abductor, flexor and extensor strength (Ambegaonkar et al., 2014). Factors such as dynamic body control (Dos'Santos et al., 2021), hip mobility (Dos'Santos, & Jones, 2021b; Falch, Rædergård, & van den Tillaar, 2020b), hamstring stiffness, and hip muscle strength (Falch, Rædergård, & Van den Tillaar, 2020c) may directly influence COD performance. These findings could justify why previous studies have identified a significant relationship between dynamic balance and multidirectional speed in basketball (Gonzalo-Skok et al., 2015), football and rugby players (Lockie et al., 2016).

Anthropometric characteristics

Anthropometry is another area analysed in the scientific literature regarding its effect on COD performance. While several studies have analysed the influence of anthropometric variables such as height, BM or fat mass percentage on COD performance, the findings remain contradictory. Among these variables, fat mass percentage and BM have shown the highest correlations with COD actions (Gonzalo-Skok & Tous, 2015). In this context, BM has demonstrated a moderate to high relationship with COD tests —such as the T-Test or the 505-test— in young athletes (Peterson et al., 2006), professional rugby players (Delaney et al., 2015), and elite basketball players (Chaouachi et al., 2009). Furthermore, previous research (Nimphius et al., 2010) found 'near-perfect' correlations between BM and COD performance throughout the season in female softball players. Similarly, Ryan et al. (2022) reported that BM affected the ability to execute a 180° COD, observing significantly slower times in heavier players during three of the COD sub-phases. These findings support the notion of a direct relationship between BM and COD performance. However, this influence may depend on the characteristics of the sample analysed, as no such relationships were observed in other groups, like rugby players (Gabbett et al., 2011).

Regarding the fat mass percentage, it is reasonable to assume that athletes with lower fat mass percentage achieve a higher performance in multidirectional movements (Gonzalo-Skok & Tous, 2015). This may be because athletes with higher fat mass require greater force production per unit of muscle mass to execute a COD or modify their velocity (Enoka, 2008). In this regard, previous studies carried out with basketball players have identified a strong relationship between fat mass percentage and COD performance (Chaouachi et al., 2009). Lastly, athlete height does not appear to be associated with COD performance (Chaouachi et al., 2009); taking into account that a potential limiting factor in this context could be the height of the centre of mass during COD execution (Shimokochi et al., 2013).

TOOLS AND TESTS FOR ASSESSING CHANGES OF DIRECTION

The assessment of speed in sports has frequently been conducted using linear tests exceeding 20 metres, designed to evaluate both the acceleration and the maximum velocity (Asimakidis et al., 2025). However, in sports such as basketball, which is characterised by a small court, with frequent short and multidirectional movements, the use of long-distance linear tests may have little relevance. Given the multidirectional nature and specific characteristics of the sport, it might be recommended to implement tests that include both short linear and multidirectional movements to more accurately assess basketball players' speed. Selecting appropriate tests is essential for identifying areas for improvement and optimising athletic performance. Furthermore, to ensure that the collected data will be useful and reliable, it is essential to follow a standardised assessment protocol and employ valid instruments that minimise potential measurement errors. Therefore, conducting a preliminary analysis of the tests and assessment tools is crucial.

Assessment tests

Due to the importance of COD in basketball and the growing scientific interest in these actions (Mancha-Triguero et al., 2019), several studies have aimed to develop and validate new multidirectional speed tests adapted to sport-specific movements patterns and distances (Stojanović et al., 2019). Currently, more than 50 different tests have been designed to assess COD ability in basketball players (Sugiyama et al., 2021). Rather than facilitating the daily practice of strength and conditioning coaches, this diversity of tests may pose a challenge, as it complicates the standardisation of assessment. Each COD test has different characteristics and, therefore, assesses different aspects of performance.

In this regard, one of the main limitations of many traditional COD tests is their duration. These tests often involve long distances, multiples COD and execution times exceeding five seconds (Nimphius et al., 2018). This approach may be problematic, as longer tests engage additional physical capacities, such as aerobic capacity or linear speed, loosing focus on the specific assessment of COD action. To ensure a more accurate assessment, execution times should remain shorter and below five seconds (Nimphius et al., 2016). Furthermore, most tests frequently used to assess COD ability primarily assess athletes' manoeuvrability rather than the isolated COD capacity. For instance, tests such as the T-Test, the L-Run or the Illinois Test include curvilinear movements and specific motions patterns that may influence results, making them more dependent on the type of movement than on the athletes' pure COD ability (Nimphius et al., 2018). Conversely, tests designed with shorter approach and departure distances (i.e., less than 1 meter before and after the cut) are also not ideal due to the low reliability of measurement instruments associated with such short distances (Sayers, 2015). Therefore, caution should be exercised when selecting and designing a test battery to assess multidirectional speed in basketball players. It is essential to prioritise tests that align with the sport-specific characteristics, avoiding both excessive distances and specific movement patterns that introduce external variables, which may affect the reliability of the results.

The ‘Gold-Standard’ test for assessing COD ability does not yet exist and, most likely, may never be developed unless we reconsider how this ability is evaluated. Due to the unpredictable nature and wide variety of movements performed by basketball players on the court, involving a broad range of approach distances and COD angles (Gonzalo-Skok et al., 2023). Because of this diversity, it would be unfeasible to define a single test as the absolute standard test for COD assessment. Moreover, the lack of consensus on an ideal methodology has led to the use of different tests across research. This variability makes it difficult to directly compare results, as an athlete's performance in a COD test is highly dependent on specific characteristics of the test, such as the distance covered, number of cuts and cutting angle (Dos’Santos, Comfort, et al., 2018). This heterogeneity in assessment methods complicates scientific knowledge on COD, as it hinders the establishment of generalisable conclusions. Therefore, it is strongly recommended to standardise COD tests and develop a multidirectional COD angle profile for athletes, enabling a more comprehensive understanding of their performance in sport specific scenarios (Asimakidis et al., 2025; Gonzalo-Skok et al., 2023).

In the analysis and assessment of, for example, vertical jumping actions, it is well established and widely accepted that different types of jumps exhibit distinct kinetic and kinematic differences (e.g., Squat Jumps, with no SSC involvement; Countermovement Jumps, with a slow SSC; or Drop Jumps, with a fast SSC) (Makaracı et al., 2021; Van Hooren & Zolotarjova, 2017). These differences generate specific neuromuscular demands depending on the type of jump assessed (Van Hooren & Zolotarjova, 2017). Consequently, strength and conditioning coaches should understand the characteristics of each jump type to select the most appropriate test according to the neuromuscular capacity they aim to assess in the athletes. However, this depth of knowledge and specificity, which is well-documented in the scientific literature for vertical jump assessment, has not yet been fully reflected in COD assessment.

In this context, it is worth highlighting that both the traditional 505 test (i.e., 15-metres before, cut, and five metres after) and the modified 505 test (i.e., five metres before, cut, and five metres after) mitigate many of the limitations associated with other COD tests (Sayers, 2014). Furthermore, these two protocols have been extensively researched in the scientific literature (Asimakidis et al., 2025; Ryan et al., 2021, 2023). This test avoids the limitation of test duration, as execution times are between 2 and 3 seconds (Nimphius et al., 2016). Additionally, the 505 test removes much of the complexity of the task, as it involves a single cut with a clear COD step contact and does not require running around cones (i.e., manoeuvrability test). Therefore, it provides a measure of COD ability with a particular emphasis on deceleration capacity before the cut in the traditional 505 test (i.e., 180° COD), making it a potential 'two-in-one' test for assessing both COD ability and deceleration of athletes ***(Figure 10)*** (Westheim et al., 2023). To contextualise, the normative values for execution time in the traditional 505 test reported in previous scientific literature for senior male basketball players have been 2.62 ± 0.21 on average (Ryan et al., 2021). For a kinetic assessment (i.e., accelerations and decelerations) of athletes during this test, in addition to measuring total execution time, instantaneous velocity should be assessed using appropriate instruments such as monitored resistance devices, radar, lasers systems or mobile applications. However, these technologies are often costly and, therefore, unaffordable for many sports practitioners. As a result, their use may be restricted to high-performance environments or specific research studies.

As previously mentioned, each cutting angle presents different kinetic, kinematic and biomechanical characteristics (Dos'Santos, & Jones, 2021b). Therefore, the neuromuscular demands and the load supported by the athlete during the traditional 505 test at 180º does not represent other COD angles. Given the wide range of multidirectional movements required in basketball, and the necessity for players to be equally proficient in both right- and left-footed COD across a spectrum of cutting angles (Gonzalo-Skok et al., 2023); it would be recommended to adopt a comprehensive perspective on multidirectional speed performance. To achieve this, COD ability should be assessed using the modified 505 test at different cutting angles —505 modified at 45º (shear), 90º (moderate), and 180º (sharp) of cut— to develop an individual COD angle profile for each player ***(Figure 4)*** (Beato et al., 2024; Dos'Santos, Comfort, et al., 2018).

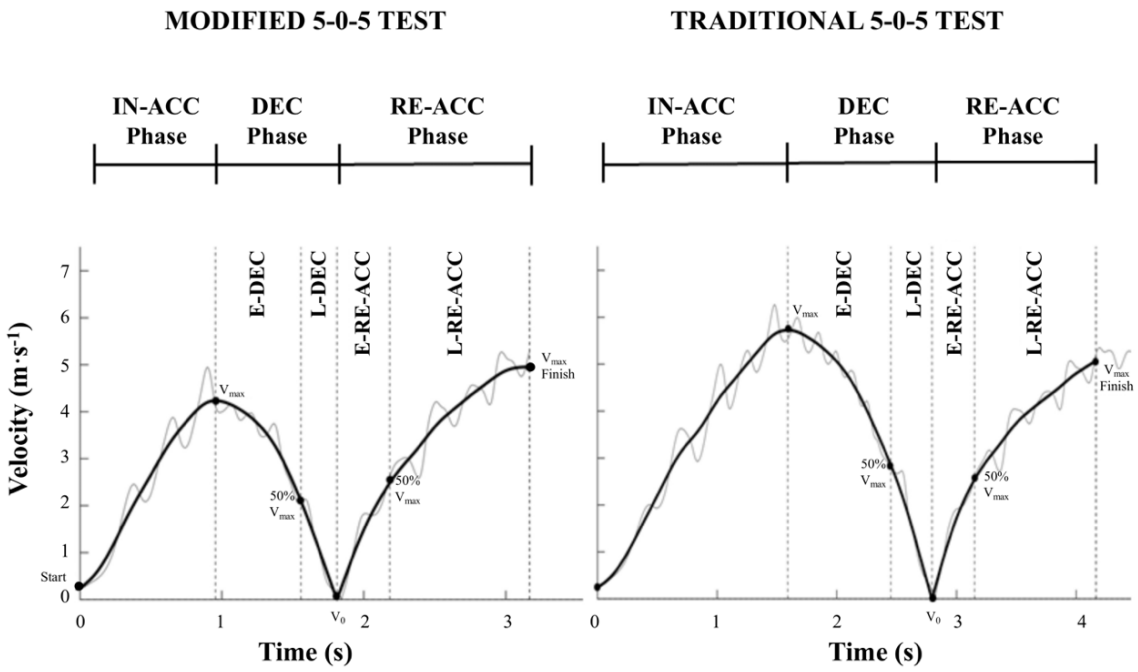


Figure 10. Example change of direction velocity-time profiles in modified and traditional 505 180º change of direction tests, enabling identification and evaluation of change of direction sub-phase (i.e., initial acceleration, deceleration, turn and re-acceleration) performances. Extracted and adapted from Westheim et al. (2023).
Abbreviations: IN-ACC, initial-acceleration; DEC, deceleration; RE-ACC, re-acceleration; E-DEC, early deceleration; L-DEC, late deceleration; E-RE-ACC, early re-acceleration; L-RE-ACC, late re-acceleration.

However, the total execution time of a 505 test may not necessarily provide an accurate measure of an athlete's COD capacity. Previous studies found that the cutting action only accounts for ~23–31% of the total time in a traditional 505 test (Ken-ichi et al., 2019; Nimphius et al., 2016; Ryan et al., 2022), while the remaining time is spent on linear acceleration and deceleration phases. Consequently, linear sprinting ability may also influence 505 completion times, and this effect is likely more pronounced in traditional 505 tests compared to modified 505 tests due to the higher approach speed. In basketball players, 74.8% of the variance in these COD tests is explained by linear speed (Delextrat et al., 2017). Therefore, assessing COD actions solely through execution time may not be considered an appropriate strategy if aiming to isolate COD ability. To address this limitation, previous studies have developed the concept of CODD.

The CODD aims to effectively isolate the COD action from the player's linear speed ability (Nimphius et al., 2013). Initially, this variable was calculated as the difference between COD time and linear sprint time (Nimphius et al., 2013). However, this measurement varied considerably depending on the unit of measurement used for the same test —total time or velocity—. More recently, it has been proposed to calculate CODD based on the percentage difference between the linear speed and COD ability of each athlete, allowing for standardised comparisons between both speed tests (Freitas, Pereira, et al., 2021). In both cases, CODD represents the amount of time a player specifically spent on COD actions during testing and indicates the athlete's efficiency in these movements (Freitas, Pereira, et al., 2021; Nimphius et al., 2013). A lower CODD

value suggests greater COD ability or, alternatively, lower linear speed. Previous studies (Nimphius et al., 2013, 2016) found that CODD correlated with COD performance —measured by execution time—, although no significant correlations were observed between CODD and linear speed tests. These results suggest the use of the CODD to isolate and quantify the athlete's performance and efficiency in COD actions, regardless of their linear speed. Furthermore, CODD has been further explored at various cutting angles (Cuthbert et al., 2019) and different types of displacements (e.g., from linear speed to lateral shuffle) (Nimphius et al., 2018). It has been shown to be more sensitive detecting inter-limb asymmetries in COD actions during a 505 test (Gonzalo-Skok et al., 2023). Therefore, analysing CODD should be a minimum requirement when assessing the athlete's COD capacity.

On the other hand, given the high incidence of non-contact injuries occurring during cutting actions, such as anterior cruciate ligament injury (Kadlec et al., 2023), it is recommended to consider qualitative assessment tools to obtain a more comprehensive understanding of multidirectional actions in basketball players. COD actions generate high joint torques and significant muscular demands on the lower limbs. These demands are even greater in real game situations, where athletes execute cutting actions in response to external stimuli (Brown et al., 2014). Specifically, the load acceptance during the COD foot plant phase has been identified as the most hazardous for athletes, with a higher injury risk in female players (Brown et al., 2014). For these reasons, it should be recommended to use qualitative COD assessment to analyse athletes' biomechanics during these actions and minimise injury risk factors during COD (Jones et al., 2017). To this end, Dos'Santos, McBurnie, Donelon, et al. (2019) have developed and validated the CMAS ***(Table 6)***, a qualitative observational tool to assess injury risk based on cutting mechanics (Dos'Santos, McBurnie, Donelon, et al., 2019; Jones et al., 2017). This tool enables sport professionals to determine the risk players face when performing COD in their sport context and propose specific interventions to address each athlete's biomechanical needs ***(Figure 5)*** (Dos'Santos et al., 2021). Additionally, CMAS could help improve movement mechanics, reduce joint loading, and minimise the risk of injury during COD actions (Dos'Santos et al., 2021).

Finally, to ensure that an appropriate test battery has been created for the players, the included tests should allow the strength and conditioning coach to at least: (1) classify the player to compare their performance with teammates or a similar sample —inter-individual comparison—; (2) monitor and control the evolution of the athlete's performance in the assessed physical ability —intra-individual comparison—; and (3) classify the athlete according to their physical needs to prescribe an individualised training programme, thus improving more efficiently the performance of the assessed skill (James et al., 2024; Weakley et al., 2023). Although much progress has been made in recent years regarding COD assessment, unfortunately, there is still no quantitative COD assessment approach that encompasses all three of the above-mentioned points to take full advantage of athlete assessment. Currently, by evaluating COD actions using any of the mentioned methods throughout this doctoral thesis, it is possible (1) to compare the athlete with other players of similar characteristics and, (2) to control their

performance evolution. However, none of these methods allows the sport practitioner (3) to understand the individual physical needs of the athlete to prescribe an individualised training programme and improve player performance in a more efficient way.

Although more research is still needed in this area, this doctoral thesis aims to initiate a study line and further investigate it. It would be recommended to take into account all the previously detailed considerations to properly assess COD actions in sport. In addition, the use of specific linear and multidirectional speed tests alongside other performance tests that analyse key factors of both COD performance and other sport-specific actions in basketball should be part of the test battery. This combination will allow athletes to be classified according to individual needs in multiple physical abilities determinants to basketball player's performance. This may help the strength and conditioning coach to get a more holistic vision of their players and will allow them to make better decisions, as well as individualise training to maximise athletic performance.

Assessment tools

In addition to the correct selection of assessment tests, choosing a valid and reliable measurement tool is crucial for obtaining relevant data about the athletes' performance. Since COD actions involve movement over a surface following a specific trajectory, performance in these actions is assessed using tools that measure time and/or velocity. For this purpose, a wide range of assessment tools are available —including stopwatches, photo-finish cameras, electronic timing gates, global positioning systems, monitored resistance devices, mobile applications with video analysis, laser guns or radars—. Each of these devices has its own advantages and disadvantages, as highlighted in previous scientific literature (Altmann et al., 2018), which it is essential to be aware of before using them.

In general, both linear and multidirectional speed tests are field-based assessments conducted outside the laboratory, on the specific playing surface of each sport. Therefore, assessment tools must be portable and adaptable to any sport context. In this regard, the most commonly used tools for assessing COD tests are electronic time gates, which measure time, and radars devices, which measure velocity. These tools are widely accepted as 'Gold-Standard' measurement tools in the scientific literature (Altmann et al., 2018). This means that they are considered to have minimal measurement error in speed assessments. However, this technology also presents several disadvantages, such as: (1) the mere use of these tools does not guarantee valid measurements —proper evaluations require systematic procedures and advanced technical knowledge—. For example, it is crucial to consider the position and height at which the timing gates and their reflector are placed. A setup that is too high or too low could increase measurement errors. This occurs when the athlete's head or limbs break the laser beam before their own centre of mass, which would significantly reduce the total execution time or exaggerate the athlete's speed during the test. Additionally, the main limitation of this technology is (2) its high cost, which may restrict access for coaches and institutions with limited budgets constraints, making its use unfeasible in many sporting contexts.

Currently, the most affordable and accessible method to overcome the economic limitation of 'Gold-Standard' tools for measuring time in speed tests are manual timing devices. However, although coaches experienced with the use of stopwatches can reliably assess speed tests (Mann et al., 2015), the accuracy of such devices is significantly affected by the evaluator's reaction time, leading to considerable measurement errors (Chen et al., 2021). Furthermore, incorporating a correction factor to adjust manually recorded times does not appear to effectively improve measurement accuracy (Hetzler et al., 2008). For this reason, manual timing is not recommended for assessing maximal speed and COD actions.

To overcome the aforementioned limitations, a wide variety of smartphone applications have emerged as a cost-effective and portable alternative to traditional 'Gold-Standard' laboratory equipment for assessing sport performance. While not all of these apps have undergone empirical validation for reliability and accuracy, previous research has demonstrated that they could serve as valid and reliable tools for assessing different physical capacities, such as jump performance (Turan et al., 2022), bar velocity in strength exercises (Pérez-Castilla et al., 2019), velocity in linear speed tests (Romero-Franco et al., 2017), and COD (Silva et al., 2021). This reliability is mainly attributed to the high-speed cameras integrated into current smartphones. However, the use of these applications introduces new limitations. Most lack real-time feedback requiring coaches to manually assess their athletes after recording. This results in time-consuming assessments that do not facilitate real-time decision-making during training sessions. Fortunately, advances in artificial intelligence (AI) and computer vision offer a solution to overcome this limitation, enabling smartphones to autonomously identify athletes, analyse their performance and provide real-time feedback on specific performance tests. Due to the novelty of this technology, validation and reliability studies using AI in sports testing are limited. However, recent research has validated AI-based applications for sport assessments, such as barbell trajectory tracking in weightlifting movements (Balsalobre-Fernández et al., 2020), joint range-of-motion assessment (Carrasco-Uribarren et al., 2023), bar velocity measurement in strength exercises (Balsalobre-Fernandez, 2023; Taber et al., 2023), jump height (Balsalobre-Fernández, 2024) or the analysis of the trajectory of a bowling throw in cricket (Tissera et al., 2024). For speed and COD assessment, there is no scientifically validated AI or computer vision-based tool so far, that addresses and minimises the main disadvantages of the currently available tools for these assessments.

TRAINING APPROACHES FOR THE DEVELOPMENT OF CHANGE OF DIRECTION

Due to the great relevance of multidirectional actions and their influence on final scores in sports like basketball, there are already many intervention programmes described in the scientific literature, with different approaches, which aim to improve this skill in basketball players among other team sports (Asadi et al., 2016; Carvajal-Espinoza et al., 2023; Falch et al., 2019; Liu et al., 2020; Ramirez-Campillo et al., 2021). As

detailed so far in previous sections, COD is a complex action influenced by numerous factors (Young et al., 2002). This is why, it is recommended to consider the characteristics of this skill to design training programmes to address them from a specific approach and adapted to each athlete's physical needs and context (Falch et al., 2019; Young, 2006). In this regard, there are many other variables to control for optimising training adaptations and achieving the greatest possible improvements in athlete performance. For instance, a recent network meta-analysis (Chen et al., 2025) reported that the choice of training intervention should be determined on the COD angle —suggesting that when the COD angle exceeds 90º, eccentric-overload training may be the optimal intervention; whereas combined training may be better for improving COD at angles below 90º—. Thus, according to the initial athlete's characteristics or the target cutting angle to be improved, the choice of the correct (1) *training methodology* will be of critical relevance for post-intervention adaptations in COD performance. In this respect, plyometric, strength, speed, power and agility training have been shown to be effective training methods for improving COD capacity (Carvajal-Espinoza et al., 2023). However, each of these training methodologies have one or more moderating variables that influence their implementation and the final outcome of the intervention. These moderating variables may be determinant in the training effect and are mainly variables related to (2) the *training load* control. Factors such as volume, intensity or frequency of training could vary depending on the methodology used (Falch et al., 2019) and directly affect the athlete's adaptation to the training programme (Asadi et al., 2016). Finally, seeking a greater specificity to COD actions, (3) the *laterality, unilateral versus bilateral training*; and (4) the *force orientation* during training may also be decisive factors to find an optimal and efficient training programme for COD performance development in basketball players.

Training methodology

Numerous training methodologies have been used in scientific literature with the aim of improving COD performance (Falch et al., 2019). Among them, strength training, plyometric training (Asadi et al., 2016), eccentric overload training (Liu et al., 2020), specific speed and COD training, as well as the combination of several of these methodologies were highlighted. A descriptive analysis of the effects of the different methodologies mentioned on COD performance will be conducted below, trying to identify the most effective methods, along with their advantages and disadvantages.

- ***Strength training***

Due to the importance of the different strength qualities in sport performance and, specifically, in COD actions, the current literature suggests that this training methodology is suitable for COD performance optimisation (Falch et al., 2019). A recent meta-analysis (Falch et al., 2019) specified that most of the strength training proposed in the literature covers a period of 8 weeks with a frequency of two strength sessions per week. These trainings usually include multi-joint strength exercises —such as the squat—, performed at moderate to high intensities —70% to 90% of the repetition maximum— (Hammami

et al., 2017, 2018); or with accommodated resistance with elastic bands (Aloui et al., 2019).

Within this training methodology, it is recommended to use range-of-motion exercises specific to COD actions. In this regard, previous research revealed that squats executed with a partial range improved jumping, sprinting, and COD performance compared to full-squats (Rhea et al., 2016). However, relying exclusively on general strength exercises may become problematic, as it could result in reduced COD performance. Although these exercises demand significant effort and high levels of force, the application of this force does not necessarily align with COD-specific demands. For instance, during a traditional squat, force is generated vertically, whereas deceleration and acceleration in COD actions require a combined vertical-horizontal force application (Young & Farrow, 2006). Therefore, it is recommended to combine general strength exercises with movements that involve multidirectional force application to ensure effective transfer to COD performance.

Moreover, COD actions exhibit distinct lower limb and trunk muscle activation patterns compared to other athletic actions such as jumping (Falch, Rædergård, & Van den Tillaar, 2020c; Horníková & Zemková, 2024). In this context, the trunk musculature (Horníková & Zemková, 2024) along with the adductor longus and hamstring muscles (Falch, Rædergård, & Van den Tillaar, 2020c), show high peaks of muscle activation during COD actions, as they play a crucial role in stabilising the hip and controlling the knee joint movements during deceleration and turns involved in COD. Therefore, in addition to including multi-joint exercises to improve general strength, it would be recommended to include specific strength training for those muscle groups that experience high force peaks during COD actions. Previous studies have demonstrated improvements in COD performance following training programmes specifically targeted at core strengthening (Dong et al., 2023) or hamstring-focused exercise (Siddle et al., 2019).

Finally, it is important to highlight that the current scientific literature offers limited individualised strength training programmes based on each basketball player's needs. To the author's knowledge, only one recently published scientific study (Pleša et al., 2024) has adapted strength training based on each player's dynamic strength index. This intervention demonstrated a significant improvement (η^2 >0.16, p <0.05) in COD performance in basketball players, suggesting the need to rethink training approaches and encourage the development of individualised training programmes. In this regard, further research is required to identify optimal strategies for designing strength training programmes that maximise COD performance in basketball players.

- ***Eccentric-overload training***

Eccentric muscle strength is particularly important for decelerating the athlete's inertia and stabilising different body segments during the braking phase included of high-intensity COD tasks (Jones et al., 2022). Given the high eccentric strength demands in COD actions and the fact that, force production during this muscle action is 20 – 60%

greater compared to isometric or concentric muscle actions (Hollander et al., 2007; Hortobágyi & Katch, 1990), training programmes that challenge players' ability to apply eccentric force seem essential for optimising COD performance. In this regard, eccentric overload training is recommended, as it involves both concentric and eccentric muscle actions —while emphasising the eccentric action—, with the aim of improving COD performance (Chaabene et al., 2018).

Specifically, de Hoyo et al. (2016) investigated the effects of eccentric overload training in football players, reporting significant moderate to large improvements in COD actions (cross-over cut: ES = 0.46–1.34; side-step cut: ES = 0.48–1.24). Similarly, Gonzalo-Skok, Tous-Fajardo, Valero-Campo, et al. (2017) identified significant improvements (3.0%, ES = 0.61, p <0.01) in COD performance following an intervention incorporating variable, unilateral and multidirectional eccentric overload in basketball players. Moreover, eccentric-focused training targeting hamstring —such as the nordic hamstring exercise— also led to a 2.46% improvement in COD performance (Siddle et al., 2019). Overall, a recent meta-analysis assessing the effect of eccentric overload training on COD performance concluded that COD test execution time were reduced by 1.35 standard deviations (SD) after eccentric training (Liu et al., 2020). Therefore, the current scientific literature supports the use of eccentric overload training to improve COD performance.

These adaptations in COD performance following eccentric overload training may be attributed to the fact that this type of training enhances concentric muscle power, improves SSC efficiency (Elmer et al., 2012; Liu et al., 2013), and promotes greater muscle mass gains compared to traditional strength training (Douglas et al., 2017). Specifically, eccentric strength training has been shown to stimulate serial sarcomere formation, resulting in increased muscle fascicle length (Blazevich et al., 2007; Franchi et al., 2014). Additionally, selective hypertrophy of fast-twitch muscle fibres has been observed following eccentric overload training (Vogt & Hoppeler, 2014). This increase in the cross-sectional area of fast-twitch fibres, combined with the improvement in the mechanical properties of the muscle, may explain the enhanced performance in COD actions (Mohr et al., 2016).

- ***Plyometric training***

This is the most widely used and studied training methodology for improving COD actions in the scientific literature (Asadi et al., 2016). Specifically, previous meta-analyses (Asadi et al., 2016; Ramirez-Campillo et al., 2021) suggest that this training methodology improves COD ability with an effect size ranging from small (ES = 0.26) to large (ES = 2.8), depending on the type of COD test analysed. These significant improvements in COD performance following plyometric training may be attributed to the interaction of several neuromuscular adaptations, including: (1) enhanced neural drive to agonist muscles, (2) optimisations of neuromuscular patterns that facilitate a rapid transition between deceleration and acceleration movements (i.e., greater SSC efficiency), and (3)

the development of muscle activation strategies that promote improved inter- and intra-muscular coordination (Hakkinen et al., 1985; Markovic & Mikulic, 2010). Additionally, plyometric training can reduce ground contact times by increasing muscle force production and movement efficiency (Nimphius et al., 2010), which positively impacts speed in COD actions. Specifically, basketball players seem to benefit more from this training methodology compared to football or rugby players (Asadi et al., 2016), as plyometric training is more specific to basketball than to other sports (Ramirez-Campillo et al., 2021). This may be due to the nature of basketball, which involves horizontal and lateral movements, together with fast multidirectional actions against opponents, and high-intensity jumping tasks (Arazi et al., 2012). As a result, basketball players may exhibit greater adaptive responses to plyometric training, leading to enhanced COD performance.

Given the existence of COD actions that are more velocity-oriented or force-oriented (Bourgeois et al., 2017), the selection of plyometric exercises in training appears to be crucial depending on the objective and the cutting angle to be developed. For instance, in sharper and more force-oriented cutting angles, drop jumps offer certain advantages over other types of jumps, such as squat jumps. Drop jumps involve an eccentric phase that requires lower limbs to generate greater force. Additionally, the eccentric strength of the lower limb muscles, among other factors, has been shown to be crucial during the deceleration phase in COD (Chaouachi et al., 2012). Therefore, it is suggested that plyometric training aimed at developing COD ability includes a variety of exercises tailored to the specific skills targeted for improvement (Brughelli et al., 2008). This should include both bilateral and unilateral exercises, ensuring the application of force against the ground in different directions (i.e., vertical, horizontal, or lateral).

Another important factor to consider when using this training methodology to improve COD performance is gender, baseline strength level, and athletes' plyometric training experience (Falch et al., 2019). Previous research has indicated that physically stronger athletes benefit more from plyometric training compared to weaker athletes (Bourgeois et al., 2017). Additionally, it is well known that women tend to have less muscle mass and a higher fat mass, leading to lower relative strength (Miller et al., 1993). This difference could represent a potential disadvantage in plyometric training adaptations for female basketball players. However, despite these limitations, plyometric training has been shown to be effective in both genders, with significant effects on COD performance (Falch et al., 2019). This may be explained by similar adaptations in tendon stiffness between genders (Markovic & Mikulic, 2010). In this regard, high tendon stiffness is a key factor for performance enhancement in actions involving fast SSC, such as COD (Markovic & Mikulic, 2010).

Finally, the surface on which plyometric training is performed also influences its effectiveness. It has been observed that plyometrics exercise performed in water or sand seems to generate a greater effect on COD performance (Asadi et al., 2016). Previous studies reported that executing plyometric exercises in aquatic environments (Arazi et al., 2012) or on sand (Arazi, Mohammadi, et al., 2014; Mirzaei et al., 2014), was more beneficial compared to hard surfaces for enhancing COD capacity. These findings may

be explained by a greater neural adaptation and improved recruitment of motor units on soft surfaces (Martel et al., 2005; Stemm & Jacobson, 2007). Moreover, the implementation of plyometric training on these surfaces requires increased activation of muscle fibres to overcome and mobilise the resistance generated by the environment (Bishop, 2003; Impellizzeri et al., 2008), which could contribute to the improvement of COD performance.

- ***Linear speed and COD training***

Given the great importance of COD actions in basketball, the introduction of tasks involving sprints and COD at high velocities should be a priority. As a general recommendation, to implement both linear and multidirectional repeated sprint ability training, recent systematic reviews (Kyles et al., 2023; Thurlow et al., 2025) recommended including 3 to 4 sets of exercises of 6 to 8 repetitions between 20 to 40 metres with at least one COD (e.g., 30 metres = 15 metres + 180º COD + 15 metres), and an active recovery lasting 15 seconds (e.g., work:rest rate of ≤1:4). However, to optimise training it is essential to understand that the specific demands of COD depend directly of the cutting angle (Dos'Santos, Comfort, et al., 2018). Thus, COD can be classified into those more velocity-oriented (<90º) and those more force-oriented (>90º) (Bourgeois et al., 2017). Based on this classification, it could be understood that specific training of linear speed and COD might be associated to a greater extent with improved performance in velocity-oriented COD actions, although they might have a limited effect on force-oriented COD performance (Bourgeois et al., 2017).

To the author's knowledge, linear speed training interventions aimed at improving COD performance are scarce in the scientific literature. Nevertheless, a recent meta-analysis (Falch et al., 2019) determined that sprint training protocols led to a 2% improvement in COD performance, with an effect size ranging from small (ES <0.5) to large (ES >0.8). The studies that reported the greatest impact on COD performance involved football (Bouguezzi et al., 2020) and handball players (Hammami, Gaamouri, Aloui, et al., 2019) with a mean age of 14.6 years, concluding that age is a key factor when implementing this training methodology. Juniors' players exhibit the greatest improvements in COD performance (Falch et al., 2019). The low effect of sprint training observed in other studies (Falch et al., 2019) could primarily be attributed to the use of excessively long linear distances or the lack of external loads to resist sprinting. During the acceleration phase of COD actions, the horizontal force applied to the ground is decisive for performance, regardless of the maximum velocity the athlete could reach over longer distances (Baena-Raya, Rodríguez-Pérez, et al., 2021). Therefore, Bourgeois et al. (2017) recommended training linear speed with a focus on the acceleration phase with short-distance sprints (<10 m) to develop COD ability. Additionally, Morin et al. (2017) highlighted the importance of resisted sprints with high loads to optimise horizontal force application during the acceleration phase, both in linear speed and COD actions. In line with this, a previous study (Baena-Raya et al., 2024) analysed the effect of resisted sprints over 20 metres with low loads (25% loss velocity) and over 10 metres with high loads (75% loss velocity) on COD performance in football players. The results

showed that high-load resisted sprint training was more effective in improving curved sprint (ES >0.89; p <0.01) and 180° COD (ES >0.80; p <0.01) performance compared to the low-load sprint or control group.

On the other hand, previous studies (Born et al., 2016; Chtara et al., 2017) that implemented COD specific training programmes to enhance COD performance in young football players, reported significant improvements when athletes trained with repeated COD drills, maintaining the same distance and cutting angles as those assessed. These findings could be explained, besides the age of the athletes, by the specificity of the training to the assessments undertaken. Young athletes typically have less experience with COD training, and training specifically with the same COD tests used for assessment may offer advantages over more general training approaches. Similarly, Thieschäfer et al. (2023) showed that a six-week cutting technique modification training program meaningfully improved cutting movement quality in adolescent American football players without negatively affecting agility performance. Furthermore, Zoppirolli et al. (2025) found that a single 15-minute session of COD technique in youth football players improved acutely COD kinematic —including a shorter ground contact time, greater deceleration, a greater hip flexion angle, and a longer centre of mass/centre of pressure horizontal distance at COD step—, concluding that this may be the first step toward long-term adaptation in COD performance and injury risk reduction in adolescent athletes. Thus, even if there is no immediate improvement in agility performance, refined cutting kinematics constitute the technical foundation for safe and fast cuttings from which the athletes will most likely benefit in their further agility development (Thieschäfer et al., 2024).

In professional adult basketball players, Brini et al. (2022) found that multidirectional repeated sprint training programme only improved T-test performance by 1.80%. Additionally, within the COD-specific training proposals, interventions that aimed to refine the technique of each COD phase (i.e., acceleration, deceleration and COD foot contact) in football players (Dos'Santos, McBurnie, Comfort, et al., 2019) or adult multidirectional sports athletes, demonstrated substantial improvements in COD performance (ES =1.31, p <0.01) (Dos'santos et al., 2022; Lockie, Schultz, et al., 2014). Specifically, Dos'santos et al. (2022) attribute these technical improvements in COD performance, primarily to an increased in velocity in key COD moments, greater propulsive force with shorter ground contact times, and a reduced knee flexion range of motion during the cutting step. This enhances athlete reactivity, allowing for faster exit immediately after the cut. These findings support the use of COD technique training, as it is a simple and effective training method, requiring minimal equipment, capable of increasing performance while potentially reducing knee joint loading, thereby decreasing the risk of injury during COD execution (Dos'Santos et al., 2021). However, given the complexity of COD actions, this does not imply that training only speed or COD movements in isolation is the most efficient way to improve performance. Practitioners should consider the implementation of a combined strength, neuromuscular, and perception and anticipation training in conjunction with technique modification training to trigger potential synergistic effects on technique change, ACL strain attenuation, and

COD performance (Thieschäfer et al., 2024). Additionally, it is recommended that this training be individually tailored to each athlete's technical needs, as Dos'Santos et al. (2021) found that only the group classified as potentially high-risk significantly improved COD mechanics.

- ***Small-side games***

The use of Small Side Games (SSG) to enhance COD performance in multidirectional sports, such as basketball, is considerably emerging (Halouani et al., 2014). It is important to highlight that, among the training methodologies discussed so far, SSG are the most sport-specific for COD actions in a real-game context, as they require athletes to react to external stimuli (i.e., involving agility — ***Figure 2***). This may explain why previous studies (Büjalance-Moreno et al., 2018; Coutinho et al., 2018) have reported large improvements in COD performance (7.23%, ES =0.8, p <0.01) following SSG-based training in football players. Gabbett (2006) found that SSG-based training significantly improved rugby players' performance in linear speed, COD and agility actions. However, no significant differences were observed between the improvements achieved by an SSG-based intervention and a traditional speed-based training.

Conversely, the findings of Young & Rogers (2014) in a study comparing two training interventions -one based on COD exercises and the other on SSG- with Australian football players were particularly insightful. The results indicated that neither training approach significantly improved the athletes' running speed, so no COD performance improvements were observed. However, the group that trained with SSG showed a considerable improvement in agility test performance (ES =0.93, p <0.01), particularly in response to a specific stimulus. This was entirely attributed to an enhancement in players' decision-making time (ES =2.32, p <0.01). In contrast, the COD-training group showed no changes in these variables. These findings suggest that SSG may not improve sprint speed or COD ability, whereas SSG may improve athletes' agility performance through optimising perception, processing and decision-making mechanisms ***(Figure 2)***. Therefore, integrating SSG with other training methodologies that target other additional key determinants of COD performance may lead to a more comprehensive and efficient COD training programme. Specifically, incorporating basketball-specific actions within SSG may provide an optimal approach for COD development in basketball players.

In this regard, the goal of any training intervention, beyond enhancing isolated physical capacities, is to improve sport-specific performance in real-game situations. Considering that basketball is a sport in which athletes must execute a wide variety of movement mechanics in an unpredictable and constantly changing environment — characterised by multiple forces, angles, and speeds, as well as responses to stimuli— decision-making and perceptual-cognitive capacities become critical factors in enabling players to move faster on the court (Jones & Dos'Santos, 2023). To achieve this, it would be recommended to adopt a training philosophy that fosters a rich learning environment, incorporating high degree of variability, controlled chaos, play and emphasises differential learning to develop highly adaptable and self-organizing athletes (Jones & Dos'Santos, 2023). Undoubtedly, SSG with modifications of the original rules are the

most effective tool to achieve this, as they appear to be the only training methodology capable of specifically developing multidirectional speed in real-game contexts for agility enhancing.

- ***Combined training***

In this section, the term *combined training* will be understood as the integration of the different methodologies previously described, programming each of them both intra- and/or inter-sessions. As highlighted throughout the thesis, multidirectional COD actions are highly complex and rely on multiple physical attributes that influence overall performance (Young et al., 2002). Therefore, in theory, implementing a combined training approach that develops the key physical attributes required for COD performance while leveraging the benefits of each training methodology could represent the most efficient strategy to optimise performance in these actions. However, in practice, this remains a challenging prospect. Because combining different training methodologies involves numerous variables that must be carefully controlled, making it difficult to analyse the isolated effects of each individual training method. Consequently, the vast number of possible training combinations makes it virtually impossible for the scientific literature to systematically analyse all potential interactions (Falch et al., 2019).

Despite this limitation, combined training has been shown to produce significant improvements on COD performance, with reported changes ranging from 0.66% (Fernandez-Fernandez et al., 2018) to 8.2% (Arazi, Asadi, et al., 2014). While the effectiveness of these trainings is influenced by the methodologies employed, among other variables, the intervention with the greatest impact on COD performance combined plyometric training with sprints (Arazi, Asadi, et al., 2014). Similarly, Gil et al. (2018) reported substantial improvements in COD performance (Mean Difference [MD] =6.2, ES =1.6) in football players following a combined training incorporating vertical jumps, sprints and both resisted and unresisted COD exercises. Furthermore, the implementation of a combined training programme with strength and plyometrics exercises was found to be more effective ($\eta_p^2 = 0.17$, $p < 0.01$) than using plyometrics in isolation for improving COD performance in football players (Hammami, Gaamouri, Shephard, et al., 2019).

In professional basketball players, Brini et al. (2022) found that a training program combining jump exercises with repeated multidirectional sprints was the most effective methodology, exhibiting a significant improvement in COD performance ($\Delta\% = 2.49$, $p < 0.01$) compared to the isolated application of each training method. These findings reinforce the idea that combined training surpasses isolated approaches in effectiveness, as it allows for the simultaneous improvement of multiple key factors for COD performance. Furthermore, in real-game scenarios, the demands of COD vary depending on approach speed and cutting angle. Therefore, a combined training approach better prepares athletes to respond effectively to competitive demands in a wider variety of real game situations (Young & Farrow, 2006). Despite these relevant findings supporting combined training, caution should be exercised with its implementation, due to the large number of variables that may influence the final outcome.

To better understand the different ways of combining stimuli within a training session, Marshall et al. (2021) conducted a recent meta-analysis examining the effect of different training sequences ***(Table 7)*** on key variables influencing COD performance (i.e., vertical jump, speed, lower-limb strength and power). The main finding was that different methods of organising combined training (i.e., cluster, contrast, complex or traditional) were effective for athletic development, provided that the various areas of the force-velocity continuum were addressed, optimising both force-oriented and velocity-oriented actions (Marshall et al., 2021). Among these session structures, complex and contrast training appears to offer greater benefits for power development and performance enhancement in high-intensity ballistic actions such as COD. Furthermore, these session organisation strategies have shown both acute effects —improving performance through post-activation performance enhancement immediately after conditional activity (Prieske et al., 2020)— as well as chronic effects, leading to sustained improvements after a continuous training period (Marshall et al., 2021).

Table 7. Terms and definitions of different approaches to organising a combined training session. Extracted and adapted from Marshall et al. (2021).

Term	Definition
Cluster training	Set structures inclusive of normal inter-set rest periods accompanied by pre-planned rest intervals within a set
Cluster sets	A traditional set with additional short rest periods of typically 15–45 s inserted within each set
Complex training	Multiple sets of a heavy resistance exercise followed by sets of a lighter resistance exercise
Contrast training	A workout that involves the use of exercises of contrasting loads, that is, alternating heavy and light exercises set for set
Traditional training	Multiple sets of lighter resistances before heavy resistances
Traditional sets	A straight set with no recovery until all repetitions are complete

However, combining different training methodologies could be detrimental to athletic performance due to the interference effect. This phenomenon occurs when adaptations induced by different types of training may produce opposing effects on the athlete's system (García-Pallares & Izquierdo, 2011), potentially hindering the expected improvements. To minimise this interference, the scientific literature has introduced the concept of 'microdosing', which has raised significant interest among sports practitioners (Afonso, Nakamura, et al., 2022). In the context of athletic training, this term refers to dividing the total training volume within a microcycle into multiple, shorter, and more frequent sessions (Cuthbert et al., 2021). This microcycle organisation strategy could be particularly beneficial in sports with congested competition schedules or short microcycles lasting up to a week (Cuthbert et al., 2023), as is often the case in basketball. In this regard, strength and conditioning coaches may integrate this strategy into their team planning to optimise performance (Vretaros, 2022). Moreover, a microcycle structure based on microdoses offers multiple advantages, including: (1) minimising the interference effect associated with combining different training methodologies; (2) enabling the introduction of new stimuli or skills development into the athlete's programme without neglecting other physical capacities; (3) potentially has a post-

activation performance enhancement effect; (4) maximises the residual training effect while simultaneously minimising fatigue caused by conditional training sessions; (5) enhances motor learning through increased repetition frequency of the skill and; (6) allowing for more precise and frequent individualisation and adjustment of training loads (Cuthbert et al., 2023).

In summary, current scientific literature supports the use of combined training, both intra- and inter-session, as an effective strategy to enhance performance in complex multidirectional actions such as COD. However, further scientific research is still needed to explore additional strategies for structuring combined training and to analyse their effect on COD performance.

Training load

The athlete's performance adaptation to the workload after applying one or more training stimuli results from the complex interaction between volume, intensity and training frequency variables, as well as the impact of this training on the recovery of specific tissues and systems (Gabbett & Oetter, 2024). Managing and controlling all these variables is crucial for strength, hypertrophy, neuromuscular adaptations and overall physical performance improvements that occur with an appropriate training programme (Pareja-Blanco, Rodríguez-Rosell, Sánchez-Medina, Sanchis-Moysi, et al., 2017). While traditionally, high training volumes, close to muscular failure, have been suggested to maximise strength gains (Kraemer & Ratamess, 2004). Numerous current studies (Davies et al., 2016; Pareja-Blanco, Rodríguez-Rosell, Sánchez-Medina, Sanchis-Moysi, et al., 2017; Rodríguez-Rosell et al., 2020) indicate that high training volumes are not essential to induce positive adaptations in athletic performance.

High training volumes induce high levels of mechanical, metabolic and hormonal stress on the athlete (González-Badillo et al., 2016; Pareja-Blanco, Rodríguez-Rosell, Sánchez-Medina, Ribas-Serna, et al., 2017); leading to a considerable decrease in the rate of force development (Andersen et al., 2010) and, consequently, a reduction in performance during high-intensity actions such as COD (Pareja-Blanco, Rodríguez-Rosell, Sánchez-Medina, Sanchis-Moysi, et al., 2017). In this regard, recent research suggests that lower training volumes (~10% velocity loss per set in strength exercises), may be more efficient for improving basketball player's performance (Rodríguez-Rosell et al., 2020). Regarding exercise intensity, a novel and individualised approach recommends adapting it to each athlete's needs according to their force-velocity profile (Samozino et al., 2012). For instance, training with high external loads may elicit entirely different stimuli in athletes with varying baseline strength levels (Jiménez-Reyes et al., 2016, 2019). This suggests that training adaptations will differ depending on each player's starting point. In this context, adjusting training intensity according to each athlete's force demands, whether through the force-velocity profile or other similar variables such as the dynamic strength index (Pleša et al., 2024), seems to be the best effective strategy. From another perspective, it is recommended that exercise intensity —understood as the movement velocity at which the player is able to move under specific loads (González-Badillo & Sánchez-Medina, 2010)— should always be maximum to optimise the rate of

force development. This approach enhances the basketball player's ability to apply more force in less time under the same load (i.e., their BM), which is essential in specific game situations (González Badillo & Ribas-Serna, 2019).

Moreover, it is essential to emphasise that these training load control variables are directly influenced by the training methodology used. In this regard, plyometric training has been recommended to improve COD performance using a low frequency (twice per week), ensuring optimal recovery through 72-hours rest intervals (Asadi et al., 2016). Additionally, the intensity of these exercises should range from moderate to high, with a volume of approximately 100 jumps per session, to maximise improvements in COD ability (Asadi et al., 2016). Finally, incorporating a variety of plyometric exercises (e.g., drop jumps, vertical jumps or standing long jumps) was also recommended, as this approach demonstrated superior improvements in COD performance compared to using a single modality (Asadi et al., 2016). Similarly, regarding eccentric overload training, a low training frequency (1–2 sessions per week) has been recommended, incorporating 1–4 exercises per session, 1–3 sets of each exercise with a low to moderate inertial intensity. Additionally, at least two minutes of rest between sets and 3–6 repetitions per set were suggested to ensure adequate recovery and maximise power output per repetition (Martínez-Hernández, 2023). By following these parameters, eccentric overload training could be optimised to produce the greatest adaptations in COD performance (Liu et al., 2020). In summary, a low training frequency (two sessions per week), combined with low to moderate training volumes (depending on the type of exercises used), and an intensity adapted to each player's needs, with adequate rest intervals to facilitate intra-training recovery, appears to be an effective load management strategy for optimising the effects of training on COD performance (Falch et al., 2019).

Laterality: Bilateral versus unilateral

The mechanics of COD during multidirectional actions in sports contexts are highly variable, primarily depending on the cutting angle and approach velocity (Dos'Santos, Comfort, et al., 2018). These actions are predominantly unilateral, as the COD movement itself is executed with support on a single leg. However, depending on the context and in response to sharper and force-demanding cutting angles, the action may be performed using an asymmetrical bilateral strategy (Jones & Dos'Santos, 2023). This could justify the analysis and implementation of both training approaches —unilateral and bilateral— to improve COD performance.

Although unilateral training might be more similar to the movement pattern during the different phases of COD (i.e., deceleration, cutting step and propulsion) and appears to be the only one approach that reduces asymmetries in basketball players (Gonzalo-Skok, Tous-Fajardo, Suarez-Arrones, et al., 2017), both unilateral and bilateral strength training have shown improvements in COD performance with no significant differences between them. Similarly, previous studies with football players (Ramirez-Campillo et al., 2018; Stern et al., 2020) have also reported improvements in COD performance with both methods, though unilateral training yielded significantly greater improvements. Other studies also reported superior performance in basketball players who trained unilaterally

using plyometric exercises (Gonzalo-Skok et al., 2019), or eccentric overload training (Gonzalo-Skok, Tous-Fajardo, Valero-Campo, et al., 2017). However, these findings may be attributed to the specificity of the force orientation trained, as the bilateral group trained with a vertical orientation, whereas the unilateral group focused on horizontal force orientation. Interestingly, Appleby et al. (2020) found that, although both training modalities improved maximal lower limb strength and linear acceleration, bilateral training exhibited the greatest improvements in COD performance. More recently, Duan et al. (2024) found that unilateral training may offer advantages in improving unilateral power and COD ability in the non-dominant leg of basketball players, whereas bilateral training appeared to be more effective for improving bilateral power and maximal strength.

As observed in the literature, findings can sometimes be contradictory due to the multiple variables influencing the outcomes of training interventions. Meta-analysis studies encompassing the current scientific literature on this topic conclude that, although unilateral training appears to have a greater effect on performance in speed actions with unilateral movement patterns (Wallin, 2014; Zhang et al., 2023), these differences are not significant and have a small effect size. While this might seem to contradict the principle of training specificity, current literature does not support the notion that unilateral training is more effective than bilateral training for enhancing COD performance (Moran et al., 2021b). These findings highlight that training specificity should not be based solely on selecting exercises with specific movement patterns to the target skill, but rather on focusing on the underlying physiological stimulus that drives adaptation (Appleby et al., 2020). That is, a training prescription aimed at improving the lower limb rate of force development may be likely to enhance the ability to generate the necessary forces for COD actions (Guppy et al., 2024), regardless of laterality. Therefore, coaches and strength and conditioning professionals are advised to consider the individual strength requirements of their athletes —taking into account factors such as gender and baseline strength levels— to tailor training programmes. This should involve a combination of strength and plyometric exercises, both unilateral and bilateral, to maximise force production per unit of time, which is essential for COD performance (Moran et al., 2021b).

Force orientation

In line with the pursuit of true specificity in training (Goodwin & Cleather, 2016) to enhance transfer to the sporting context, force orientation remains an understudied variable that could be key in training adaptations aimed at improving specific actions such as CODs (Randell et al., 2010). In this regard, previous research (Randell et al., 2010; Zweifel, 2017) highlights the importance of training force orientation, recommending that it should be specific to improve the desired capacity. However, recent meta-analysis studies (Huang et al., 2024; Junge et al., 2023) found no significant effect between different force orientations (i.e., horizontal or vertical) on improving performance in vertical actions, such as vertical jumps. Nevertheless, for enhancing performance in horizontal actions (i.e., accelerations, decelerations, sprints, or COD), strength or

plyometric training with a horizontal force orientation could lead to greater performance adaptations (Bartolomei et al., 2024; Junge et al., 2023; Moran et al., 2021a).

When analysing the effect of force orientation in training programmes aimed at improving COD actions in basketball players, it was observed that the specificity of the trained force orientation influenced the intervention outcomes (Aztarain-Cardiel et al., 2022). In these studies, vertical and horizontal jump performance significantly improved following a plyometric training programme with a vertical and horizontal force orientation, respectively. Furthermore, combining both force orientations proved to be the most effective approach for enhancing complex multidirectional actions, such as COD (Aztarain-Cardiel et al., 2022). Sánchez-Sabaté et al. (2024) highlighted the need to integrate training with a force orientation specific to the targeted skill, underscoring the importance of applying specific strength training protocols for basketball players.

COD actions are multidirectional movements involving the interaction of both vertical and horizontal forces. On the one hand, vertical gravitational forces are always present in all sport actions (Randell et al., 2010); however, previous research has shown that the horizontal force demands in COD actions are greater than the vertical ones (Baena-Raya et al., 2020; McBurnie & Dos'Santos, 2022; Pleša et al., 2021; Robles-Ruiz et al., 2021). Consequently, training approaches with a horizontal force orientation have been recommended to achieve greater improvements in COD-specific actions. Nevertheless, current literature on horizontally oriented training strategies for basketball players is quite scarce (Aztarain-Cardiel et al., 2022; Brini et al., 2020, 2022; Sánchez-Sabaté et al., 2024), and has not demonstrated any significant effect on COD performance. This lack of effect could be attributed to several factors. Firstly, although the proposed interventions were specific in terms of applied force orientation, they (1) did not consider the characteristics of the different phases involved in COD actions. All identified interventions focused mainly on the concentric and acceleration phase of COD (Clarke et al., 2020), but none included targeted horizontal deceleration training, which plays a crucial role in these actions (Harper et al., 2022; McBurnie, Harper, et al., 2021). Previous studies (Freitas, Pereira, et al., 2021; Lazić et al., 2022) recommended placing greater emphasis on eccentric actions and horizontal deceleration to enhance this phase of COD.

On the other hand, contrary to what frequently occurs with strength training in a vertical vector —where loads are typically adjusted based on the athletes' strength needs (Jiménez-Reyes et al., 2019; Pleša et al., 2024)—; in horizontal-orientated training protocols in the current literature with basketball players, (2) the training stimuli were not adapted to each athlete's individual needs, nor external loads were generally incorporated. Consequently, it could be assumed that the applied training stimuli may not have been appropriate or sufficient to induce performance adaptations in the athletes. Therefore, considering only force orientation during training to improve sport-specific multidirectional actions may be insufficient. Beyond this factor, it would be recommended to account for the specific characteristics of these multidirectional movements and the individual strength demands of each athlete, taking into consideration variables such as gender and experience level.

AIMS AND HYPOTHESIS

Following a comprehensive review of the scientific literature on all influential factors in COD actions, as well as current assessment and training proposals aimed to enhancing performance in these actions, it was deemed necessary to establish the following aims alongside their initial hypotheses in order to deepen and advance scientific knowledge on the topic under study.

Aim 1. To identify the key factors influencing COD performance in basketball players.

- ***Aim 1A.*** To determine the relationship between different anthropometric variables and COD actions based on cutting angle.

  Hypothesis 1A. Anthropometric variables will have a non-significant effect on COD performance.

- ***Aim 1B.*** To determine the relationship between different functional movement variables and COD actions based on cutting angle.

  Hypothesis 1B. Despite previous literature identifying a significant relationship, it is hypothesised that functional movement variables will have a non-significant effect on COD performance.

- ***Aim 1C.*** To determine the effect of different strength variables, considering the type of action and muscle qualities, on COD performance based on cutting angle.

  Hypothesis 1C. Strength variables will be the most decisive factors influencing COD performance. In line with previous studies, it is hypothesised that eccentric muscle action will show the strongest relationship with COD actions.

- ***Aim 1D.*** To determine the effect of inter-limb asymmetry on performance in team sports.

Hypothesis 1D. Although previous scientific literature has attempted to link inter-limb asymmetries to physical performance, asymmetries are likely largely independent of sports performance.

- ***Aim 1E.*** To analyse the effect of age category on anthropometric, functional movement, speed and strength variables.

  Hypothesis 1E. In line with previous scientific literature, it is hypothesised that age category influences athletes' physical performance.

- ***Aim 1F.*** To analyse the influence of gender on the association of different physical and functional movement variables with COD performance at different cutting angles.

  Hypothesis 1F. While previous research has confirmed differences in sport performance between genders, it is hypothesised that gender differences also exist in the variables influencing COD performance.

- ***Aim 1G.*** To assess the influence of force orientation on COD performance at different cutting angles.

  Hypothesis 1F. Given that specificity is one of the key principles of training, in this sense it is hypothesised that a horizontal force orientation may show a greater relationship with COD actions.

- ***Aim 1H.*** To analyse the influence of different physical and functional movement variables on different approaches to assessing COD performance, including execution time and CODD.

  Hypothesis 1F. The relationship between the different physical variables assessed with COD will depend mainly on the COD unit of measurement used as a reference.

Aim 2. To standardise and improve the accessibility of linear and multidirectional speed assessment for sports professionals.

- ***Aim 2A.*** To develop a standardised COD assessment at various cutting angles to creates a ‘COD angle profile’ for basketball players.

  Hypothesis 2A. The best approach to assessing COD would involve a battery of speed tests incorporating short-duration tests with a single cut at various angles; to create an individual basketball player's COD angle profile.

- ***Aim 2B.*** To develop and validate a classification based on CODD to identify the specific linear and multidirectional speed needs of each basketball player according to gender.

  Hypothesis 2B. CODD is an efficiency variable in COD actions, and the athlete classification based on this metric will depend mainly on the evaluated cutting angle.

- ***Aim 2C.*** To create and validate a novel AI-based linear and multidirectional speed assessment tool that minimises the limitations of currently available tools and, makes speed assessment accessible to all sports professionals.

  Hypothesis 2C. Asstrapp will be a valid and reliable time measurement tool for speed tests compared to gold-standard methods.

Aim 3. To analyse the effect of different individualised training approaches on physical performance in basketball players.

- ***Aim 3A.*** To describe the effect of different training interventions on COD performance in basketball players.

  Hypothesis 3A. Based on current scientific literature, it is hypothesised that multiple training methodologies are expected to positively affect COD performance.

- ***Aim 3B.*** To determine the effect of different training methodologies on COD performance in basketball players, depending on the force orientation trained.

  Hypothesis 3B. Based on the principle of training specificity, a training methodology focused on a horizontal force orientation could generate greater magnitudes of change in COD performance.

- ***Aim 3C.*** To analyse the effect of an individualised training program based on the individual vertical force-velocity profile on basketball players' physical performance.

  Hypothesis 3C. An individualised training program based on the vertical force-velocity profile will efficiently improve vertical jump, and enhance both linear and multidirectional speed performance in basketball players.

- ***Aim 3D.*** To examine the effect of an individualised training program based on individual CODD on linear and multidirectional speed performance in basketball players.

  Hypothesis 3D. Individualised training based on CODD will be the most effective method for achieving the greatest improvements in multidirectional performance in the shortest time.

- ***Aim 3E.*** To investigate the effect of an individualised training program based on individual CODD on vertical jumping performance in basketball players.

  Hypothesis 3E. Although an individualised training program based on CODD is more specific to multidirectional movement actions, this type of training will lead to neuromuscular improvements with positive transfer to vertical jumping performance.

- ***Aim 3F.*** To determine the minimum training period required to achieve positive adaptations in basketball players' performance.

  Hypothesis 3F. Following the recommendations of previous scientific literature, at least six-weeks of training may be necessary for significant improvements in COD

performance, while vertical jump performance may show significant changes within four-weeks of specific training.

- ***Aim 3G.*** To observe inter-individual differences in the adaptations on performance in basketball players of various individualised training approaches.

  Hypothesis 3G. Individualised training programs based on player's needs will demonstrate to be more efficient in improving sports performance compared to general training programs or sport-specific practice on its own.

RELATIONSHIP BETWEEN THE AIMS OF THE THESIS AND THE AIMS OF EACH STUDY

Table 8 shows the relationship between the aims of the doctoral thesis and the specific aims of each study undertaken.

Table 8. Relationship between the general aims of the doctoral thesis and the specific aims of each study.

Study	Specific study aim	Thesis aim
Chapter 1. Decisive factors for a greater performance in changes of direction.		
1. Decisive factors for a greater performance in the change of direction and its angulations in male basketball players.	To evaluate whether the age category could influence anthropometric measurements, functional movement tests, linear sprint (30 metres), and strength. To examine the relationship between the time execution in different COD tests and angles with the analyzed sport performance variables.	1A 1B 1C 1E
2. Influence of dynamic balance on jumping-based asymmetries in team sport: A between-sports comparison in basketball and handball athletes.	To determine mobility, Dynamic balance and lower-limb strength and the prevalence of asymmetry according to the type of sport. To assess the association between inter-limb asymmetry and different sport performance variables.	1D
3. The influence of functional movement and strength upon linear and change of direction speed in male and female basketball players.	To analyse the relationship between functional movement and strength variables in several linear speed and COD tests based on gender. To identify the determinants of performance of linear speed and COD according to gender.	1B 1C 1F 1G
4. Strength characteristics in faster change of direction basketball players: A comparison across cutting angles.	To examine the differences in strength measures for different lower limb muscle actions between faster and slower basketball players in COD actions at different angles. To analyse the relationship between isometric, concentric and eccentric strength measures and COD performance at different cutting angles.	1C
5. Influence of functional movement, jump and linear speed on change of direction speed in female basketball players: Novel vs. traditional approaches	To analyse and compare the relationships among functional movement, jump and linear speed performance using two different methods of measuring COD performance in female basketball players, with a focus on differentiating between cutting angles.	1B 1C 1G 1H

Table 8 (continued).

Study	Specific study aim	Thesis aim
Chapter 2. New tools and standardization to assess change of direction.		
6. Determination of change of direction deficit thresholds across a spectrum of angles in basketball players.	To determine the CODD thresholds for different COD angulations in basketball players according to gender. To analyse the relationships between CODD and execution time in speed tests based on gender.	2A 2B
7. Validity and inter-device reliability of an artificial intelligence app for real-time assessment of 505 change of direction tests.	To examine the validity and reliability of Asstrapp in the traditional 505 and modified 505 COD tests.	2C
Chapter 3. New approach to individualised change of direction training.		
8. Vertical versus horizontal training for improving the change of direction speed in adult basketball players: A systematic review and meta-analysis.	To describe the effect of different training interventions that focus on COD performance in adult basketball players of both genders and classify them according to the force-orientation in which the training was conducted (vertical, horizontal, or mixed). To determine the magnitude of the effect on COD, considering the specific force-orientation primarily trained in the intervention. To provide practical recommendations around specific force-orientation training to support programming decisions for coaches and trainers.	3A 3B
9. Effect of individualised strength and plyometric training on the physical performance of basketball players.	To examine the effects of an individualised combined strength and plyometric training program on physical performance of basketball players. To analyse the differences in physical performance between two periods of time (four to eight weeks) with the same training.	3C 3F
10. Effect of individualized training based on change of direction deficit upon speed performance in basketball players.	To analyse the effect of an individualised CODD-based training program on linear and multidirectional speed efficiency and performance in male basketball players. To analyse the differences in speed performance between two time points (four and eight weeks) with an individualised versus a general training program.	3D 3F
11. Effect of different individualised strength training approaches to improve physical performance in male basketball players.	To analyse the effects of two individualised training approaches, one based F-V profile and the other based on change of direction deficit (CODD) on performance in male basketball players. To assess differences in physical performance between two different time periods (four-eight weeks of training intervention). To compare the inter-individual differences in adaptations of these physical abilities.	3C 3D 3E 3F 3G

METHODOLOGY

This doctoral thesis includes studies with cross-sectional designs ***(Table 9, Studies 1–7)***, experimental designs ***(Table 9, Studies 9–11)*** and systematic review with meta-analysis ***(Table 9, Study 8)***, according to the aim addressed in each of them ***(Table 9)***. This section provides a general description of the methodology used throughout the different studies included in the thesis. Furthermore, the full and detailed methodology of each study can be consulted in the methodology section included in each study.

PARTICIPANTS

The sample size was calculated, were required, using the G*Power software (version 3.1.9.6, Kiel, Germany). For the development of the several studies included in this doctoral thesis, a total of 412 basketball players (35.6% female; age, 21.4 ± 2.77 years; height, 191 ± 7.69 cm; BM: 84.4 ± 11. 2 kg), 23 male handball players (age, 23.9 ± 3.97 years; height, 181 ± 7.69 cm; BM: 78.5 ± 13.6 kg) and 25 male sports science students (age, 23.5 ± 3.27 years; height, 178 ± 9.76 cm; BM, 79.4 ± 14.7 kg). All participants met the following general inclusion criteria across different studies: (i) having at least one year of strength training experience; (ii) participating in regular sports practice at least three days a week during the competitive season; and (iii) no injury or health problem in the six months prior to the evaluation. Additional specific criteria can be consulted in each individual study.

All subjects participated voluntarily and were informed about the objectives, potential risks and benefits of the studies before participation. To ensure their understanding, prior to the evaluation process, all participants signed an informed consent form detailing all relevant information. Furthermore, the research included in this doctoral thesis was conducted following ethical principles in accordance with the guidelines established in the Declaration of Helsinki. Ethical approval was obtained from the Andalusian Ethics Committee of Biomedical Research (reference number:

FBD_UHU202020; approval date: 08 october 2020 — reference number: TES_COD_23; approval date: 21 September 2023); and the University of Salford Ethics Committee (reference number: HSR2324-001). Specifically, for the systematic review with meta-analysis study ***(Table 9, Study 8)***, which did not involve human participants, the protocol was pre-registered in the International Prospective Register of Systematic Reviews (PROSPERO), with registration number: CRD42022374206.

PROCEDURES

In all studies included in this doctoral thesis, at least one familiarisation session was conducted during the week prior to the start of the study, provided that the participants in each study were not already familiar with the test procedures. Familiarisation and evaluation sessions were conducted on indoor basketball courts with parquet flooring, where the basketball teams trained. However, the validity and reliability study were conducted on the indoor athletic track (Mondo, SportsFlex, 10 mm; Mondo America, Inc., Mondo, Summit, NJ) at the Human Performance Laboratory of the University of Salford (Manchester, United Kingdom). Additionally, all participants in the studies were instructed to attend the evaluation sessions with proper hydration and rest, without any training session or vigorous physical activity within 24 hours prior to the evaluation. They were also advised to refrain from consuming caffeine or eating any food three hours before testing, as well as abstaining from alcohol consumption 24 hours prior to the evaluations.

Before starting the assessments, all sessions began with a standardised warm-up lasting 15-20 minutes, which included low-intensity activities (e.g., different kinds of movements); lower limb joint mobility exercises and core muscle activation; jumps, landings, accelerations and decelerations with progressively increasing intensity; and concluded with at least two approximations of the tests to be assessed. Once all the athletes were deemed to perform the tests, the assessment began. Most studies conducted the assessment in a single session, whereas others divided them into two sessions to minimise the potential effects of accumulated test-induced fatigue. Detailed information regarding this procedure and the specific tests performed can be found in the methodology section of each study included in this thesis.

Finally, the training interventions carried out in the quasi-experimental repeated measures studies were organised following the recommendations from previous scientific literature (Jiménez-Reyes et al., 2016, 2019). Specifically, 18 sets were performed weekly, divided into six exercises (i.e., three sets/exercise) across two days per week, with at least 72 hours of rest between sessions, over a period of 8 weeks (i.e., 16 training sessions in total). For full details of the training interventions, please refer to the corresponding section in each of the included studies.

STATISTICAL ANALYSIS

To analyse the data from the different studies included in this doctoral thesis, a similar process was followed for each study, using statistical tests adapted to the characteristics of the data and the variables analysed. Descriptive data of the sample was reported as mean ± SD in all studies. Before conducting statistical analysis, the normality and homoscedasticity of the data for each evaluated variable were assessed using the Shapiro-Wilk and Levene's test, respectively. The absolute and relative reliability of all evaluated variables was assessed using the CV and the Intraclass Correlation Coefficient (ICC), respectively.

Once this process was completed, various statistical procedures were applied, depending on the characteristics of the variables and the objectives of each study. Mainly, two types of analysis were conducted to meet the objectives of most of the studies in chapter one and two: (1) correlation analysis and (2) between-group comparison analysis. The statistical tests used varied depending on the sample characteristics and data distribution. When the data followed a normal distribution, a Pearson correlation analysis (r) was performed and, when the normality statistic was significant, Spearman's correlation analysis was used instead. For between-group comparison, different statistical tests were used in each study based on the number of groups being compared and the normal distribution of the data ***(Table 9)***. Additionally, to determine the actual impact of independent variables on COD performance, some studies employed multiple regression analysis ***(Table 9, Study 3 and 5)***. A collinearity diagnosis was conducted to prevent overestimation of the regression model. For the cross-sectional validation and reliability study ***(Table 9, Study 7)***, in addition to the aforementioned statistical tests, the Bland-Altman analysis was used to identify potential systematic bias. Furthermore, in the study aimed at creating a classification based on the CODD and grouping athletes according to their multidirectional speed needs ***(Table 9, Study 6)***, a K-mean cluster analysis was performed.

Finally, chapter three includes a systematic review with meta-analysis study and three quasi-experimental repeated measures interventional studies over eight weeks. In the first study, statistical tests specific to systematic reviews were applied to evaluate methodological quality and heterogeneity. For the meta-analyses, effect sizes of the different training interventions were calculated while controlling for potential moderating variables. For the quasi-experimental repeated measures intervention studies, statistical analyses followed a similar approach to those included in chapters one and two. However, correlation analysis was not conducted in these studies. Instead, a repeated measures ANOVA with a Bonferroni post-hoc test was used to compare groups across multiple time points, aligning with the study objectives ***(Table 9, Study 9, 10 and 11)***.

Table 9 showed a summary of the most important methodological information used in each study. Additionally, this information can be consulted in detail in the corresponding section of each study.

Table 9. Summary of each study's methodology included in this doctoral thesis.

Study	Desing	Sample	Variables (tool)	Statistical analysis
			CHAPTER 1	
1	Cross-sectional	n = 23 male basketball players 12 junior (16.2 ± 0.45 years) 11 senior (19.0 ± 2.90 years)	Anthropometric Measurements (Inbody 230 Multi-frequency Segmental Body Composition Analyzer, Barcelona, Spain). WB-DF (Dorsiflex iPhone App [Apple Inc., Cupertino, CA, USA]) (Balsalobre-Fernández, Romero-Franco, et al., 2019). SEBT & YBT (OctoBalance, Check your Motion, Albacete, Spain). Velocity Test (Chronojump BoscoSystem®, Barcelona, Spain). Jump Test (Chronojump BoscoSystem®, Barcelona, Spain). F-V profile.	Descriptive, normality and homoscedasticity data Inter-groups comparison analysis Pearson´s correlation analysis (r)
2	Cross-sectional	n = 48 male team sport athletes (18.9 ± 3.97 years) 23 basketball players 25 handball players	Anthropometric Measurements (Inbody 230 Multi-frequency Segmental Body Composition Analyzer, Barcelona, Spain). WB-DF (Dorsiflex iPhone App [Apple Inc., Cupertino, CA, USA]) (Balsalobre-Fernández, Romero-Franco, et al., 2019). YBT (OctoBalance, Check your Motion, Albacete, Spain). Jump Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012).	Descriptive, normality and homoscedasticity data Inter-groups comparison analysis Pearson´s correlation analysis (r)
3	Cross-sectional	n = 50 basketball players 23 male (23.9 ± 5.70 years) 27 female (22.7 ± 3.81 years)	WB-DF (Dorsiflex iPhone App [Apple Inc., Cupertino, CA, USA]) (Balsalobre-Fernández, Romero-Franco, et al., 2019). YBT (OctoBalance, Check your Motion, Albacete, Spain). Velocity Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012). Jump Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012).	Descriptive, normality, homoscedasticity and heteroscedasticity data Absolute (CV) and relative reliability (ICC) Inter-groups comparison analysis (Student's T-Test for independent samples) Pearson´s correlation analysis (r) Forward stepwise multiple regression analysis (R^2) Collinearity diagnostic (tolerance and VIF)
4	Cross-sectional	n = 25 basketball player (44% female, 23.2 ± 4.69 years)	Velocity Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012). Isokinetic and isometric strength (FEMD [Myoquality, Spain]) (del-Cuerpo et al., 2023).	Descriptive, normality and homoscedasticity data Absolute (CV) and relative reliability (ICC) Inter-groups comparison analysis (Mann–Whitney U-Test) Spearman's correlation analysis (Rho)

Table 9 (continued).

Study	Desing	Sample	Variables (tool)	Statistical analysis
			CHAPTER 1	
5	Cross-sectional	n = 50 female basketball players (23.7 ± 3.81 years)	WB-DF (Dorsiflex iPhone App [Apple Inc., Cupertino, CA, USA]) (Balsalobre-Fernández, Romero-Franco, et al., 2019). YBT (OctoBalance, Check your Motion, Albacete, Spain). Velocity Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012). Jump Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012).	Descriptive, normality and homoscedasticity data Absolute (CV) and relative reliability (ICC) Inter-groups comparison analysis (Bayesian Student's T-Test for independent samples) Bayesian regression analyses (R^2)
			CHAPTER 2	
6	Cross-sectional	n = 130 basketball player (46% female, 23.7 ± 5.29 years)	Velocity Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012).	Descriptive, normality and homoscedasticity data Absolute (CV and TEM) and relative reliability (ICC) Inter-groups comparison analysis (Student's T-Test for independent samples and one-factor ANOVA with Bonferroni post-hoc) Pearson´s correlation analysis (r) K-means cluster analysis
7	Reliability and validity cross-sectional study	n = 25 male sports science students	COD test (traditional and modified 505 Test [Electronic Timing Gate —Draper, UT— and iPhone App —ASSTRAPP—]).	Descriptive, normality and homoscedasticity data Absolute (CV and SEE) and relative reliability (ICC) Inter-trials comparison analysis (Paired samples t-test and Bland-Altman) Pearson´s correlation analysis (r) Collinearity diagnostic (tolerance, VIF and Durbin-Watson test)

Table 9 (continued).

Study	Desing	Sample	Variables (tool)	Statistical analysis
			CHAPTER 3	
8	Systematic Review with Meta-analysis	558 basketball players (18% female) 28 intergroup comparisons 16 studies	COD Test (Illinois test, T-Test, V-Cut and Lane Test).	Cochran Q statistic Egger's regression test Heterogeneity (I^2) Standardized mean difference inter-groups (using a random-effects model estimated with the DerSimonian and Laird method) Analysis effects of moderator variables
9	Randomised controlled trial	n = 30 basketball players 15 INT (22.9 ± 6.52 years) 15 CON (22.7 ± 4.93 years)	Velocity Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012). Jump Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012). F-V profile.	Descriptive, normality and homoscedasticity data Absolute (CV) and relative reliability (ICC) Inter-groups comparison analysis (2×3 repeated measures ANOVA model with Bonferroni post-hoc)
10	Quasi-experimental repeated measures	n = 36 basketball players 18 INT (20.1 ± 1.45 years) 18 CON (22.7 ± 4.93 years)	Velocity Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012).	Descriptive, normality and homoscedasticity data Absolute (CV) and relative reliability (ICC) Inter-groups comparison analysis (2×3 repeated measures ANOVA model with Bonferroni post-hoc)
11	Quasi-experimental repeated measures	n = 45 basketball players 15 VG (22.9 ± 6.52 years) 15 HG (21.1 ± 1.45 years) 15 CG (22.7 ± 4.93 years)	Velocity Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012). Jump Test (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012). F-V profile.	Descriptive, normality and homoscedasticity data Absolute (CV) and relative reliability (ICC). Responder to intervention (2CV). Inter-groups comparison analysis (3×3 repeated measures ANOVA model with Bonferroni post-hoc)

RESULTS

For a better understanding of the results presented in this doctoral thesis, the included scientific studies were grouped into three different chapters, as illustrated in ***figure 1***.

Chapter 1. Decisive factors for a greater performance in changes of direction.

This chapter comprises five scientific publications, all cross-sectional studies, that examine the relationships between multiple variables and COD actions. These studies explore the influence of variables such as age category, gender, force orientation or cutting angle, addressing the first aim of this doctoral thesis.

Chapter 2. New tools and standardization to assess change of direction.

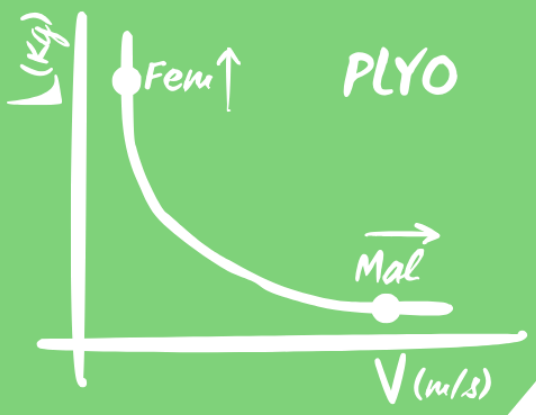
The second chapter included two scientific publications that seek to answer the second aim of this doctoral thesis. These cross-sectional studies utilise a large sample to develop a CODD-based classification system for basketball players and to validate a novel tool for assessing both linear and multidirectional speed performance.

Chapter 3. New approach to individualised change of direction training.

The third chapter involved four scientific studies, including a systematic review with meta-analysis and three original intervention studies with a quasi-experimental repeated measures design. The objective of this section was twofold: first, to analyse the existing literature on COD training; and second, to evaluate the effect of novel, individualised training approaches on basketball players' performance. This chapter directly addresses the third aim of the doctoral thesis.

CHAPTER 1.

Decisive factors for a greater performance in changes of direction



Study 1

Barrera-Domínguez, F. J., Almagro, B. J., Tornero-Quiñones, I., Sáez-Padilla, J., Sierra-Robles, Á., & Molina-López, J. **(2020)**. Decisive factors for a greater performance in the change of direction and its angulation in male basketball players. *International journal of environmental research and public health*, 17(18), 6598.

Study 2

Barrera-Domínguez, F. J., Carmona-Gómez, A., Tornero-Quiñones, I., Sáez-Padilla, J., Sierra-Robles, Á., & Molina-López, J. **(2021)**. Influence of dynamic balance on jumping-based asymmetries in team sport: A between-sports comparison in basketball and handball athletes. *International journal of environmental research and public health,* 18(4), 1866.

Study 3

Barrera-Domínguez, F. J., Almagro, B. J., & Molina-López, J. **(2024)**. The Influence of Functional Movement and Strength upon Linear and Change of Direction Speed in Male and Female Basketball Players. *Journal of Human Kinetics*, 92, 147-159.

Study 4

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Study 5

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STUDY 1

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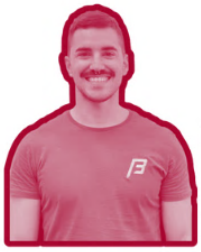
Decisive factors for a greater performance in the change of direction and its angulations in male basketball players



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Article

Decisive Factors for a Greater Performance in the Change of Direction and Its Angulation in Male Basketball Players

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Abstract: A study was made to initially evaluate whether the age category directly could influence anthropometric measurements, functional movement tests, linear sprint (30 m) and strength. Moreover, and as the main purpose, this study aimed to examine the relationship between the time execution and angles in different changes of direction (COD) test with the analyzed sport performance variables. A total sample of 23 basketball players (age: 17.5 ± 2.42 years; height: 184.6 ± 6.68 cm; body weight: 78.09 ± 11.9 kg). Between-groups' comparison explored the differences between basketball categories (Junior, n = 12; Senior, n = 11). The COD variables were divided by the time execution into low responders (LR) and high responders (HR) to establish comparisons between groups related to COD time execution. Pearson's correlation coefficient was used to establish correlations between different CODs and sport performance variables. The results showed a greater influence of age category upon COD performance, especially when the cutting angle was sharper (7.05% [Confidence limits (CL) 90%: 2.33; 11.99]; Quantitative chances (QC) 0/2/98), in which athletes need greater application of strength. Moreover, the sharper the angle or the larger the number of cuts made, the greater the relationship with the vertical force–velocity profile (−42.39 [CL 90%: −57.37; −22.16]; QC 100/0/0%). Thus, the usefulness of the f–v profile to implement training programs that optimize the f–v imbalance and the improvement of the COD performance in basketball players is suggested.

Keywords: team sports; category; force–velocity profile; reactive strength index; body composition; functional movement

1. Introduction

Basketball is characterized by high-intensity actions in the form of jumps, accelerations, decelerations, and rapid changes of direction (COD) that are regarded as key components of this sport [1]. Basketball players have been found to make an average of 1050 movements during a competitive game, resulting in a change in speed or direction every two seconds, and demonstrating the highly intermittent character of basketball [2]. Also, elite athletes tend to cover a distance of 991 m with high-intensity actions, averaging 40–60 maximum jumps and 50–60 speed changes and CODs [2]. Specifically, 52% of all sprints during a basketball match involve fast CODs [3]; the efficiency of both ball and nonball CODs is, therefore, a critical component in sports performance.

Agility has been defined as a rapid whole-body movement with a change of speed or direction in response to a stimulus [4]. Agility comprises a process of perception and decision making that results in COD or speed, but a COD and speed that does not involve the perception of a stimulus and decision making is no longer agility but a COD or speed skill [5,6]. It has been argued that this COD skill is a fundamental prerequisite for success in modern sports [7]. Our main interest focused on COD as a component of agility. Many factors can influence the speed of COD due to its multifactorial character [6]. Among them, technical, anthropometric, and physical factors stand out [4], with both linear velocity and muscular activity of the lower limbs through strength and power being of particular relevance [8]. Based on previous evidence, all of these factors might vary between basketball players of different age categories or playing levels [9,10]. Although many studies have focused on COD and its relation to physical performance, to our knowledge no studies have examined all these variables simultaneously in one, same sample, which would allow analysis of the real influence of each parameter upon COD. To date, the literature offers only limited and conflicting results regarding the possible relationship between these physical parameters.

In this context, previous evidence examined isolated sports performance variables such as linear velocity finding an association with COD involving small angles [11]. Previous studies added that shorter sprints prior to COD did not allow high accelerations [12]. Furthermore, several authors [12,13] showed that in young basketball players shuttle sprinting with a COD of 180° both oxygen uptake and blood lactate concentration increases with the shuttle distance, while the metabolic cost decreases. Therefore, within the COD itself, the distance of sprinting carried out prior to the COD affects metabolic involvement, acceleration, and braking forces. Strength is another essential skill for optimal performance in COD actions [14]. Specifically, the countermovement jump (CMJ), together with the drop jump (DJ), is the most used test for evaluating strength in relation to COD [15]. However, there is no clear consensus about the results of this relationship between jumps and COD [16,17]. Moreover, previous studies have analyzed strength by separating the different phases of muscle contraction [18,19] as a strength. The present study considered analysis of the force–velocity (f-v) profile through different CMJs, where the stretch-shortening cycle was used (as in the COD), with loads from body weight (BW) itself up to 60 kg extra. In this way, we can analyze a broader spectrum of the force–velocity curve, with force being understood as a single physical capacity without differentiating between its different manifestations. To asses COD, specifically in basketball, the T-test is the most used [18–21], where the player has to cover a circuit in the form of a T with the aim of moving in all directions in the least time possible, moving forward, sideways, and backward (a similar situation to that encountered in a real game) [21]. To our knowledge, many studies carried out the 505, test with 180° COD [14,19] but other angulations have not been studied, this would be important because basketball is a sport that involves many COD with different angulations.

Therefore, the present study initially sought to evaluate whether the age category could influence anthropometric measurements, functional movement tests, linear sprint (30 m), and strength. Moreover, and as the main purpose, the present study aimed to examine the relationship between the time execution in different COD tests and angles with the analyzed sport performance variables. Such knowledge could be crucial for strength and conditioning practitioners.

2. Materials and Methods

2.1. Participants

A cross-sectional study was performed with 23 amateur basketball players aged between 16 and 27 years. The sample comprised two age categories: A junior group (n = 12) (age: 16.25 ± 0.45 years; height: 181.9 ± 6.36 cm; body weight: 72.02 ± 8.46 kg) and a senior group playing in the Spanish National Division (n = 11) (age: 19.00 ± 2.90 years; height: 187.6 ± 6.59 cm; body weight: 84.73 ± 11.87 kg). Subjects were eligible for inclusion if they had at least five years of previous experience, played at a federated level, no injuries during and at least six months before the study, and had regular

training between three or four days per week during the competitive period. All players were trained by the same coach and strength-conditioning trainer, were in good health, and passed a medical examination before starting their basketball season. Data collection was conducted after the preseason, coinciding with the start of the competitive period. During and prior to the data collection period, the training duration of the athletes consisted of 7.1 ± 1.2 h/week of a basketball training regimen including both indoor and integrated conditioning exercises, in addition to competition in matches on weekends. The predesigned weekly training schedule of the basketball teams comprised the following: Day 1–strength training and individual technique; Day 2–integrated strength training and small side games; Day 3–offensive and defensive technical–tactical training; Day 4–match. All players were informed about the objectives of the study and gave consent to participation. The procedures followed the rules established by the Declaration of Helsinki. The present research was approved by the Andalusian Ethics Committee of Biomedical Research (reference number: FBD_UHU2020).

2.2. Procedure

During the preseason, familiarization sessions were held so that the players would have performed each test at least 3–6 times. During the measuring days, all tests were performed on the surface where they train and compete. All players were instructed to attend with good hydration and rest, without vigorous training in the previous 24 h, no caffeine, drink, or food intake in the three hours before the test, no alcohol intake in the previous 24 h, and urination immediately before the anthropometric measurement.

Prior to data collection, all subjects performed a standardized warm-up including a routine of 5 min of low intensity with ball, 5 min of hip mobility and core activation, 5 min of low-impact landings, accelerations, and plyometrics and, finally, 5 min of approximation to the tests, increasing the intensity in each repetition. The proposed tests were grouped together to be performed in four different sessions: (1) anthropometric measurements and weight-bearing dorsiflexion test (WB-DF), star execution balance test (SEBT), and Y balance test (YBT); (2) linear speed test using a 30-m sprint test (30S) and triple hop test for distance unilateral (THTU); (3) vertical force–velocity profile of each player using four CMJ at different loads and drop jump unilateral test (DJU) at a height of 30 cm; and (4) proposed COD test: Modified T-test and the 5 + 5 test with different angles at 45°, 90°, and 180°.

2.3. Anthropometric Measurements

Body height was measured with a stadiometer (0.1 cm, Secca 220, BLINDED). While this was done, the players remained static in the anatomical position with their heels together. The highest point of the head was taken as reference. Body composition measurements were taken by multi-frequency bioelectrical impedance (Inbody 230 Multi-frequency Segmental Body Composition Analyzer, Barcelona, Spain). The analyzer complied with the applicable European standards (93/42 European Economic Community (EEC), 90/384 EEC) for use in the medical industry. The impedance between the two feet was measured while an alternating current (50 kHz, 90 milliamps) was passed through the lower body. Participants were informed in advance of the conditions that had to be sustained prior to measurement: No alcohol for at least 24 h before the measurement, no vigorous exercise for at least 12 h before, no food or drink for at least three hours before, and urination immediately before the measurement. The following measurements were taken: Weight, body mass index (BMI), lean mass, and fat mass expressed as a percentage of total body fat.

2.4. Weight-Bearing Dorsiflexion Test (WB-DF)

Ankle dorsiflexion was evaluated through the Dorsiflex iPhone App (Apple Inc., Cupertino, CA, USA) [22]. Initially, each player stood with his hands on his hips, placing the leg to be measured forward and the opposite leg resting one foot behind. The test was performed without any type of footwear. While maintaining the position, the player was instructed to bring the knee forward while keeping the foot completely on the ground. The device was placed vertically on the anterior border of

the tibia, just below the tibial tuberosity, determining the range of dorsiflexion in degrees. Each player had three measurements taken for each leg, obtaining an average of the three for subsequent analysis.

2.5. Star Excursion Balance Test (SEBT) and Y Balance Test (YBT)

Dynamic balance (SEBT) was performed (OctoBalance, Check your Motion, Albacete, Spain) to determine the dynamic stability of the lower limbs [23]. In this test, the subjects were asked to adopt a unilateral equilibrium position, executing a series of unilateral squats where they tried to reach the maximum distance possible in eight different directions with the other extremity: Three in front, two at the sides, and three at the back [24]. The current literature also includes the modified SEBT or YBT [25]. Both tests, SEBT and YBT, were performed. To be valid, each player had to: (1) Place the heel of the supporting foot on the rear edge of the octagon and the head of the second metatarsal on the front line (red), (2) keep his hands on his hips, and (3) rest only the reaching foot on the platform. The measurements were made only once per leg, since these were experienced subjects [23], and were made with both legs to determine asymmetry between both body hemispheres.

2.6. The 30-M Sprint Test (30S)

Linear speed was determined by performing the 30-m sprint test with the MySprint App (Apple Inc., USA) [26]. The test consists of covering a distance of 30 m at maximum speed from a standing position in which the subject is positioned behind the starting line with one foot forward. The time starts to count just as the back foot is separated from the ground with cuts at 5, 10, and 30 m and at the moment the hip passes through the marker, until the last marker is reached. Each athlete performed the test twice, with a break of at least two minutes between each attempt. Individual force–velocity relationships in sprinting were assessed with MySprint app [26]. This app uses the Samozino's method to determine the theoretical maximum values of force (F0), velocity (V0), and power (Pmax) in sprinting [27]. Samozino's method provides a simple method of obtaining the force–velocity relationship from the application of basic laws of motion using the running speed and the body mass of the athlete as main inputs [27]. From all the data obtained, the rate of force at 10 meters (RF-10M) and the split times of 5, 10, and 30 m of the best attempt were used for further analysis.

2.7. Triple Hop Test for Distance Unilateral (THTU)

The analysis of the elastic–reactive force in the horizontal vector of the lower extremities (LE) was carried out by means of the triple jump test in a unilateral manner due to the predictive power of muscle strength and the power of the LE [28,29]. Each participant positioned the leg to be measured, resting the big toe on the starting line. Once each player performed three consecutive maximum forward jumps with the same limb, the researcher measured the total distance jumped from the start to the point where the heel hit the ground upon completion of the third jump [30,31]. Arms' swinging was allowed, and attempts were considered failed if the participant: (1) Did not complete the test as instructed, (2) lost balance during any part of the test, or (3) was unable to maintain the final posture on one limb for at least two seconds. Each athlete performed the test twice with a break of at least two minutes and the best attempt was used for further analysis.

2.8. Countermovement Jump (CMJ) Test

The vertical jump test was determined using a Chronojump (Chronojump BoscoSystem®, Barcelona, Spain) [32]. Starting from an initial position with both feet on the ground and both hands on the hips, a squat was executed with countermovement. A jump was considered valid if it was performed with the hands on the hips, without bending the knees during flight time, and landing at the same point where the jump was made. Each player made a total of three valid attempts, and the best attempt was recorded.

2.9. Drop Jump Unilateral (DJU) Test

The vertical jump test was determined using a Chronojump (Chronojump BoscoSystem®, Barcelona, Spain) [32]. From an initial height of 30 cm, each subject was dropped to the ground on one leg in search of the maximum application of forces reacting against the ground to jump as high as possible. Each attempt was considered valid when both hands were on the hips, the knees were not bent, and both landings were made at the same point. A total of three valid attempts were made with each leg, with a total of 30 s of recovery between each attempt. Finally, the best of these attempts was used for further analysis. The reactive strength index (RSI) was calculated using the time of flight to contact time ratio for each leg.

2.10. Vertical Force–Velocity Profile

The force–velocity profile was determined by the neuromuscular relationship between force and speed of the LE using CMJ with a hex bar. Each subject performed a maximum vertical CMJ jump with their body weight (BW), without loading, and then five more jumps with an extra load between 10 and 60 kg in random order. To be valid, each player had to reach at least 10 cm in height with the attempted load [33]. Before the first CMJ jump, and although the players knew the test, the execution of all jumps both without and with loading was explained to them. The CMJ without additional loading was performed as already explained in CMJ test. The differently loaded CMJs were performed with the hands holding the hex bar with the load being distributed equally between both sides of the bar, the elbows were kept extended, and the shoulders relaxed. The jump was carried out in the same way as the CMJ test. Each attempt was accompanied by two minutes of rest to ensure maximum performance.

The vertical jump test was determined using a Chronojump (Chronojump BoscoSystem®, Barcelona, Spain) [32]. Finally, multiple jumps were used to calculate the f–v profile, specifically the best four jumps. The data obtained were manually entered into the MyJump2 App (Apple Inc., USA) [34] to apply Samozino's method [35] and estimate the mean force, velocity, and power of the jump considering three simple input variables: The height of the jump, body mass, and thrust distance, with the last calculated as the difference between the length of the extended leg (from the anterior superior iliac crest (ASIC) to the toes with plantar flexion) and the length from the ASIC to the ground in the squatting position. The values were F0, V0, and the f–v profile, as previously proposed [36]. Likewise, the theoretical optimal f–v profile was calculated individually for each subject, together with the imbalance in the f–v profile [37].

2.11. Change of Direction (COD)

The 5+5 test. Timing photocells (Chronojump BoscoSystem®, Barcelona, Spain) were placed to 0.5 m from starting line with a width of 2 m and 5 m from the pivot point marked on the floor, where the athlete performed changes of direction at 45°, 90°, and 180°, setting the designated leg and turning to the opposite side (side step) to go to the second time gate placed 5 m away in the shortest time possible. Each athlete had two attempts for each leg, and the best attempt was used for analysis. Between each attempt the players rested for at least two minutes.

Modified T-test. Timing photocells were placed at the starting and finish lines (Chronojump BoscoSystem®, Barcelona, Spain). Subjects began with both feet 0.5 m behind the starting line. Each subject was required to sprint forward as far as the first cone, located 5 m away, to the starting line and touch the base of it with the right hand. Facing forward and without crossing feet, they shuffled to the left cone and touched its base with the left hand. Subjects then shuffled to the right cone and touched its base with the right hand. Finally, they shuffled back to the left to the central cone with a lateral displacement of 2.5 m and touched its base with the left hand just before running backwards as fast as possible to the finish line [20]. The test was considered invalid if the subject crossed the feet in front of each other, did not touch the base of a cone, or did not look forward during the entire test.

Each athlete had two attempts and the best attempt was used for analysis. Between each attempt the players rested for at least two minutes.

2.12. Statistical Analysis

Statistical analyses were performed using the SPSS version 25 statistical package for MS Windows (SPSS, Inc., Chicago, IL, USA). Data were expressed as means and standard deviations (SD). Data normality was checked using the Shapiro–Wilks test. A between-groups' comparison analysis was carried out to determine the differences between basketball categories. Then, the COD variables were divided by the median into two groups to examine the influence of each COD upon performance: High responders (HRs), defined as players who performed above the 50 percentile for each COD, and low responders (LRs), defined as players who performed below the 50 percentile for each COD. The model was adjusted by age. The effect sizes (ES) were calculated using the Hedge's g on the pooled SD together, and the 90% confidence intervals (CI) were calculated for all dependent variables. Probabilities were also calculated to determine whether true (unknown) differences were smaller, similar, or larger than the smallest worthwhile difference or change (0.2 × SD between subjects) [38]. Quantitative chances of better or worse effects were determined as follows: <1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; and >99%, most likely [39,40]. Finally, if the chances of obtaining a beneficial/better or detrimental/worse effect were both >5%, the effect was assessed as unclear [41,42]. An Excel spreadsheet downloaded from sportsci.org was used to examine comparisons between groups (xCompare2groups.xls). On the other hand, Pearson's correlation coefficient was used to establish correlations between different CODs and sport performance variables.

3. Results

Table 1 shows the comparative analysis of the mean values referred to body composition, mobility, dynamic balance, linear sprint, strength, and COD according to player category. Body composition showed a greater influence of the category upon lean mass and BMI. Regarding mobility and dynamic balance, a high percentage of change was observed for the analyzed variables depending on the category. On the other hand, linear speed showed no relationship with the category except for the run time at 30 m. The strength variables, likewise, showed no relationship between them with the category except for imbalance in the f–v profile, which did show variation (27.89% [Confidence limit (CL) 90%: −10.70; 83.16]; Quantitative chances (QC) 4/25/71). Lastly, the changes observed for the COD test were greater as the angle of COD increased, with the greatest variation being recorded for COD 180° (7.05% [CL 90%: 2.33; 11.99]; QC = 0/2/98). The comparative analysis of each COD, defined as LR and HR, and the sport performance-related variables are shown in Table 2. For linear velocity, a greater impact was observed with COD as the angle and number of CODs increased. Specifically, execution of the linear sprint in the first 10 m showed higher percentages of change for COD180° (−4.84% [CL 90%: −7.74; −1.86]) and for the T-test (−5.29% [CL 90%: −7.98; −2.52]). No significant differences were observed in the determination of the elastic–reactive force in the horizontal axis. In relation to the vertical axis elastic–reactive force for the DJU test, the group of HR players showed a greater percentage of change with respect to RSI (26.87 to 32.2% [CL 90%: 8.31; 48.61 RSI Right to 11.56; 56.66 RSI Left]) than for the height of the jump (7.5 to 17.7% [CL 90%: −3.88; 20.34 DJU R to 2.16; 35.59 DJU L]), with a greater change of this index being for the T-test, independently of the leg of execution. Finally, asymmetry analyzed in the f–v profile was determined, and a relationship was obtained with the different types of CODs evaluated. Greater changes were observed for the COD180° and T test, with the latter showing the greatest variation (−42.39% [CL 90%: −57.37; −22,16]).

Table 1. Data description referred to body composition, mobility, dynamic balance, linear sprint, strength, and change of direction according to player category.

Variables	JUNIOR		SENIOR		% (CL 90%)	ES (CL 90%)	Chances (%)	Outcome
	Mean	SD	Mean	SD				
Body Composition								
BMI (kg/cm^2)	21.8	2.90	24.1	2.87	−9.65 (−17.81; −0.68)	−0.81 (−1.57; −0.05)	91/7/2	Likely
Lean mass (kg)	35.9	4.12	42.8	4.45	15.83 (−22.44; −8.67)	−1.58 (−2.33; −0.83)	100/0/0	Most likely
Fat mass (%)	11.9	6.61	11.4	5.08	−5.77 (−36.02; 38.77)	−0.13 (−0.95; 0.70)	44/31/25	Unclear
Mobility								
WB-DF R (°)	40.7	5.65	37.1	4.31	9.86 (0.19; 20.45)	0.78 (0.02; 1.54)	2/8/90	Likely
WB-DF L (°)	40.1	5.60	38.4	3.77	3.77 (−5.68; 14.15)	0.34 (−5.54; 1.22)	15/24/61	Unclear
Dynamic Balance								
SEBT R (cm)	57.6	7.31	63.5	4.97	−8.77 (−15.67; −1.30)	−1.08 (−2.00; −0.15)	94/4/1	Likely
SEBT L (cm)	57.3	7.60	63.2	6.27	−8.80 (−16.62; −0.25)	−0.85 (−1.67; −0.02)	90/7/2	Likely
YBT R (cm)	62.9	7.05	69.0	6.34	−7.94 (−14.69; −0.66)	−0.81 (−1.56; −0.06)	91/7/2	Likely
YBT L (cm)	62.8	7.97	67.9	7.79	−6.73 (−14.93; 2.26)	−0.56 (−1.29; 0.18)	79/16/5	Likely
Linear Sprint								
5 m sprint (s)	0.89	0.04	0.88	0.04	0.87 (−2.46; 4.31)	0.17 (−0.49; 0.84)	17/36/47	Unclear
10 m sprint (s)	1.48	0.06	1.47	0.08	0.87 (−2.69; 4.57)	0.15 (−0.48; 0.78)	17/38/45	Unclear
30 m sprint (s)	4.31	0.14	4.16	0.19	3.18 (−0.23; 6.71)	0.58 (−0.04; 1.20)	2/13/85	Likely
RF-10M	0.30	0.01	0.31	0.02	−2.33 (−5.87; 1.33)	−0.41 (−1.04; 0.23)	71/23/6	Unclear
Strength								
CMJ (cm)	34.9	5.14	35.6	4.78	−0.51 (−10.45; 10.54)	−0.03 (−0.72; 0.65)	34/38/28	Unclear
DJU R (cm)	17.5	3.41	17.6	1.00	−1.93 (−12.55; 9.97)	−0.32 (−2.21; 1.57)	55/14/32	Unclear
DJU L (cm)	17.1	3.45	16.3	3.40	5.63 (−10.06; 24.05)	0.23 (−0.45; 0.91)	14/33/53	Unclear
RSI R	0.93	0.28	0.99	0.21	7.78 (−25.03; 13.42)	−0.32 (−1.13; 0.50)	60/26/14	Unclear
RSI L	0.93	0.31	0.87	0.25	4.79 (−16.89; 32.14)	0.15 (−0.59; 0.89)	21/33/45	Unclear
THT R (cm)	566.3	42.4	566.1	59.5	1.64 (−4.90; 8.62)	0.14 (−0.43; 0.70)	16/42/42	Unclear
THT L (cm)	570.3	58.2	598.5	63.9	−2.96 (−9.70; 4.29)	−0.26 (−0.87; 0.36)	56/33/11	Unclear
F-V	61.8	17.3	51.0	20.5	27.89 (−10.70; 83.16)	0.37 (−0.17; 0.91)	4/25/71	Possibly
COD								
COD45° R (s)	2.01	0.09	2.03	0.11	−1.81 (−4.96; 1.44)	−0.33 (−0.91; 0.26)	65/29/7	Unclear
COD45° L (s)	2.02	0.08	2.05	0.16	−1.52 (−5.94; 3.09)	−0.19 (−0.74; 0.37)	48/40/12	Unclear
COD90° R (s)	2.37	0.13	2.26	0.12	4.40 (0.24; 8.73)	0.77 (0.04; 1.49)	2/8/90	Likely
COD90° L (s)	2.35	0.09	2.27	0.10	3.00 (−0.14; 6.23)	0.63 (−0.03; 1.28)	2/12/86	Likely
COD180° R (s)	2.75	0.16	2.61	0.10	4.68 (0.90; 8.59)	1.12 (0.22; 2.02)	1/4//95	Very likely
COD180° L (s)	2.77	0.18	2.58	0.14	7.05 (2.33; 11.99)	1.19 (0.40; 1.97)	0/2/98	Very likely
COD T-test (s)	6.75	0.39	6.49	0.34	3.48 (−0.67; 7.80)	0.61 (−0.12; 1.35)	4/14/83	Likely

BMI: Body mass index; R: Right; L: Left; WB-DF: Weight-bearing dorsiflexion; SEBT: Star excursion balance test; YBT: Y balance test; RF: Rate of force; CMJ: Countermovement jump; DJU: Drop jump unilateral; RSI: Reactive strength index; THT: Triple hop test; f-v: Vertical force–velocity profile; COD: Change of direction; SD: Standard deviation; CL: Confidence limits; ES: Effect size.

Practical, worthwhile differences between groups seemed evident as supported by the magnitudes of the ES and qualitative outcomes (Figure 1). The COD180° and the modified T-Test showed most likely and very likely positive effects on 5- and 10-m linear sprint (COD180°, QC 99/1/0%; T-test, QC 100/0/0%), the reactive strength index (RSI) (COD180°, 0/3/97%; T-test, QC 0/4/95%), and the vertical force–velocity profile (COD180° and T-test, QC 100/0/0%), whereas the other two CODs (COD 45° and 90°) showed unclear or likely effects.

Table 2. Comparison of the 5, 10, and 30 m linear sprint, the rate of force at 10 m, the vertical jump through countermovement jump and drop jump unilateral, the reactive strength index, the horizontal jump through triple hop test, and the vertical force–velocity profile between low responders (LH) and high responders (HR) classified by each change of direction (COD) execution time.

Variables	LR		HR		% (CL 90%)	ES (CL 90%)
	Mean	SD	Mean	SD		
COD45°						
5 m sprint (s)	0.90	0.04	0.87	0.04	−2.43 (−5.23; 0.46)	−0.64 (−1.40; 0.12)
10 m sprint (s)	1.50	0.07	1.45	0.07	−2.66 (−5.52; 0.29)	−0.69 (−1.46; 0.07)
30 m sprint (s)	4.15	0.17	4.33	0.13	−3.86 (−6.73; −0.91)	−1.06 (−1.87; −0.25)
RF-10M	0.30	0.01	0.31	0.02	3.53 (0.16; 7.02)	0.89 (0.04; 1.74)
CMJ (cm)	32.6	4.41	37.7	4.00	15.97 (5.57; 27.39)	0.97 (0.36; 1.59)
DJU R (cm)	17.1	2.97	17.9	2.04	6.21 (−5.10; 18.87)	0.30 (−0.26; 0.87)
DJU L (cm)	14.6	2.77	18.6	2.74	26.81 (11.22; 44.59)	1.06 (0.48; 1.65)
RSI R	0.86	0.19	1.04	0.27	20.04 (−0.30; 44.52)	0.75 (−0.01; 1.50)
RSI L	0.77	0.17	1.03	0.30	29.20 (5.92; 57.58)	1.03 (0.23; 1.82)
THT R (cm)	564.9	45.8	567.4	55.7	−0.02 (−6.76; 7.21)	0.00 (−0.75; 0.74)
THT L (cm)	569.2	50.7	597.1	69.0	5.03 (−2.87; 13.57)	0.47 (−0.28; 1.22)
F-V	61.5	18.0	52.2	20.0	−19.95 (−44.29; 15.05)	−0.57 (−1.49; 0.36)
COD90°						
5 m sprint (s)	0.88	0.04	0.88	0.04	−0.93 (−4.56; 2.84)	−0.20 (−0.98; 0.59)
10 m sprint (s)	1.47	0.06	1.48	0.08	1.35 (−2.54; 5.40)	0.33 (−0.63; 1.29)
30 m sprint (s)	4.29	0.16	4.19	0.18	−2.19 (−5.96; 1.73)	−0.44 (−1.23; 0.34)
RF-10M	0.30	0.01	0.31	0.02	3.06 (−1.09; 7.38)	0.60 (−0.22; 1.41)
CMJ (cm)	33.7	5.51	36.6	3.94	12.25 (−1.93; 28.48)	0.62 (−0.10; 1.34)
DJU R (cm)	16.5	2.22	18.5	2.41	9.83 (−2.72; 24.01)	0.60 (−0.18; 1.38)
DJU L (cm)	15.3	3.40	18.0	2.91	30.40 (8.97; 56.05)	1.08 (0.35; 1.80)
RSI R	0.84	0.25	1.06	0.20	17.03 (−6.83; 47.00)	0.52 (−0.23; 1.27)
RSI L	0.81	0.29	0.99	0.25	34.59 (2.05; 77.50)	0.80 (0.05; 1.55)
THT R (cm)	563.1	43.7	569.1	57.1	−0.53 (−8.05; 7.62)	−0.06 (−0.98; 0.86)
THT L (cm)	581.2	64.3	586.1	61.1	−2.41 (−11.37; 7.45)	−0.20 (−1.01; 0.60)
F-V	64.9	15.7	49.0	19.5	−30.84 (−51.75; −0.88)	−1.30 (−2.58; −0.03)
COD180°						
5 m sprint (s)	0.90	0.04	0.86	0.03	−4.39 (−6.74; −1.99)	−1.15 (−1.79; −0.51)
10 m sprint (s)	1.51	0.07	1.44	0.05	−4.84 (−7.74; −1.86)	−0.99 (−1.60; −0.37)
30 m sprint (s)	4.35	0.19	4.13	0.10	−4.47 (−7.31; −1.54)	−0.89 (−1.48; −0.30)
RF-10M	0.30	0.01	0.31	0.01	5.05 (1.83; 8.38)	1.00 (0.37; 1.64)
CMJ (cm)	33.82	5.11	36.54	4.46	8.36 (−2.46; 20.37)	0.48 (−0.15; 1.11)
DJU R (cm)	16.39	2.18	18.60	2.39	13.69 (3.23; 25.22)	0.83 (0.20; 1.45)
DJU L (cm)	15.32	2.65	17.99	3.55	16.61 (0.97; 34.68)	0.82 (0.05; 1.58)
RSI R	0.84	0.23	1.06	0.22	27.61 (9.17; 49.18)	0.91 (0.33; 1.49)
RSI L	0.79	0.20	1.00	0.31	25.44 (3.46; 52.09)	0.80 (0.12; 1.47)
THT R (cm)	572.4	47.8	560.6	53.5	−2.14 (−8.61; 4.78)	−0.22 (−0.93; 0.48)
THT L (cm)	586.9	66.4	580.8	59.0	−0.91 (−8.75; 7.60)	−0.07 (−0.68; 0.55)
F-V	69.2	12.7	45.1	17.0	−40.19 (−56.19; −18.33)	−2.29 (−3.68; −0.90)
T-Test						
5 m sprint (s)	0.91	0.03	0.86	0.03	−4.88 (−7.02; −2.68)	−1.42 (−2.06; −0.77)
10 m sprint (s)	1.52	0.06	1.44	0.05	−5.29 (−7.98; −2.52)	−1.18 (−1.80; −0.55)
30 m sprint (s)	4.37	0.16	4.11	0.11	−5.29 (−7.88; −2.63)	−1.21 (−1.83; −0.60)
RF-10M	0.30	0.01	0.31	0.01	5.46 (2.34; 8.68)	1.16 (0.50; 1.81)
CMJ (cm)	33.7	4.96	36.7	4.52	9.15 (−1.65; 21.14)	0.54 (−0.10; 1.18)
DJU R (cm)	17.0	3.07	18.1	1.84	7.55 (−3.88; 20.34)	0.36 (−0.19; 0.91)
DJU L (cm)	15.2	2.49	18.1	3.58	17.69 (2.16; 35.59)	0.91 (0.12; 1.70)
RSI R	0.84	0.23	1.06	0.22	26.87 (8.31; 48.61)	0.88 (0.29; 1.46)
RSI L	0.76	0.17	1.03	0.30	32.20 (11.56; 56.66)	1.15 (0.45; 1.85)
THT R (cm)	566.5	47.7	566.0	54.3	−0.17 (−6.67; 6.79)	−0.02 (−0.72; 0.68)
THT L (cm)	573.9	60.3	592.8	63.4	3.28 (−4.75; 11.99)	0.26 (−0.40; 0.92)
F-V	70.2	11.0	44.2	16.6	−42.39 (−57.37; −22,16)	−3.01 (−4.65; −1.37)

The model was adjusted by age. R: Right; L: Left; RF: Rate of force; CMJ: Countermovement jump; DJU: Drop jump unilateral; RSI: Reactive strength index; THT: Triple hop test; F–V: Vertical force–velocity profile; COD: Change of direction; SD: Standard deviation; CL: Confidence limits; ES: Effect size; LR: Low responder; HR: High responder.

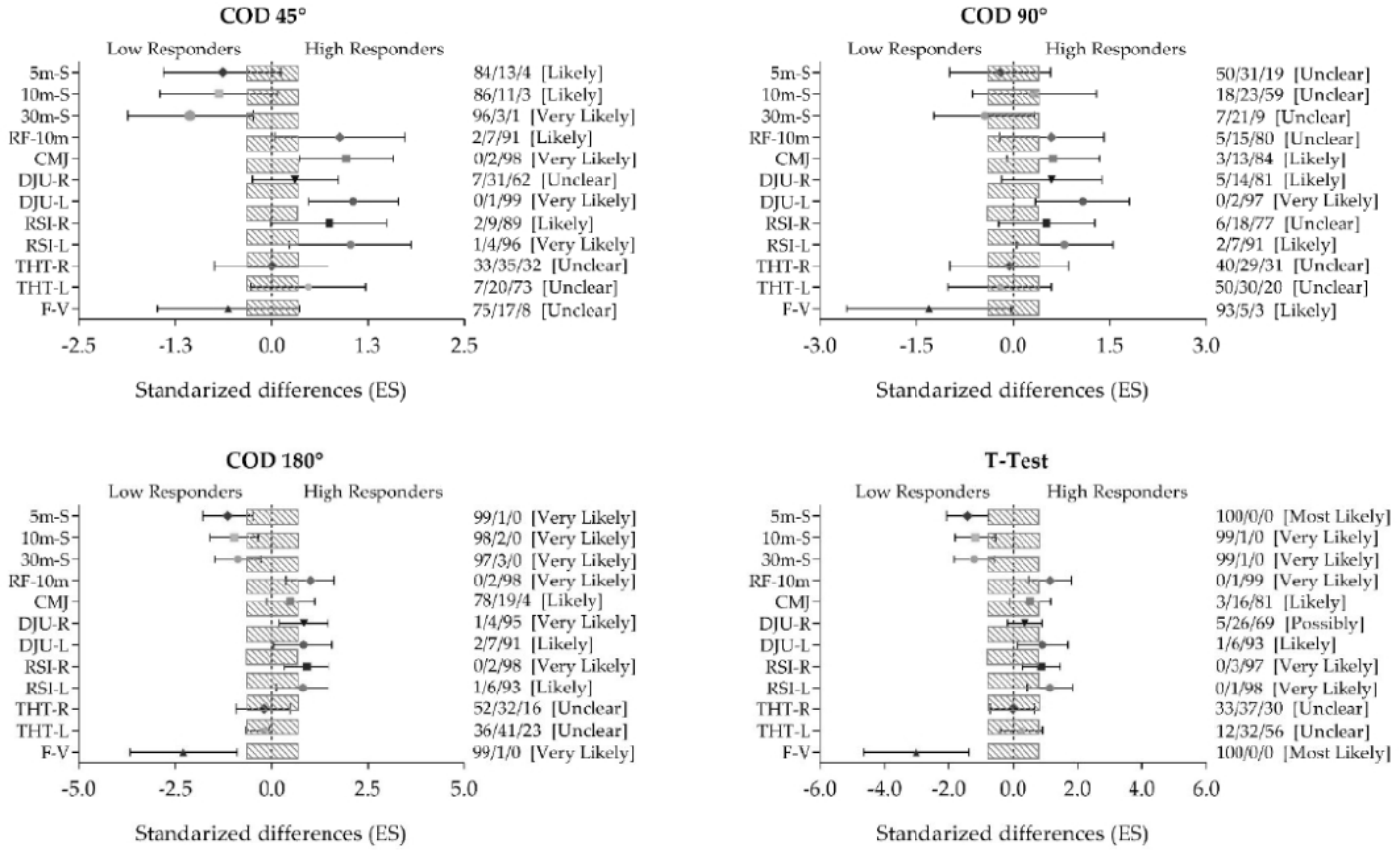

Figure 1. Between-group comparisons for the 5-, 10-, and 30-m linear sprint, the rate of force at 10 m, the vertical jump through countermovement jump and drop jump unilateral, the reactive strength index, the horizontal jump through triple hop test, and the vertical force–velocity profile between low responders (LH) and high responders (HR) classified by each change of direction (COD) execution time. The model was adjusted by age. Bars indicate uncertainty in the true mean changes with 90% confidence intervals. Trivial (shaded) areas were calculated from the smallest worthwhile change. Quantitative chances of better or worse effects were determined as follows: <1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; and >99%, most likely [33,34]. R: Right; L: Left; RF: Rate of force; CMJ: Countermovement jump; DJU: Drop jump unilateral; RSI: Reactive strength index; THT: Triple hop test; F–V: Vertical force–velocity profile; COD: Change of direction; ES: Effect size.

The matrix of correlations between the different types of COD tests performed and the sports performance variables analyzed is shown in Table 3. For anthropometric measures, lean mass was positively correlated only with COD45°. With respect to linear velocity, a negative association was observed with the RF-10M variable in COD90°, COD180°, and the T-test. In contrast, a positive correlation of linear sprint speed was observed at 5 m and 10 m and the COD180° and T-test, and with the linear sprint at 30 m and the four analyzed angles. For strength, execution time at COD45° and CD180° showed a negative correlation with bilateral CMJ, DJU, and RSI. However, the execution time at COD90° and T-test were negatively correlated with DJU and RSI. Lastly, for the strength tests evaluated using the f–v profile and its analyzed variables, a positive association was observed with asymmetry, V0, and Pmax and, conversely, a negative association was found with F0 as both the number of COD or the angulation increased.

Table 3. Association matrix between COD and body composition, mobility, dynamic balance, linear sprint, and strength.

Variables	COD45°		COD90°		COD180°		COD
	L (s)	R (s)	L (s)	R (s)	L (s)	R (s)	T-Test (s)
Body Composition							
BMI (kg/height)	0.165	0.278	−0.075	−0.052	−0.048	−0.203	−0.226
Lean mass (kg)	0.167	−0.076	−0.341	−0.300	−0.380	−0.374	−0.370
Fat mass (%)	0.193	0.527 **	0.246	0.154	0.384	0.184	0.100
Mobility							
WB-DF R (°)	−0.056	−0.128	0.089	−0.008	−0.011	0.058	0.055
WB-DF L (°)	−0.121	0.144	0.316	0.196	0.085	0.132	0.128
Dynamic Balance							
SEBT L (cm)	0.222	−0.187	−0.394	−0.086	−0.237	−0.193	−0.171
SEBT R (cm)	0.132	−0.226	−0.403	−0.187	−0.334	−0.262	−0.148
YBT L (cm)	0.211	−0.144	−0.414 *	−0.139	−0.231	−0.153	−0.141
YBT R (cm)	0.099	−0.240	−0.430 *	−0.251	−0.383	−0.269	−0.178
Linear Sprint							
5 m sprint (s)	0.176	0.125	0.227	−0.050	0.382	0.476 *	0.456 *
10 m sprint (s)	0.153	0.104	0.233	−0.037	0.404	0.461 *	0.427 *
30 m sprint (s)	0.164	0.355 *	0.441 *	0.214	0.498 *	0.537 **	0.501 *
RF-10M	−0.180	−0.339	−0.433 *	−0.169	−0.470 *	−0.514 *	−0.472 *
Strength							
CMJ (cm)	−0.215	−0.668 **	−0.340	−0.226	−0.462 *	−0.443 *	−0.314
DJU L (cm)	−0.293	−0.632 **	−0.532 **	−0.273	−0.451 *	−0.400	−0.541 **
DJU R (cm)	−0.261	−0.162	−0.294	−0.170	−0.451 *	−0.515 *	−0.360
RSI L	−0.368	−0.446 *	−0.427 *	−0.246	−0.504 *	−0.420 *	−0.626 **
RSI R	−0.265	−0.378	−0.465 *	−0.339	−0.546 **	−0.579 **	−0.656 **
THT R (cm)	0.232	−0.295	−0.289	0.057	0.107	0.053	−0.129
THT L (cm)	−0.284	−0.196	−0.311	−0.245	−0.034	−0.036	−0.121
F-V Profile							
F-V Imbalance	0.183	0.255	0.603 **	0.407	0.523 *	0.589 **	0.784 **
F-V V0	0.219	0.171	0.379	0.330	0.441 *	0.530 **	0.680 **
F-V F0	−0.344	−0.330	−0.711 **	−0.555 **	−0.605 **	−0.621 **	−0.778 **
F-V Pmax	0.097	0.065	0.193	0.166	0.244	0.342	0.468 *

BMI: Body mass index; R: Right; L: Left; WB-DF: Weight-bearing dorsiflexion; SEBT: Star excursion balance test; YBT: Y balance test; RF: Rate of force; CMJ: Countermovement jump; DJU: Drop jump unilateral; RSI: Reactive strength index; THT: Triple hop test; F–V: Vertical force–velocity profile; V0: theoretical maximal unloaded velocity; F0: Theoretical maximal force; Pmax: Maximal power; COD: Change of direction; * $p < 0.05$; ** $p < 0.001$.

4. Discussion

The present study initially sought to evaluate whether the age category could influence anthropometric measurements, functional movement tests, linear sprint (30 m), and strength in basketball players. Moreover, and as the main purpose, the present study aimed to examine the relationship between the analyzed sport performance variables and the time in different COD tests and angles. Our study showed age-category differences in body composition and functional movements and planned COD test. Increases in the differences between categories were seen as the cut angle increased, and the analyzed categories were higher. On the other hand, we mainly aimed to evaluate the influence of different time-executed CODs and their angulation upon the analyzed sport performance variables. Our findings suggest an interesting relationship between performance variables and CODs. Specifically, RSI was the strength variable showing the strongest relationship with all the COD tests. Also, it is important to note that as a novelty, linear velocity and asymmetry in the f-v profile increased in relation to the angulation or number of cuts in the COD, which would confirm greater dependence upon these variables at higher angulations in the CODs.

4.1. Influence of Age Category on Sport Performance-Related Variables

In daily basketball practice, the physical and performance characteristics of basketball players according to age help coaches and strength-conditioning trainers to design training programs. Specifically, in basketball, anthropometric characteristics play a very important role, for example, height is considered to be the most important physical attribute and this parameter is an important factor when identifying and selecting talents [43]. This study identified differences in anthropometrics' factors and body composition, mainly in lean mass and BMI. This idea is in accordance with previous studies that confirmed it, and also added that the greatest changes occurred between Under 14–15 and Under 17 categories [44]. Regarding positions, it must be noted that from early ages there are morphological differences between centers and guards, which serve us as references to be able to select [44], although early specialization is not recommended. In addition, other variables analyzed such as functional movements showed dependency with the age category, as several studies have claimed in young and elite basketball players [44,45], though no differences were observed in the linear sprint or strength tests, with the exception of the vertical f–v profile. In contrast with this, research [9] has shown that improved performance through vertical jumping depends on the level and category of the team sports athlete, and being more significant in basketball players especially between U14 and U17 categories [44]. Regarding the planned COD tests, increased differences between categories were seen as the cut angle increased, with better performance results in the higher categories. This could have been explained mainly by a better balance in the f–v profile of senior athletes and the relationship of this balance with changes in direction as the cut angle increased, in addition to the greater amount of lean mass in senior athletes. Similarly, for agility, it has been seen that reactive agility discriminates between basketball players of different levels [9,10], but that planned agility does not. The latter contradicts our results, but this may be due to the sample used or the type of COD test evaluated. For all aforementioned, it was clear that the age category influences anthropometric factors, but there is no clear consensus on the influence of age category on performance factors. This may be largely due to the variability of the tests used to measure performance, different performance variables assessed, or different samples used.

4.2. Influence of Sport Performance-Related Variables on the Time Execution COD and Angles

Basketball is an intermittent sport with demanding COD and, as each sport does, demands specific anthropometric and physical requirements. Knowledge of these requirements is of special interest to coaches and physical trainers who want to maximize the performance of their players. In this line, anthropometric variables such as body height or leg length can influence COD performance, since a shorter individual would need less time to lower the center of mass [4,7]. COD performance is based

on greater acceleration of BW; therefore, a lower fat percentage together with high relative strength would benefit COD performance [46]. In this regard, the association observed between fat mass and its influence upon the type of COD45° may explain why those players with a higher fat component took longer in performing COD45°. According to our results, other studies in elite basketball players [19,47] observed the same association, but through the T-test. In addition, several studies have evidenced a weak [48] and moderate–high relationship [46,47] between BW and the T-test in athletes and elite basketball players. From a logical point of view, it seems reasonable that an athlete with a low fat percentage would perform better in COD, but what appears even more clearly is the importance of a decrease in fat mass or an increase in maximum strength without an increase in BW, which would increase the relative strength of the athlete [49].

Ankle dorsiflexion limitation observed throughout the WB-DF test suggests possible movement deterioration that may alter the mechanics of movement in multidirectional tasks [25]. Studies such as that carried out by Gonzalo-Skok et al. [25] in 15 elite male basketball players have concluded that leg asymmetry determined by the WB-DF test is related to a decrease in performance in tasks, including CODs. In contrast, the results of our study show that neither a lack of ankle mobility analyzed by the WB-DF test nor asymmetry between both legs seems to affect performance within the COD tests evaluated. Furthermore, none of the dynamic equilibrium tests—either SEBT or YBT—were found to be related to CODs, excepting left YBT with left COD90°. Other authors [25,50], however, confirmed the relationship between dynamic equilibrium and COD in a similar sport population. Although the assessment of leg asymmetry may offer a prediction of sports injuries [51], our study identified no relationship with COD performance. On analyzing each excursion separately, the only one affording high correlation with all the analyzed COD tests was found to be lower limb lateral excursion. This could be explained by the great involvement of the frontal plane in COD actions [52].

Although linear velocity and velocity in CODs are considered two different capabilities [11], the literature accepts that the former affects the latter [6]. The greater the angle of rotation, the lower the relationship with linear velocity [11]. Therefore, CODs that cover angles of less than 90° are more velocity-oriented, in contrast to angles of more than 90° that are more force-oriented [49]. In our study, angles smaller than 90° had less effect on the variation in linear velocity and, contrary to scientific evidence, we observed that the relationship between linear velocity and COD increased at the same time as the COD angle or the number of cuts. These contradictions could be solved by introducing the concept of deficit in COD, where COD action is isolated from linear action within the tests [53]. While several studies [54,55] have shown the relationship of CODs to the deficit itself, no considerations have been made with linear velocity. Although some authors [56] still suggest linear velocity to be a determining factor for COD performance, high COD approaching velocities may increase the loads which the knee receives in valgus. So, it should be important to seek optimal balance between force and speed in order to minimize the drop in velocity prior to COD [56]. Likewise, in relation to linear velocity, the application of forces in the horizontal vector during sprint determined by the variable RF-10M showed high correlation with COD90°. In line with this, other studies [14,57] have found that those team sports' athletes who performed better in the COD 505 test showed higher maximum horizontal propulsion forces and shorter ground contact times, as well as equally higher approaching velocities and greater speed reductions during cutting action. The key to better performance in COD actions is to minimize contact times in the field [14], and strength affords the ability to do so. High horizontal propulsion forces and low vertical impact forces in the last step, together with high braking forces in the penultimate step, are associated to higher COD performance [14]. Faster female basketball athletes produce higher braking forces, helping to increase the starting speed during COD due to the storage and utilization of elastic energy, and propulsion [19]. Therefore, it is clear that strength is a determining factor for improving performance in COD. However, the scientific literature does not clarify which of the different manifestations is the most determining, since COD is a dynamic and complex action that involves application of the stretching–shortening cycle in a vertical and horizontal axis unilaterally.

In relation to vertical force through the CMJ, DJU, and CODs, the literature affords contradictory results with CMJ [16], mainly due to gender differences [46]. Our results would partially confirm this relationship of CMJ with COD45° and COD180°. Regarding the relationship between COD and DJU, we observed that both variables have similar technical execution mechanisms and were significantly related, as also confirmed by Young et al. [11]. Interestingly, however, in our study we found RSI to be more determinant for COD than the height of the jump, since this index is determined by capacity in the application of forces with low contact times [14]. In this respect, a maximum force development of approximately 0.44–0.72 s is required for COD [58]. When studying the association with force in the horizontal axis by THTU, we found no statistically significant associations with the different CODs evaluated. In addition to COD performance with bilateral vertical and unilateral horizontal jumping, recent research [59] has determined a similar muscle activation pattern during both actions, though activation of the long adductor, biceps femoris, and semitendinosus muscles was increased in COD actions to stabilize the hip and slow knee joint movements when turning compared to jumping. On the other hand, asymmetry assessed in all the tests performed in single mode revealed no negative impact on the performance of basketball players (data not shown), as confirmed by other studies, and points to the need to clarify the magnitude of changes in COD performance that can be explained by asymmetries [60].

During COD, the use of the stretching–shortening cycle requires all phases of muscle contraction (concentric, eccentric, and isometric) to be present and to develop in similar proportions [19]. For this reason, we considered that it would not be appropriate to evaluate the different manifestations of force in an isolated manner. We, therefore, hypothesized that the influence of the force and speed imbalance with the f–v profile could have an impact on COD capacity. To our knowledge, the present study is the first to evidence this relationship. Interestingly, this profile creates an individualized graphic representation of the force that can be applied to different loads, it being possible to obtain an optimal profile in which maximum power against BW may be achieved during a vertical jump [36]. When working on reducing this imbalance between force and speed, the neuromuscular system is optimized, securing maximum power in ballistic movements with BW itself, such as jumping or sprinting [37]. So, it seems logical that improvements are also obtained in terms of COD performance. Our hypothesis would be confirmed by the results showing a strong correlation between the different variables obtained from the f–v profile and the COD test, with this relationship being stronger the greater the angle of change and/or the number of cuts. Therefore, not only are improvements in the application of forces with BW itself achieved in the face of changes with sharper angles, which will be the most demanding of forces [56], but also the fatigue generated by several consecutive BWs is reduced - as occurs in real game action - and performance is improved.

Finally, COD and agility movements are multidimensional skills involving numerous variables to produce a faster performance [4] and its performance depends on the specific sport and position [10], making it challenging to asses these variables all at once. Despite the usefulness of these findings, the present study has some limitations that should be addressed. Firstly, the authors focused on analyzing the variables that contribute to the performance of the COD, to a greater or lesser extent, exposed throughout the study, but the performance of the COD is multifactorial, as abovementioned. So, some factors such as electromyographic muscle activation were not investigated and are limitations of this study. In addition, this research was inherently limited by its cross-sectional design and the size of sample. Although these findings are limited to a small sample, it was performed with basketball players from two different age categories who trained in the same basketball club, following the same physical, technical, and tactical training programs. This certainly reinforces the applicability and relevance of our findings.

5. Conclusions

To summarize, the present study evidences age-category differences in body composition, functional movements, and planned COD test. Moreover, those differences were larger with increasing

the cutting angle and the age category. In contrast, although body composition, mobility, and balance were not relevant to COD, both linear velocity and strength showed a strong association with COD at sharper angles. Specifically, the unilateral strength test in the vertical vector seems best option for determining COD performance, probably due to the reactive strength and the time of contact with the field, required for optimal force application. Lastly, the large changes determined by the f–v profile for CODs afford new insight to the enhancement of COD performance. Therefore, this study shows the relevance of the f–v profile in order to design training programs to optimize not only jumping and sprinting performance, as already studied, but also performance in COD actions, although more research is needed to confirm this.

6. Practical Application

Coaches must know the specific movement demands of each sport, and, as has been previously demonstrated, basketball is a sport in which fast actions such as jumping and COD are particularly important, with performance in these types of actions making the difference in the final result. The findings of the present study demonstrate the relationship between the f–v profile and the improvement of results in those actions that are determinant for performance of the sport. Therefore, coaches must carry out intervention programs with their players, with the aim of improving the optimal and individualized f–v profile of each player. This will allow better development of power for each athlete, resulting in improved performance of each individual.

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STUDY 2

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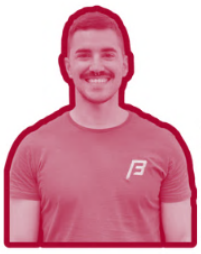
Influence of Dynamic Balance on Jumping-Based Asymmetries in Team Sport: A between-Sports Comparison in Basketball and Handball Athletes



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Article

Influence of Dynamic Balance on Jumping-Based Asymmetries in Team Sport: A between-Sports Comparison in Basketball and Handball Athletes

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Abstract: The aims of the present study were to analyze mobility, dynamic balance and lower-limb strength and the prevalence of asymmetry according to the type of sport and assess the association between inter-limb asymmetry and sports performance. A total of 23 basketball and 25 handball players performed a test battery consisting of functional movements and a jump test. Inter-limb asymmetry was calculated using a standard percentage difference equation. A between-groups comparison analysis was carried out, and Pearson's correlation coefficients (r) were calculated to establish a relationship between asymmetries and physical performance. The results found athletes in different sports to exhibit different performance in functional movements and the jump test, but no bilateral asymmetries. The reactive strength index (RSI) and stiffness asymmetries were significantly associated with the anterior reach Y-balance test (YBT) ($r = -0.412$; $p < 0.01$ and $r = -0.359$; $p < 0.05$, respectively), and the unilateral triple hop test (THTU) was negatively correlated to anterior reach, posterior lateral reach YBT and YBT composite YBT ($r = -0.341$ to -0.377; $p < 0.05$). These findings suggest that the asymmetries exhibited important dispersion not dependent upon the type of sport but on each individual and the applied test. In addition, asymmetry in anterior direction YBT showed the strongest association to the rest of the sports performance variables.

Keywords: inter-limb asymmetry; functional test; sports performance; lower limb strength

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1. Introduction

Team sports are characterized by high-intensity unilateral actions such as sprints, jumps or changes of direction (COD) [1]. On-court sports such as basketball and handball are two different team sports; however, given their characteristics and rules, many game actions, physiological demands and movement patterns are similar [2,3]. Speed actions, lateral movements, jumps or COD are skills common to both modalities and determinants of their athletic demands [2]. Thus, athletes may require adequate neuromuscular coordination and motor control to produce high levels of specific unilateral strength during game actions [4]. Recent research shows that these actions are unlikely to occur in a similar amount for both extremities [5,6]. Therefore, it has been suggested that unilateral actions develop and increase inter-limb imbalances in team sports, creating a dominant side [7]. The existence of inter-limb asymmetries, therefore, would be expected in team sports athletes [8].

Inter-limb differences and their relation to sports performance have been widely addressed in the scientific literature [9]. On one hand, a high imbalance between legs in relation to sport performance variables such as strength or speed has been marginally

associated with a decrease in sports performance [7,10]. On the other hand, inter-limb asymmetries in strength or power have also been proposed as a major risk factor for sports injuries [11]. Specifically, the literature has described various thresholds that have been widely evaluated, establishing that athletes with over 10% [12] or 15% [11] of inter-limb asymmetries may have a higher incidence of injuries compared to those below these thresholds. Therefore, an increase in inter-limb symmetry could be considered as a marker of success in the re-adaptation process since it enhances the athlete's confidence and makes a return to play safer and more effective [11]. In a critical review, Maloney [13] pointed out that sports professionals should consider that the weakest limb presents a greater "window of opportunity" with which to improve overall performance. However, when the asymmetry between legs is analyzed and compared using different tests, the results prove inconsistent, and the dominant leg may even change depending on the test used [14]—thus suggesting a clear test-dependent relationship regarding the presence of asymmetry. Despite the prior evidence on inter-limb asymmetry in a wide range of team sports [14,15], few studies have analyzed asymmetries in handball and established comparisons with a similar on-court sport such as basketball.

Given the usefulness of clarifying the role of inter-limb asymmetry in sports performance for coaches and trainers, interest in the topic has grown. In reference to the factors affecting athletic performance, previous evidence has shown that functional tests such as dorsiflexion or dynamic balance asymmetries could be related to an increase in strength values during sprinting [16], as well as to decline in sports performance related to COD actions or to vertical jump through the countermovement jump (CMJ) [17]. With respect to asymmetry measured through jumping actions in both force vectors, several authors have reviewed the existing evidence, with contradictory results [11,13].

Based on the above, the existing evidence yields inconclusive results when trying to determine the association between limb asymmetry and sports performance measures and indicates that the observation of asymmetry alone offers little information for sports physicians [8]. In addition, the important heterogeneity observed in terms of leg asymmetry, even within the same team, could make it difficult to establish relationships between inter-limb asymmetry and its correlation to usual performance parameters. The observed contradictions may be due to age, gender, the tests used to evaluate asymmetries, or the sport-specific characteristics of the sample analyzed. Moreover, there is a dearth of studies investigating the relationship between limb asymmetries and performance tests in handball athletes. Therefore, the present study was designed to (i) determine mobility, dynamic balance and lower-limb strength and the prevalence of asymmetry according to the type of sport; and (ii) to assess the association between inter-limb asymmetry and different sport performance variables.

2. Materials and Methods

2.1. Design

A cross-sectional was employed to determine the mobility, the dynamic balance, the lower-limb strength and the prevalence of asymmetry according to the type of sport, as well as the association between inter-limb asymmetry and different sport performance variables, respectively. All tests were performed in November 2019. The procedures followed the rules defined by the Declaration of Helsinki. This study was authorized by the Andalusian Committee of Ethics in Biomedical Research (reference number: FBD_UHU2020).

2.2. Participants

Forty-eight competitive team sports athletes, specifically basketball (n = 23) and handball (n = 25) (mean age: 18.98 ± 3.97 years; mean height: 181.40 ± 7.69 cm; mean body weight: 78.45 ± 13.62 kg) were informed and gave their consent to participate in this study. Subjects were assessed for eligibility if they had at least 5 years of previous experience; played at a federated level; had regular training three days or more per week during the study period. Subjects were excluded if they presented any injury during and

at least 6 months prior to the study; they were not in good health or did not pass a medical exam before the season.

2.3. Procedure

One week before the data collection, all participants were familiarized with the performance test procedures enabling them to perform each test between 3–6 times. During the testing days, all players completed a previously published standardized warm-up [18] consisting of 5 min low-intensity with the ball, 5 min of hip mobility and core activation, 5 min of low-impact landings, accelerations and plyometrics. Following the warm-up, subjects were allowed to train the trials executions for at least 5 min and providing them the feedback for proper technical execution. Subjects refrained from intensive exercise and stimulants in the 24-hour period prior to testing execution. Testing was divided into two separate days with 24 h–48 h in between. The first session involved the body composition measures, the WB-DF and the YBT tests. The second session involved the jump tests: CMJ, unilateral drop jump (DJU) at the height of 25 cm and unilateral triple hop test (THTU).

2.4. Outcomes Assessment

2.4.1. Body Composition Measures

Initially, and prior to body composition, body height was determined with a stadiometer (0.1 cm, Secca 220, Spain). Later, multi-frequency bioelectrical impedance equipment (Inbody 230 Multi-frequency segmental body composition analyzer, Barcelona, Spain) was used to determine the body composition. All players had to remain static in an anatomical position with arms and legs slightly separated and placed on the electrodes. The analyzer complies with the European standards for use in the medical industry (93/42 EEC, 90/384 EEC). Weight, body mass index (BMI), lean mass, and fat mass expressed as a percentage of total body fat were determined for further analysis.

2.4.2. Weight-bearing Dorsiflexion Test (WB-DF)

Dorsiflex iPhone App [19] was used to determine ankle dorsiflexion. Initially, each player was instructed to perform the test with their hands on their hips, putting the assigned leg in front and the opposite leg is placed one foot behind, both legs are placed at the width of the hips. From this position, the athlete had to bring the knee forward without lifting the heel off the ground. The mobile device was placed with the screen touching the tibia under tibial tuberosity, showing the result of ankle dorsiflexion in degrees. All the players performed the test barefoot, three attempts per leg were measured, and the average of the three was calculated for further analysis.

2.4.3. Y-Balance Test (YBT)

Dynamic balance was evaluated by using the OctoBalance device (OctoBalance, Check your Motion, Albacete, Spain) through a modified version of the SEBT [20]. To assess dynamic balance, subjects are asked to push the point of the tape measure with their toes as far as possible in the designated direction (anterior, posteromedial, and posterolateral) while balancing with the other leg on the anteroposterior line of the platform. In order for each attempt to be considered valid, the players had to keep their hands on their hips during the test, do not raise the heel of the platform, and also the foot that reaches cannot be supported off the platform. Before starting, the measuring tape was placed at a distance of 30 cm, which is the minimum distance to be reached. Measurements were made only once per leg, as these were experienced subjects [20]. The laterality of the test was defined by the leg that was supported in the octagon at the moment of the reach.

2.4.4. Triple Hop Test for Distance Unilateral (THTU)

THTU was carried out to evaluate the elastic-reactive force of the lower extremities in the horizontal axis [21]. Before starting, each participant positioned the leg to be measured, resting the foot on the starting line, and each player performed three consecutive maximum

forward jumps with the same limb. Then, the researcher determined the total distance from the start to the point where the heel hit the ground upon completion of the third jump with a tape measure [21]. Arms swinging was allowed during the test to balance, but the attempts were considered failed if the participant lost balance during any part of the test or was unable to maintain the final posture for at least two seconds. Each athlete performed the test three times with a break of at least two minutes between each attempt, and finally, the best attempt was selected.

2.4.5. Countermovement Jump Test (CMJ)

Vertical jump height was measure using a Chronojump (Chronojump Bosco-System®, Barcelona, Spain) [22]. Within the platform, players executed a jump with a countermovement seeking the greater height. For the jump to being considered valid, it must be done with the hands on the hips, with the knees extended during the flight time, and the player must land at the same point where the jump was made. If these items were not achieved, the attempt was invalid and must be repeated. Each player made a total of three valid attempts, and the best trial was used for further analyses.

2.4.6. Unilateral Drop Jump Test (DJU)

The unilateral jump test was assessed with a Chronojump (Chronojump Bosco-System®, Barcelona, Spain) [22]. The initial height of fall was 25 cm, from where subjects were asked to jump as high as possible with each leg. In each attempt, it was indicated that both hands must be placed on the hips, the knees must be extended when the foot not in contact with the platform, and both landings must be made at the same point. A total of 3 jumps were performed with each leg, with approximately 2 minutes of recovery in between. Finally, the best of these attempts was used for a more detailed analysis. In addition to the height of the jump, other variables were extracted, such as the reactive strength index (RSI) that was calculated using the relationship between flight time and contact time, and vertical stiffness that was calculated considering the contact time, time of air and body mass and using the equation of Morin et al. [23].

2.5. Statistical Analyses

All statistical analyses were computed using the Statistics Package for Social Sciences version 25 statistical package (SPSS, IBM, Chicago, IL, USA). Descriptive statistics were derived (Mean, standard deviation, the 95% confidence limit (CL) and the range), and due to sample size, a Shapiro–Wilk test was used to check the data distribution of the tested parameters. A between-groups comparison analysis was performed to explore the basketball versus handball differences in mobility, dynamic balance, lower limb strength and asymmetries. The model was adjusted by age. Moreover, the magnitude of the difference in the analyzed parameters was determined using Hedge's effect sizes (ES) on the pooled SD together, and the 90% CL was calculated for all dependent variables. Probabilities were also calculated to determine whether true (unknown) differences were smaller, similar or larger than the smallest worthwhile difference or change (0.2 x SD between subjects) [24]. Values were interpreted as follows: < 1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; and > 99%, most likely [25,26]. Finally, if the chances of obtaining a beneficial/better or detrimental/worse were both > 5%, the effect was assessed as unclear [27,28]. Pearson's correlations (r) were computed to compare scores on asymmetries and their relationship to sports performance parameters. The magnitude of Pearson's correlation was interpreted as 0.0–0.1 = trivial; 0.1–0.3 = small; 0.3–0.5 = moderate; 0.5–0.7 = large; 0.7–0.9 = very large and 0.9–1.0 = almost perfect [27]. Statistical significance was established at $p < 0.05$.

3. Results

The descriptive results referred to sample data, mobility, dynamic balance, and lower limb strength are reported in Table 1.

Table 1. Sample data description.

Variables	Mean	SD	CL 95% (Lower; Upper)		Range
Age (years)	18.9	4.11	17.5	20.2	16–32
Weight (kg)	78.9	13.0	74.6	83.2	52–112
Height (m)	1.82	0.07	1.79	1.85	1.6–2.0
BMI (kg·m2–1)	23.7	3.15	22.6	24.6	16–29
Fat mass (%)	12.9	6.80	10.7	15.2	3.6–27
Mobility					
WB-DF R (°)	40.0	5.59	38.2	41.8	31–54
WB-DF L (°)	39.7	5.65	37.8	41.5	27–51
WB-DF C (°)	39.8	5.34	38.1	41.6	29–52
Dynamic balance					
YBT A R (cm)	51.2	8.26	48.5	53.9	33–68
YBT A L (cm)	51.9	7.70	49.3	54.4	34–68
YBT PM R (cm)	69.8	9.80	66.6	73.0	49–89
YBT PM L (cm)	68.0	7.88	65.4	70.6	50–85
YBT PL R (cm)	68.2	11.3	64.4	71.9	34–80
YBT PL L (cm)	69.5	11.1	65.8	73.1	49–89
YBT R (cm)	63.0	8.54	60.2	65.8	45–77
YBT L (cm)	63.1	8.10	60.4	65.7	47–79
Lower limb strength					
CMJ (cm)	35.9	5.19	34.2	37.7	26–45
DJU R (cm)	18.1	3.55	16.9	19.3	11–27
DJU L (cm)	18.3	4.27	16.8	19.6	9.8–29
RSI R	0.88	0.23	0.80	0.95	0.4–1.4
RSI L	0.86	0.24	0.78	0.94	0.5–1.5
Stiffness R	7.35	3.38	6.24	8.46	2.2–15.5
Stiffness L	7.12	2.97	6.14	8.09	2.4–14.1
THT R (cm)	578.8	57.7	559.8	597.8	457–738
THT L (cm)	593.9	67.3	571.8	616.0	467–799

Abbreviations: kg—kilograms; m—meter; BMI—body mass index; WB-DF—weight-bearing dorsiflexion; R—right; L—left; C—composite; cm—centimeters; YBT A—Y-balance test anterior reach; YBT PM—Y-balance test posteromedial reach; YBT PL—Y-balance test posterolateral reach; YBT—Y-balance test composite of all directions; CMJ—countermovement jump DJU—drop jump unilateral; RSI—reactive strength index; THTU—triple hop test unilateral; SD—standard deviation; CL—confidence limit.

Table 2 shows the comparative analysis of the mean values referred to mobility, dynamic balance, strength, and their respective asymmetries according to the type of sport. Regarding mobility, no changes were observed for the analyzed variables depending on the type of sport; however, the prevalence of asymmetry was 22.8% for ankle dorsiflexion. Regarding dynamic balance, basketball players showed better scores in the YBT test in all directions as well as in the overall test score. The scores in absolute values showed a change ranging from 6.23 to 14.6 percent for this test. However, a total of 16.5% of the total sample revealed asymmetries for the dynamic balance. Finally, the comparative analysis of lower limb strength revealed differences between sports for most of the parameters studied in the vertical and horizontal jump, with the exception of the CMJ, DJU R and THT L. Specifically, basketball players showed the highest percentage change for stiffness (between 32.1 to 39.5). A total of 65.3% of the athletes exhibited asymmetry of the RSI variable.

Table 2. Comparative analysis of mobility, dynamic balance and lower limb strength according to the type of sport.

Variables	BB (n = 23)		HB (n = 25)		% (CL 90%)	ES (CL 90%)	Chances (%)	Outcome
	Mean	SD	Mean	SD				
Mobility								
WB-DF R (°)	39.0	5.27	41.5	5.68	6. 36 (−0.21; 13.4)	0.46 (−0.02; 0.95)	1/17/82	Likely
WB-DF L (°)	39.3	4.78	40.6	6.16	2.96 (−3.88; 10.4)	0.23 (−0.31; 0.76)	9/37/53	Unclear
WB-DF C (°)	39.1	4.70	41.1	5.72	4.62 (−1.71; 11.4)	0.37 (−0.14; 0.89)	3/25/71	Possibly
Dynamic balance								
YBT A R (cm)	53.7	6.5	47.9	7.5	−11.3 (−17.2; −4.91)	−0.93 (−1.47; −0.39)	99/1/0	Very likely
YBT A L (cm)	54.4	7.2	47.1	6.4	−13.3 (−18.8; −7.41)	−1.02 (−1.49; −0.55)	100/0/0	Most likely
YBT PM R (cm)	72.1	9.85	65.0	9.33	−9.85 (−16.1; −3.11)	−0.69 (−1.18; −0.21)	95/4/0	Very likely
YBT PM L (cm)	69.0	8.89	64.4	5.96	−6.23 (−11.3; −0.86)	−0.47 (−0.88; −0.06)	87/13/0	Likely
YBT PL R (cm)	71.6	9.6	61.8	11.6	−14.6 (−21.8; −6.82)	−1.09 (−1.69; −0.49)	99/1/0	Very likely
YBT PL L (cm)	72.3	10.9	63.7	10.2	−12.0 (−18.8; −4.67)	−0.79 (−1.29; −0.30)	97/2/0	Very likely
YBT R (cm)	65.8	7.26	58.3	8.14	−11.8 (−17.2; −6.10)	−1.08 (−1.61; −0.54)	100/0/0	Most likely
YBT L (cm)	65.2	8.14	58.44	6.65	−10.2 (−15.4; −4.75)	−0.81 (−1.26; −0.37)	99/1/0	Very likely
Lower limb strength								
CMJ (cm)	35.2	4.87	36.8	5.71	4.25 (−3.45; 12.6)	0.28 (−0.24; 0.80)	6/33/60	Unclear
DJU R (cm)	17.5	2.51	18.5	4.13	4.13 (−5.41; 14.6)	0.27 (−0.38; 0.92)	11/31/57	Unclear
DJU L (cm)	16.7	3.37	19.9	4.13	19.4 (7.87; 32.1)	0.81 (0.35; 1.28)	0/2/98	Very likely
RSI R	0.96	0.25	0.73	0.17	−22.5 (−31.6; −12.1)	−0.91 (−1.36; −0.46)	99/1/0	Very likely
RSI L	0.90	0.28	0.78	0.16	−11.8 (−22.4; 0.19)	−0.40 (−0.81; 0.01)	79/20/1	Likely
Stiffness R	8.64	3.55	5.08	1.81	−39.5 (−51.1; −25.3)	−1.05 (−1.49; −0.60)	100/0/0	Most likely
Stiffness L	8.07	3.15	5.52	2.38	−32.1 (−45.1; −16.0)	−0.88 (−1.36; −0.40)	99/1/0	Very likely
THT R (cm)	566.2	50.1	598.9	73.5	5.46 (−0.45; 11.7)	0.57 (−0.05; 1.18)	2/14/84	Likely
THT L (cm)	583.7	61.3	599.6	77.5	2.48 (−3.71; 9.07)	0.22 (−0.35; 0.80)	11/36/53	Unclear

Abbreviations: BB—basketball; HB—handball; WB-DF—weight-bearing dorsiflexion; R—right; L—left; C—composite; YBT A—Y-balance test anterior reach; YBT PM—Y-balance test posteromedial reach; YBT PL—Y-balance test posterolateral reach; YBT—Y-balance test composite of all directions; CMJ—countermovement jump DJU—drop jump unilateral; RSI—reactive strength index; THTU—triple hop test unilateral; SD—standard deviation; CL—confidence limit; ES—effect size.

Figure 1 shows the comparative analysis of asymmetries referred to mobility, dynamic equilibrium and strength in the lower limbs according to the type of sport. The results revealed differences possibly due to the type of sport for DJU-derived parameters such as reactive strength index (31.96% (CL 90%: −13.99; 102.47)) and stiffness (50.31% (CL 90%: −14.47; 164.13)). Furthermore, when the vertical drop jump height was considered to assess asymmetry, the differences observed in the basketball players were probably due to the specificity of this sport (−30.86% (CL 90%: −54.20; 4.38)). Finally, unclear or improbable effects were observed for the rest of the analyzed parameters according to the type of sport.

Figure 2 shows a heat map correlation analysis between functional test and lower limb strength according to vertical and horizontal jump. The asymmetry in dorsiflexion was negatively correlated to scores in the anterior YBT test. In addition, dynamic stability determined by the YBT test was negatively correlated to DJU RSI, DJU STF and THTU in both the anterior and the posteromedial planes, as well as in the composite YBT score. In addition, the asymmetries of the YBT test in the different planes were found to be positively correlated to each other, as well as to the composite YBT. Similarly, positive correlations were observed between de different DJU parameters.

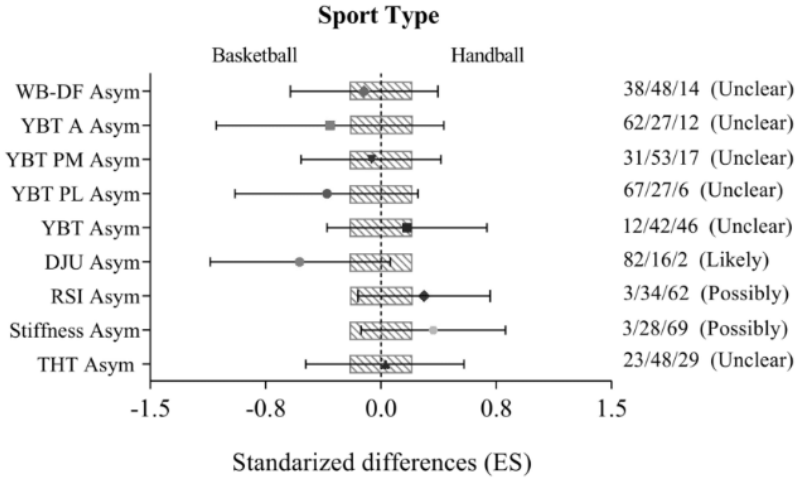

Figure 1. Comparative analysis of mobility, dynamic balance and lower limb strength asymmetries according to the type of sport. The model was adjusted for age. Bars indicate uncertainty in the true mean changes with 90% confidence intervals. Trivial (shaded) areas were calculated from the smallest worthwhile change. Quantitative chances of better or worse effects were determined as follows: <1%—almost certainly not; 1–5%—very unlikely; 5–25%—unlikely; 25–75%—possible; 75–95%—likely; 95–99%—very likely; and >99%—most likely [25,26]. Asym—asymmetry; WB-DF—weight-bearing dorsiflexion; YBT A—Y-balance test anterior reach; YBT PM—Y-balance test posteromedial reach; YBT PL—Y-balance test posterolateral reach; YBT—Y-balance test composite of all directions; DJU—drop jump unilateral; RSI—reactive strength index; THT—triple hop test; ES—effect size.

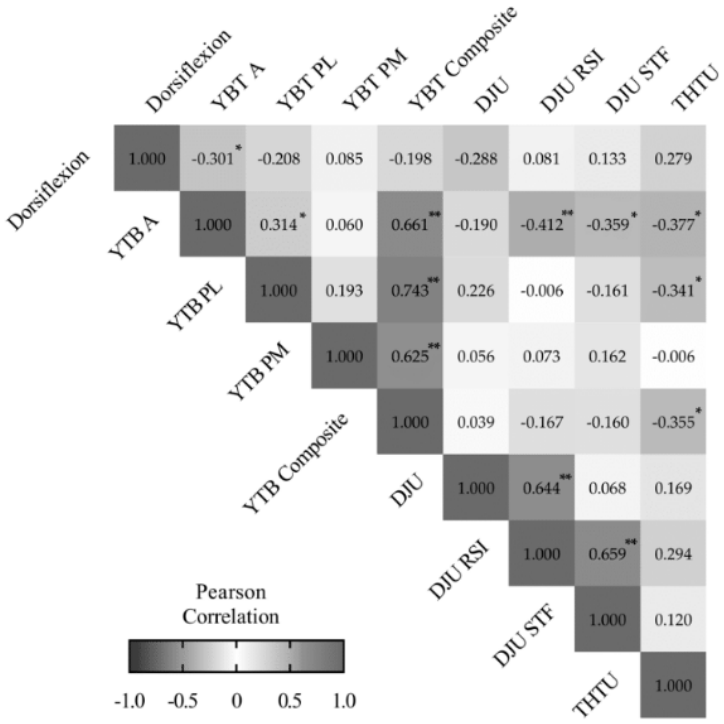

Figure 2. Matrix correlations (Pearson's r, 95% confidence intervals) between the inter-limb asymmetry scores in functional tests and lower limb strength sports performance. The model was adjusted for age. * Statistical significance at $p < 0.05$. ** Statistical significance at $p < 0.01$. YBT A—Y-balance test anterior reach; YBT PM—Y-balance test posteromedial reach; YBT PL—Y-balance test posterolateral reach; YBT—Y-balance test composite of all directions; DJU—drop jump unilateral; RSI—reactive strength index; STF—stiffness; THTU—triple hop test unilateral.

4. Discussion

One of the main findings of the study was that the type of sport influences dynamic equilibrium in all the evaluated directions and the DJU measured parameters, where the scores of the basketball players were better than those of the handball counterparts. In contrast, handball players demonstrated greater strength in the horizontal vector as evaluated through the THTU. On the other hand, it also has been observed the relationship between the asymmetries in functional tests and athletic performance variables. A moderate and negative correlation was observed between asymmetries in YBT performance, specifically in the anterior plane, and RSI, stiffness and the THT tests. This suggests that large asymmetries in the anterior direction may be related to a reduction in athlete performance as assessed by RSI, stiffness and THT (in absolute values)—these being variables previously described as important in the performance of team sports such as basketball and handball [3].

Both sports, basketball and handball, are team sports whose intensity pattern has been defined as intermittent (stop and go), and where the game itself demands mainly sprint actions, lateral movements, jumps and COD. Thus, while these are two different sports, their physiological demands and movement patterns are similar [2,3]. Even so, the evaluated dynamic balance and jumping differed on comparing them—probably because of the specificity of each sport. In this respect, our results evidenced higher performance in dynamic balance and vertical jumping actions among the basketball players; whereas, handball players achieved better performance in triple horizontal jump actions. This could be explained by previous research [29,30] that has shown a lower amount of jumping actions in handball than in basketball. Likewise, jumps in handball requires a greater demand for the horizontal component of the force since the rules allow greater contact actions through powerful lower-body movements as well as tackles of opponents, sideways running, backward running, or CODs with a high number of physical confrontations with the opponent players [31]. In contrast, in basketball, the fact that the rules are less permissive with the contact between players and the vertical backboard location will allow a greater demand for the force to be found in the vertical component [32]. These results, therefore, could confirm that the physical characteristics of strength or dynamic balance are highly specific and depend on the type of sport involved, even though comparison according to bilateral asymmetries in the lower limbs showed no differences regarding the type of sport practiced. Considering both our findings and previously published evidence [33] comparing the performance of athletes in 14 different sports referred to as lower extremity strength and dynamic balance, it could be possible to establish sport-based standardized data in terms of absolute values. Nevertheless, the lack of effect of the sport practiced upon bilateral asymmetry in the lower limbs and the range of equations applied to define asymmetries among athletes in different sports [17,34–36] make it necessary for the asymmetry values to be analyzed in detail and monitored individually for each athlete [33].

Previous studies have shown asymmetry between legs to be closely associated with an athlete's risk of injury [11,37,38]. However, given the important variability shown by asymmetry within the same sport and even within the same player [8,11,39,40], it would be premature for coaches and physicians to provide a standardized threshold above which the risk of injury increases. Furthermore, other authors [41,42] indicate that the interlimb differences should be considered as asymmetry only when they are greater than intralimb variability. Thus, it seems that there is no consensus in the scientific literature on a specific threshold to determine asymmetry, although a large part of research often proposes that 10–15% is the limit to defining a player as presenting asymmetry [11,12]. Both our results and those of other authors [33] would confirm that this threshold could differ depending on the morphological demands of the sport itself and even within the same team, given the individual demands of each player on the court [40,42]. In our study, the analysis of the asymmetries between legs obtained in the different tests carried out underscores the highly independent nature of the asymmetries according to the different tests involved, showing great variability of both inter-subject and intra-subject asymmetries for each test

(Figure S1). Different studies would confirm the existence of great variability [8,11,39] and affirm that asymmetry is highly specific to the task—causing data analysis to be rather complex and making it difficult to determine a relationship with athlete performance. Moreover, the different evaluation methods, calculations of asymmetries and samples of athletes involved may explain the lack of consensus found in the scientific literature on asymmetries between legs and their association to athletic performance [13,39].

To date, most of the literature relating asymmetries to physical performance measures has made use of jumping tests to quantify the asymmetry component [7,40,43–45]; however, the magnitude of the asymmetry would also be highly dependent upon the executed jump type. For example, for horizontal jumps (such as single, triple and crossover hop tests), an asymmetry of 6–7% has been reported [43], which is consistent with the asymmetry of 7% shown by our athletes. In contrast, when asymmetry was evaluated through vertical jumps, a significant increase in asymmetry values was observed. Specifically, the asymmetries in single-leg countermovement jump showed asymmetry values of 10% [40,45], while evaluation by drop jump showed our athletes to yield asymmetry values of 13%, 15% and 18% for peak height, RSI and stiffness, respectively—with such values possibly reaching 50% in some athletes, in accordance with previous research [46]. Since the variables analyzed from the drop jump were those that showed a greater magnitude asymmetry, and considering our established threshold of 10% for defining an asymmetrical athlete, those variables were the ones that resulted in more athletes classified as being asymmetrical, with a total of 60% of our participants. Because of the reliance on both neurological and muscular mechanisms during DJ executions, a good RSI score is achieved through maximizing jump height and minimizing ground-contact time; hence, the RSI asymmetry will represent imbalances at the neuromuscular level between a player's dominant and non-dominant side. In addition, it is evident that the magnitude of asymmetry is highly specific to the test performed, and this may be due to the absolute value obtained in each test and the equation used to calculate the asymmetry, since it has been observed that the tests in which a greater absolute result is achieved, fewer asymmetries are shown and vice versa. Therefore, if we want to define an asymmetry threshold for each player, it cannot be universal; it must be specific to each test. Furthermore, it should be noted that previous research [47] indicates that jump test values expressed as distance are not sensitive enough to detect meaningful limb differences.

In relation to functional asymmetries, our data evidenced a negative correlation between asymmetry in ankle dorsiflexion and anterior direction in YBT, which may be due because this range direction has a higher demand for mobility in ankle dorsiflexion [37]. Asymmetry in the mobility of the ankle has been previously related to different types of injuries such as damage to the anterior cruciate ligament (ACL) [48], also showing a strong association to the ability to accelerate and COD [17]—thereby showing that large asymmetry of such mobility may affect performance in the anterior reach direction of YBT. Interestingly, we observed that this same asymmetry in anterior YBT was that showing the closest relationship with the rest of the performance variables. In line with our results, previous research [11,49] would support that both the different ranges and the YBT composite are negatively associated with sports performance variables through jump height during a CMJ in basketball athletes, being relevant for this sport. Our study would add that the anterior YBT not only showed a negative correlation to the vertical jump variables but also correlated to jumps in the horizontal vector. Conversely, the posterior reach and YBT composite only showed a negative correlation to horizontal jump, which could be due to a similar movement pattern between posterior YBT and unilateral horizontal jump, and the greater demand of the posterior musculature in both the posterior directions of the YBT and the horizontal jumps [50]. In addition, high demands upon the posterior musculature are necessary for other actions decisive to the performance of these sports, such as COD or penetrations [2,3,50].

This study incorporates very interesting information, provides new evidence that has already been demonstrated, also including team sports such as handball, which have

been little studied on this topic and are compared with other team sports, but despite the usefulness of our findings, the present study has several limitations. The relationship observed between the analyzed sports performances was weak or even disappeared when analyzed according to asymmetries. This could be due to the fact that, on one hand, a small sample was used and, on the other hand, the percentage of individuals with asymmetries was relatively small. In addition, the observed variability of asymmetry was very high even within the same sport and even within the same player, depending on the test performed [40]. Therefore, we recommend the use of a larger sample with asymmetry, in addition to analyzing such asymmetries by specific positions in order to obtain a greater homogeneity of results so that clearer conclusions can be obtained. Finally, it should be added that there is no clear consensus on how to measure asymmetries, given the variety of implemented equations and the different magnitudes obtained [17,34]—which makes it difficult to draw firm conclusions on the topic.

5. Conclusions

To sum up, the present study shows that athletes of similar team sports presented different levels of both strength in the vertical and horizontal jump, and dynamic balance and mobility analyzed, though this did not occur for the asymmetry between legs, it is important for the coach or physical trainer to consider these findings. The asymmetries showed important dispersion that would not depend on the type of sport involved but on each individual and on the applied test. On the other hand, although the asymmetries showed important variability, our results indicate that large asymmetries, mainly in the previous anterior direction of YBT, might negatively affect athletic performance through the vertical and horizontal jump. Trainers and physical trainers, therefore, could consider the possibility of intervening with the aim of reducing the identified asymmetries. From a training perspective, previous literature has suggested that unilateral training may afford great improvements in asymmetry between legs [1].

Supplementary Materials: The following are available online at https://www.mdpi.com/1660-4601/18/4/1866/s1, Figure S1: Fold asymmetry expressed as a percentage of mobility, dynamic balance and lower limb strength asymmetries according to the type of sport. The model was adjusted for age. YBT A—Y-balance test anterior reach; YBT PM—Y-balance test posteromedial reach; YBT PL—Y-balance test posterolateral reach; YBT—Y-balance test composite of all directions; DJU—drop jump unilateral; RSI—reactive strength index; STF—stiffness; THT—triple hop test.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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STUDY 3

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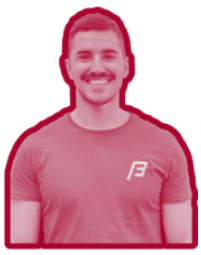
The influence of functional movement and strength upon linear and change of direction speed in male and female basketball players



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Section III – Sports and Physical Activity

The Influence of Functional Movement and Strength upon Linear and Change of Direction Speed in Male and Female Basketball Players

by

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The present study aimed to analyse the relationship between functional movement and strength variables upon linear speed (Ls) and change of direction (COD) based on gender. It also aimed to identify the determinants of performance of Ls and COD according to gender. Fifty basketball players (54% female) completed the assessment in which the weight-bearing dorsiflexion test, the Y-balance test, the unilateral countermovement jump, the unilateral drop jump, the unilateral triple hop test, Ls and CODs were performed. Speed variables were divided according to time execution into "low-performance" and "high-performance" to establish a comparison between performance groups. Strength variables significantly influenced speed tests' performance in both genders ($p < 0.05$). For males, the greater the Ls, the higher the change of direction deficit ($p < 0.001$). Multiple regression analysis revealed that a long and vertical stretch-shortening cycle (SSC) was the most influential physical ability for speed performance in females (45–65% variance explained; $p < 0.001$), while in males, a short and horizontal SSC played a significant role (30–61% variance explained; $p < 0.022$). These results suggest that gender should be considered in programming strength training to improve speed, as each gender will benefit most from the application of different force-orientations and different SSC. Also, the faster the male players were in Ls, the less efficient they were in the COD performance. This is why for men, it would be recommended to perform eccentric exercises along with deceleration and technique drills to improve COD speed.

Keywords: *multidirectional; agility; sprint; performance; team sport; gender*

Introduction

Change of direction (COD) actions are most frequent during a basketball game regardless of the playing position (Salazar et al., 2020). COD is defined as the ability to decelerate and accelerate towards a different direction in a planned manner (Nimphius et al., 2018). Although, during real game, directional changes occur mainly in reaction to external stimuli (e.g., movement of the ball or an opponent) and these agility actions may not have a direct relationship with COD performance, the planned COD movements represent the mechanical and physiological basis for understanding the real situation. In basketball, 15.1% of these actions are performed at maximum intensity (deceleration > –3.5 $m \cdot s^{-2}$) and could be decisive in the final result of the match (Svilar et al., 2018), since these actions can lead to a basket or a major change in the development of the game (Nimphius et al., 2018). COD actions are often preceded by different movements in basketball, such as linear speed in offense or lateral shuffling in a defensive context. For both the offensive and defensive purposes, these high-speed movements are essential given the short duration of decisive actions in the game. For this reason, the assessment and analysis of COD is essential to understand the needs of basketball players, being a topic of current interest to both researchers and coaches.

Previous research, which focused on studying the main determinants of COD performance (Barrera-Domínguez et al., 2020; Hewit et al., 2013; Pereira et al., 2018), has indicated that COD is a complex skill that is influenced by

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technique and different physical capacities such as dynamic balance, linear speed (Ls), as well as strength and power of lower limb muscles. However, there is still no consensus on which of these variables is the most relevant in the performance of COD actions and whether gender influences these actions. This might be explained by the type of a test used to assess COD speed (e.g., T-test, V-cut or 505-test) which could change the explanatory variables of this skill (Lazić et al., 2022; Pereira et al., 2018). Since there is no reference method to assess COD, each investigation usually uses a different COD test, thus the results among studies may not be comparable. Hence, the selection of a correct assessment is a critical factor when trying to assess these actions. In this sense, the biomechanical demands of COD are angle and task-dependent (Dos'Santos et al., 2018). Therefore, it would be advisable to assess this skill with several angulations to create a "COD angle profile" for each athlete (Dos'Santos et al., 2018; Gonzalo-Skok et al., 2023), rather than with a single test. Furthermore, it is interesting that many studies confirm that Ls is a determinant skill to improve COD speed performance with moderate to high correlations, depending on the type of a COD test used (Barrera-Domínguez et al., 2020; Chaouachi et al., 2009). Specifically, in young basketball players of both genders (Michael et al., 2021), it was observed that Ls explained significantly the variance of different COD tests. This could be because more than 70% of the total time of these COD tests are carried out through the Ls (Nimphius et al., 2016, 2018). In order to avoid this limitation, previous research has used a novel concept to assess COD actions in isolation from Ls, called the change of direction deficit (CODD) (Freitas et al., 2021b). The CODD indicates what percentage of the total time of the COD test has been spent exclusively on the COD action, thus isolating it from Ls.

Regarding the other physical abilities that were found to affect COD performance, research has shown that for the male gender there was a greater relationship between dynamic balance and COD performance (Gonzalo-Skok et al., 2015), with no such a relationship observed in the female gender (Sekulic et al., 2013). Previous research (Falch et al., 2020) analysing the relationship among lower limb muscle strength, power and COD speed performance, suggested that actions involving a stretch-shortening cycle (SSC), such as plyometric actions, were the most specific determinants of COD speed. However, these studies were carried out on a male sample; when female players were analysed, the plyometrics did not turn out to be as specific as maximum strength (Falch et al., 2021; Mikołajec et al., 2017; Spiteri et al., 2014). This could be due to a lower representation of female players in the scientific literature or due to usually lower levels of baseline strength in females. As it can be observed, previous scientific evidence does not reach a clear consensus about the most determinant variables of COD performance in basketball players for each gender. Moreover, this relationship between the different variables and the performance in speed actions differs considerably depending on the gender and the speed test used (Lazić et al., 2022). Therefore, more research comparing between gender differences using the same COD assessment tests is needed.

To the best of the authors' knowledge, there is still very little research that indicates which are the most determinant factors in COD performance differentiating and comparing directly between genders, since female athletes are less represented in COD research, which contrasts with their increasing presence in competitive sport. Thus, more data would be needed on this topic. Therefore, the main aim of this study was to analyse the relationship between functional movement and strength variables in several Ls and COD speed tests based on gender. In addition, to complement this, the study aimed to identify the determinants of performance of Ls and COD according to gender. The speed tests analysed require a greater application of force in a horizontal plane (McBurnie and Dos'Santos, 2022), thus it was hypothesised that the tests evaluated which would have a greater emphasis on this direction, would be the most determinant of speed performance in both genders. It was also hypothesised that males might benefit more from a short SSC than their female counterparts, since stronger athletes benefit to a higher extent from the short SSC than weaker ones (Bourgeois et al., 2017).

Methods

Participants

A total of fifty basketball players, twenty-three male (age: 23.9 ± 5.70 years, body height:

187.2 ± 7.59 cm; body mass: 85.9 ± 17.1 kg) and twenty-seven female (age: 22.7 ± 3.81 years, body height: 170.5 ± 7.69 cm; body mass: 64.4 ± 7.88 kg), volunteered to participate in the study. All players had their regular basketball training at least three days a week for two hours and played one federated game per week during the season. In addition, they belonged to the same competitive level, played in the Spanish N1 National League and had at least 10 years of experience playing basketball. None of the athletes included in the study had suffered an injury in the six months prior to the study. All of them were previously informed of the possible risks and benefits of participating in the study and gave their written consent before the start of testing. This research was approved by the Andalusian Biomedical Research Ethics Committee (reference number: FBD_UHU2020; approval date: 08 October 2020) in accordance with the guidelines established in the Declaration of Helsinki.

Design and Procedures

A cross-sectional experimental design was used to determine the association of functional movement and vertical and horizontal strength upon speed actions according to gender. Data collection was carried out during the competitive phase of the season. All participants performed two testing sessions with a time interval of 48 h in between. All assessments were undertaken just before each training session (between 19:00 and 21:00) and under the same conditions to avoid possible influences from the training track or weather. A familiarization protocol with the proposed tests was carried out in the week preceding testing. Before the start of the evaluation sessions, a 10-min warm-up was conducted, which included jogging, series of dynamic stretching and several acceleration runs, followed by specific potentiation exercises. Moreover, each player was instructed to attend the testing sessions adequately hydrated and rested, with no high intensity training in the previous 24 h, and to control their caffeine and food intake for at least 3 h before each evaluation.

The first testing session was devoted to quantitative movement tests: a weight-bearing dorsiflexion test (WB-DF) and the Y-Balance Test (YBT); and strength tests predominantly in a vertical direction: a unilateral Countermovement Jump (CMJu) and a unilateral Drop Jump (DJu). The second session included all horizontal tests: 10-m Ls and COD at different angles (45°, 90° and 180°); and the unilateral Triple Hop Test (THTu) to assess reactive strength predominantly in a horizontal direction. All players performed a total of three attempts of each test with a 2-min rest interval in between, achieving an Intraclass Correlation Coefficient (ICC) between 0.86 and 0.98, and a coefficient of variation (CV) of less than 5%. The mean of all attempts for each test was used for further analysis.

Weight-Bearing Dorsiflexion Test (WB-DT)

Ankle dorsiflexion was assessed with My ROM App (Apple Inc., Cupertino, CA, USA) (Balsalobre-Fernández et al., 2019) by placing the mobile device on the anterior tibial crest, just below the tibial tuberosity, recording the result in degrees. Each player placed their hands on their hips, as well as the foot to be measured in front and the opposite foot resting just behind. In this position, participants were instructed to lunge forward until their knee reached the maximum range of movement. The heel was required to remain in contact with the floor at all times. Players remained barefoot for the measurement.

Y-Balance Test (YBT)

Dynamic balance was assessed by the Y-Balance Test using the OctoBalance device (OctoBalance, Check your Motion, Albacete, Spain). Once maintaining a balanced position on one foot on the platform, each player had to reach the maximum possible distance in three directions: anterior, posteromedial and posterolateral (Onofrei et al., 2019). All attempts were supervised by the researchers and were considered valid if 1) the heel remained on the back edge of the platform and the second metatarsal was on the front line, 2) the hands were kept on the hips, and 3) the reaching foot only rested on the platform. For the final analysis, the average of the three trials was calculated and each participant's result was normalised using leg length.

Unilateral Countermovement Jump (CMJu) and Unilateral Drop Jump (DJu)

Jump height in CMJu and DJu tests was determined using a Chronojump contact platform (Chronojump BoscoSystem®, Barcelona, Spain)

(De Blas et al., 2012). Before testing, participants started with an initial position with one foot on the platform for the CMJu and on a 25-cm platform for the DJu, whereby each athlete landed with one foot on the platform with the intention of jumping as high as possible. The jump was considered valid if 1) the hands were not separated from the hips at any time, 2) the knees were not bent during the flight time, and 3) the athlete landed with only one foot on the same point from which he/she jumped, holding the position for at least 2 s. In addition, the DJu was used to calculate the reactive strength index (RSI) of each leg using the flight time/contact time ratio for each jump.

Linear Speed (Ls) and Change of Direction (COD) Speed

Execution time for speed tests was measured by Chronojump single beam photocells (Chronojump BoscoSystem®, Barcelona, Spain). The photocells were placed 2 m from each other with a height of 1.10 m (approximately the height of the players' hips). Before the start of the test, each player was positioned 0.5 m behind the first gate, in a two-point split stance (i.e., standing position with the preferred foot forward placed exactly 0.5 m behind the starting line). Then, each player accelerated at maximum speed to the second gate located 10 m away for all the tests, in a straight line for the linear speed test and with a turning point at 5 m where each athlete performed a COD45º, COD90º and COD180º to reach the second gate in the shortest possible time (Figure 1). CODs at 45°, 90° and 180° were performed on both sides and laterality was defined by the leg on which participants set on the court when performing the COD mechanics (Cuthbert et al., 2019). The CODD for each angulation (45º, 90º and 180º) was calculated using the formula: ([COD tests time – Ls time] / Ls time) * 100 (Freitas et al., 2021b); all time variables are provided in seconds.

Unilateral Triple Hop Test (THTu)

The elastic-reactive force in a horizontal direction was evaluated through the horizontal triple jump test measured with a metric tape measure. The test started when the player stood with one leg supported just behind the starting line. After performing three consecutive maximum forward jumps with the same leg, the investigator measured the total distance jumped from the take-off line to the nearest point of the landing contact (i.e., back of the heels). Arm swinging was allowed and attempts were considered failed and repeated if 1) the test was not completed as previously indicated, 2) balance was lost during any part of the test, or 3) the final position could not be maintained on one leg for at least two seconds.

Statistical Analyses

Means ± standard deviations (SDs) were used to describe variables. The assumption of normality was verified using the Shapiro-Wilk test. The relative and absolute reliability of the tests was evaluated by the ICC and the CV. A median cut-off score was established for the time execution of each Ls and COD tests, thus dividing participants according to their performance in each test. A high performance (HP) group included those participants with a performance above the 50th percentile in each speed test, while a low performance (LP) group consisted of players with a performance below the 50th percentile in each speed test. The Student's *t*-test for independent samples was used to assess the influence of gender and performance. Relationships between variables were determined using Pearson´s correlations. Finally, forward stepwise multiple regression analysis (MRA) was used to identify the effects of independent variables on performance in the different Ls and COD tests. These analyses were carried out separately for male and female players. The interpretation for Square R descriptors from MRA were < 0.04 "trivial", 0.04–0.25 "small", 0.25–0.64 "moderate", and > 0.64 "strong effect" (Cohen, 1988). The Cohen's *d* was calculated from the mean change divided by the SD of the data; thresholds for qualitative descriptors of Cohen's *d* were set at < 0.20 "trivial", 0.20–0.50 "small", 0.50–0.80 "moderate", and > 0.80 "large" (Cohen, 1988). Collinearity diagnostic tests were performed for each MRA and the thresholds for determining the presence of collinearity were set at ≤ 0.3 for tolerance and ≥ 3 for the variance inflation factor (VIF). The Breusch-Pagan test was employed to assess the presence of heteroscedasticity. Statistical significance was set at $p < 0.05$. All statistical analysis was performed using IBM SPSS Statistics for Macintosh, Version 25.0 (Armonk, NY: IBM Corp.).

Results

The average performance of the different quantitative mobility, strength, Ls and COD tests differing according to gender is presented in Table 1. Male players showed a better performance for all the strength variables analysed ($p < 0.001$) as well as for velocity variables, with COD45º being the variable that showed the greatest difference between both genders ($p < 0.001$; ES = 2.047).

Comparison of performance variables differentiating between genders and according to performance in Ls and COD tests is shown in Table 2. For all speed tests performed, the fastest athletes were also the strongest both vertically ($p < 0.021$) and horizontally ($p < 0.035$). Vertical strength showed significant differences ($p < 0.05$) in the performance of all speed tests only among female players. However, significant differences were observed between horizontal strength and performance in all speed tests for both genders. Specifically, performance in Ls and COD90º tests showed a greater relationship with all force variables in both directions. For these variables, the fastest athletes showed a higher RSI ($p < 0.05$) in both genders. Finally, a higher CODD ($p < 0.05$) was also observed in the fastest players in Ls only in the male sample.

Matrix correlation analysis is presented in Table 3. This analysis revealed that the strength variables evaluated had greater statistical significance in females compared to males. In females, the CMJu showed the highest significant correlations ($r \leq –0.684$; $p < 0.01$) with all speed tests. In the male sample, the CMJu, the DJu and the THTu showed significant relationships ($p < 0.05$) with several speed tests. Quantitative movement tests only showed significant relationships with speed performance for female gender. The YBT showed high negative relationships with all speed tests ($r \leq –0.573$; $p < 0.01$) and the WB-DT was only significantly related to COD45° ($p < 0.01$).

Finally, Table 4 shows MRA, revealing the variance and properties of each speed test based on gender using independent variables. For females, the CMJu explained between 45% and 68% ($p < 0.001$) of the performance in speed tests, being the most influential variable. On the other hand, for male players, the THTu emerged as the most significant variable, explaining up to 61% ($p < 0.001$) of their performance in the different speed tests. Collinearity was not detected in MRA (tolerance ≥ 0.92, VIF ≤ 1.09 for females; tolerance ≥ 0.95, VIF ≤ 1.02 for males). Finally, no heteroscedasticity was detected in the regression model ($p \geq 0.145$ for females; $p \geq 0.346$ for males).

Discussion

This study aimed to analyse the relationship among functional movement and strength variables with Ls and COD speed based on gender. The main findings were as follows: 1) greater performance in all jumps actions was associated with faster athletes in all speed tests. Horizontal jumps showed a stronger association with speed tests in males, while vertical jumps were more significant in females; 2) the CODD showed significant differences only in male players, suggesting that faster linear sprinters were less efficient in COD actions and had a higher CODD. In addition, the study also identified the main variables determining Ls and COD performance according to gender. In this sense, for males, 3) tests with a short SSC predominantly in a horizontal direction, like a THTu, were most significant for speed test performance, except for the COD45º. However, for females, 4) a long SSC in a vertical direction was the primary determinant of performance in all speed tests, with the WD-DF also significant for the COD45º.

As expected and consistent with prior literature (Freitas et al., 2021a; Mancha-Triguero et al., 2021; Mikolajec et al., 2017; Sekulic et al., 2013), males performed better than females in all strength and speed tests considered. These differences can be attributed to variations in body dimensions and muscle architecture (e.g., disparities in tendon length, angle of pennation and fascicle properties) between genders (Laffaye et al., 2014). In contrast, while previous studies observed gender differences in dynamic balance (Sekulic et al., 2013), no gender differences in quantitative movement tests were observed in the present study.

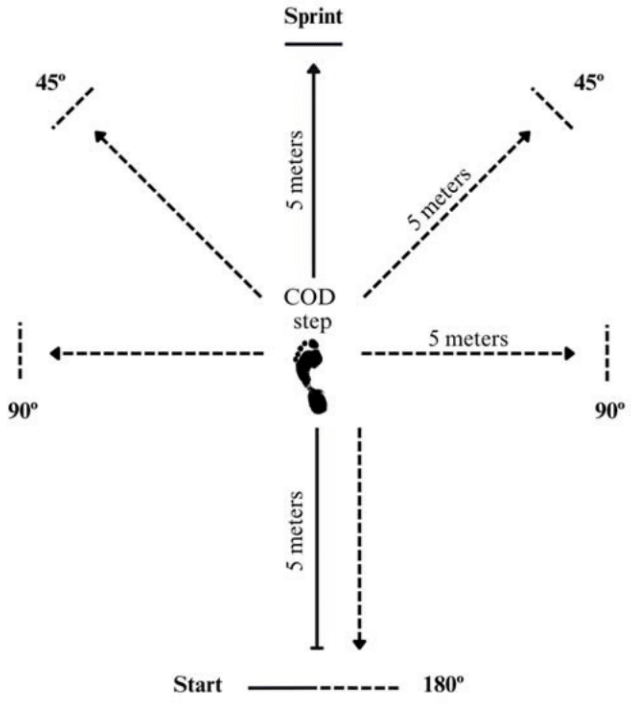

Figure 1. Schematic presentation of the linear speed test (10-m sprint) and the change of direction speed test (5+5 m at a 45º, 90º and 180º cut).

Table 1. Descriptive data (mean ± SD) of the considered performance variables differentiating between genders.

Variables	FEMALE (n = 27)		MALE (n = 23)		% difference	*p* value	ES Cohen's *d*	CV (%)
	Mean	SD	Mean	SD				
WB-DF (º)	41.2	5.13	41.7	7.25	1.21	0.784	–0.079	1.32
YBT	0.61	0.05	0.60	0.06	1.67	0.877	0.047	1.81
CMJu (cm)	10.9	3.08	17.1	3.83	56.9	<0.001	–1.838	1.94
DJu (cm)	11.0	2.59	16.2	3.37	47.3	<0.001	–1.735	2.15
RSI	0.72	0.18	0.83	0.19	15.3	0.034	–0.618	2.07
THT (cm)	464.3	45.5	535.1	60.5	15.2	<0.001	–1.331	1.98
LS (s)	1.98	0.11	1.87	0.10	5.56	0.001	1.093	1.69
COD 45º (s)	2.12	0.10	1.90	0.11	10.4	<0.001	2.047	1.76
COD 90º (s)	2.40	0.14	2.31	0.14	3.75	0.022	0.695	1.85
COD 180º (s)	2.93	0.18	2.76	0.12	5.80	<0.001	1.138	1.62
CODD 45º (%)	7.08	3.60	2.00	4.74	71.8	<0.001	1.211	–
CODD 90º (%)	21.2	4.80	23.5	5.45	10.8	0.132	–0.448	–
CODD 180º (%)	47.9	6.30	47.9	6.77	0.00	0.990	0.004	–

WB-DF, Weight-Bearing Dorsiflexion Test; YBT, Y-Balance Test; CMJu, unilateral Countermovement Jump; DJu: unilateral Drop jump; RSI: Reactive Strength Index; THT, Triple Hop Test; LS, Linear Sprint; COD, Change of Direction; CODD, Change of Direction Deficit; º, Degrees; %, Percentage; cm, Centimeters; s, Seconds; SD, Standard Deviation; ES, Effect Size.

Table 2. Comparison of the different considered performance variables between *low performance* and *high performance* classified by each linear speed and change of direction test and differentiating between genders.

	LS		COD 45º		COD 90º		COD 180º	
	LP	HP	LP	HP	LP	HP	LP	HP
WB-DF (º)								
Female	39.1 ± 5.62	42.7 ± 4.65	38.8 ± 5.56	43.0 ± 4.47	40.1 ± 6.22	41.8 ± 4.50	40.9 ± 6.35	41.0 ± 4.48
Male	38.8 ± 5.72	44.6 ± 7.69	42.8 ± 8.18	40.8 ± 6.61	40.6 ± 8.10	42.8 ± 6.50	38.5 ± 6.00	44.3 ± 7.37
p gend	0.665		0.644		0.687		0.782	
p perf	0.011		0.556		0.323		0.125	
YBT								
Female	0.58 ± 0.06[a]	0.65 ± 0.05[a]	0.58 ± 0.05[a]	0.64 ± 0.06[a]	0.57 ± 0.05[a]	0.65 ± 0.05[a]	0.58 ± 0.06[a]	0.64 ± 0.04[a]
Male	0.60 ± 0.05	0.63 ± 0.08	0.61 ± 0.06	0.60 ± 0.07	0.62 ± 0.06	0.60 ± 0.07	0.61 ± 0.02	0.60 ± 0.09
p gend	0.487		0.621		0.652		0.458	
p perf	0.006		0.077		0.038		0.041	
CMJu (cm)								
Female	8.98 ± 3.45[1a]	12.8 ±1.51[2a]	9.35 ± 3.70[1a]	12.5 ± 1.82[2a]	8.72 ± 2.95[1a]	13.1 ± 1.76[2a]	9.36 ± 3.41[1a]	12.5 ± 2.33[2a]
Male	15.3 ± 3.04[1b]	20.5 ± 2.84[2b]	16.1 ± 2.82[1]	18.2 ± 4.72[2]	15.3 ± 2.30[1]	18.6 ± 4.39[2]	15.8 ± 4.26[1]	18.5 ± 2.91[2]
p gend	< 0.001		< 0.001		< 0.001		< 0.001	
p perf	< 0.001		0.021		< 0.001		0.009	
DJu (cm)								
Female	9.06 ± 1.94[1a]	13.0 ± 1.81[2a]	9.72 ± 2.80[1a]	12.4 ± 1.98[2a]	9.08 ± 1.83[1a]	13.0 ± 1.97[2a]	9.60 ± 2.53[1a]	12.5 ± 2.16[2a]
Male	14.9 ± 2.85[1]	17.3 ± 3.50[2]	14.8 ± 1.69[1]	17.5 ± 4.05[2]	14.7 ± 1.56[1b]	17.5 ± 4.04[2b]	15.2 ± 3.49[1]	17.1 ± 3.10[2]
p gend	< 0.001		< 0.001		< 0.001		< 0.001	
p perf	< 0.001		0.002		< 0.001		0.006	
RSI								
Female	0.63 ± 0.13[1a]	0.77 ± 0.18[a]	0.66 ± 0.21	0.74 ± 0.12	0.61 ± 0.11[1a]	0.80 ± 0.17[a]	0.68 ± 0.23	0.72 ± 0.08[2]
Male	0.78 ± 0.17[1]	0.87 ± 0.21	0.80 ± 0.18	0.86 ± 0.21	0.74 ± 0.13[1b]	0.92 ± 0.20[b]	0.81 ± 0.21	0.85 ± 0.18[2]
p gend	0.016		0.020		0.009		0.021	
p perf	0.028		0.226		< 0.001		0.461	
THT (cm)								
Female	434.6 ± 37.4[1a]	492.0±35.7[2a]	441.3±40.5[1a]	485.4±42.0[2a]	440.6±40.9[1a]	486.0±40.9[2a]	445.1±44.8[1a]	481.5±41.7[2a]
Male	504.9 ± 51.1[1b]	562.9±56.5[2b]	522.9±61.0[1]	546.3±60.5[2]	500.4±51.3[1b]	566.9±51.2[2b]	509.2±58.6[1b]	558.9±53.9[2b]
p gend	< 0.001		< 0.001		< 0.001		< 0.001	
p perf	< 0.001		0.031		< 0.001		0.005	
CODD (%)								
Female	23.9 ± 4.19	26.9 ± 3.72	7.36 ± 3.92	6.80 ± 3.40[2]	22.2 ± 5.23[1]	20.3 ± 4.35	50.4 ± 5.24	45.5 ± 6.55
Male	21.2 ± 4.61[b]	27.5 ± 2.54[b]	3.56 ± 5.69	0.57 ± 3.29[2]	26.6 ± 3.52[1b]	20.7 ± 5.50[b]	48.2 ± 8.76	47.7 ± 4.66
p gend	0.342		< 0.001		0.087		0.994	
p perf	< 0.001		0.150		0.008		0.171	

LP, Low Performance; HP, High Performance; LS, Linear Speed; COD, Change of Direction; gend, gender; perf, performance; WB-DF, Weight-Bearing Dorsiflexion Test; YBT, Y-Balance Test; CMJu, unilateral Countermovement Jump; DJu: unilateral Drop Jump; RSI: Reactive Strength Index; THT, Triple Hop Test; CODD, Change of Direction Deficit; º, Degrees; %, Percentage; cm, Centimeters; s, Seconds; SD, Standard Deviation. [1] Statistical significance at $p < 0.05$ in LP controlling for gender. [2] Statistical significance at $p < 0.05$ in HP controlling for gender. [a] Statistical significance at $p < 0.05$ in females controlling for performance. [b] Statistical significance at $p < 0.05$ in males controlling for performance.

Table 3. Correlation coefficients between the movement and performance variables with the linear speed and change of direction performance according to gender.

Variables	LS		COD 45º		COD 90º		COD 180º	
	Male	Female	Male	Female	Male	Female	Male	Female
WB-DF (º)	–0.252	–0.270	–0.003	–0.533††	–0.152	–0.282	–0.217	–0.299
YBT (cm)	–0.177	–0.597††	–0.181	–0.573††	–0.015	–0.607††	0.018	–0.625††
CMJu (cm)	–0.678††	–0.730††	–0.401	–0.750††	–0.417	–0.792††	–0.538†	–0.684††
DJu (cm)	–0.513†	–0.829††	–0.488†	–0.666††	–0.455†	–0.701††	–0.511†	–0.642††
RSI	–0.403	–0.450†	–0.252	–0.493††	–0.379	–0.533††	–0.318	–0.307
THT (cm)	–0.607††	–0.663††	–0.397	–0.679††	–0.561††	–0.655††	–0.512†	–0.640††

LS, Linear Speed; COD, Change of Direction; WB-DF, Weight-Bearing Dorsiflexion Test; YBT, Y-Balance Test; CMJu, unilateral Countermovement Jump; DJu: unilateral Drop Jump; RSI: Reactive Strength Index; THT, unilateral Triple Hop Test.
† Significant correlation ($p < 0.05$); †† Significant correlation ($p < 0.01$)

Table 4. Stepwise multiple regression analysis between performance variables assessed and linear-change of direction speed performance.

Dependent variable	Independent variables	Standardised coefficients (Beta)	Coefficients' significance (p)	R^2	R^2 adjusted
Female					
LS	DJu	–0.829	<0.001	0.687	0.673
COD 45º	CMJu	–0.652	<0.001	0.675	0.644
	WB-DF	–0.348	0.014		
COD 90º	CMJu	–0.792	<0.001	0.628	0.611
COD 180º	CMJu	–0.684	<0.001	0.467	0.443
Male					
LS	THT	–0.796	<0.001	0.634	0.606
COD 45º	DJu	–0.488	0.018	0.238	0.201
COD 90º	THT	–0.585	0.022	0.342	0.292
COD 180º	THT	–0.770	0.001	0.593	0.561

R^2, Coefficient of determination; LS, Linear Speed; COD, Change of Direction; WB-DF, Weight-Bearing Dorsiflexion Test; CMJu, unilateral Countermovement Jump; DJu: unilateral Drop Jump; THT, Triple Hop Test.

For the female sample, all strength variables in different directions significantly differed between performance levels for both Ls and COD speed tests, aligning with previous research (Spiteri et al., 2013, 2015). Further analysis using MRA revealed that the CMJu, involving vertical forces through a long SSC (> 250 ms) (Turner and Jeffreys, 2010), was the most significant variable determining speed performance in female athletes. While previous studies emphasized the importance of developing all strength components for female basketball players (Spiteri et al., 2014, 2015), our findings suggest that to improve COD performance in females, maximum strength exercises with vertical directions should be of the prime focus. This is at odds with previous research

(Falch et al., 2020) that favoured exercises with a short SSC as more specific to the COD. The discrepancy could be due to a longer SSC being more relevant to COD actions in athletes with lower relative strength, as observed in the female sample compared to the male one in this study. In relation to this, it was suggested that there might be a strength threshold above which athletes benefit more from short SSC exercises (Falch et al., 2021), but below this threshold, the focus should be on maximal strength and long SSC exercises. Furthermore, it was initially hypothesised that speed tests would emphasise horizontal directions force, but our results showed just the contrary. This finding could be explained by the fact that vertically oriented exercises have previously been demonstrated to be more effective in improving Ls and COD performance (Zweifel, 2017); and this effectiveness was higher in less experienced and weaker athletes, such as female players in our sample.

In the male sample, significant differences were observed between performance in all speed tests and horizontal strength variables with a short SSC (< 250 ms) (Turner and Jeffreys, 2010). Specifically, the THTu had the greatest impact on speed performance in MRA. This could be because the analysed Ls and COD tests required a greater application of force in a horizontal direction (Baena-Raya et al., 2020; McBurnie and Dos'Santos, 2022; Robles-Ruiz et al., 2021). Previous interventions with male basketball players have shown that horizontal plyometric training leads to greater improvements in COD performance compared to vertical training (Aztarain-Cardiel et al., 2022; Gonzalo-Skok et al., 2019). Moreover, male players exhibited higher levels of strength, enabling them to take better advantage of a shorter SSC compared to female players. This suggests that males benefit more from a short SSC, as in previous research they have been shown to have a 1.5 times greater rate of force development than females (Laffaye et al., 2014). Finally, among the quantitative movement tests assessed, the YBT showed significant differences for all speed test performance variables, but only in the female sample. In contrast, no relationship was found between performance in speed and quantitative movement tests for male players, which differs from previous research that observed correlations between the YBT and speed tests in male basketball players (Gonzalo-Skok et al., 2015). This lack of consensus may be explained by the use of different speed tests, as each test has its own biomechanical and physical demands (Dos'Santos et al., 2018).

Although Ls and COD speed are considered to be two different capacities (Young et al., 2015), it is now accepted in the literature that one affects another, mainly regarding the lower cutting angle (Young et al., 2015). Previous research (Nimphius et al., 2016, 2018) states that the COD used in the literature may not isolate the COD ability, leading to observed relationships between Ls and COD speed possibly due to inadequate test variables, with over 70% of the total test time being devoted to Ls. Caution is advised when comparing these two variables, and using them as dependent variables when comparing them with other performance variables is recommended. To address this limitation, the CODD concept was proposed (Freitas et al., 2021b). Our results showed significant differences in the CODD for males, indicating less efficiency in COD actions despite their higher Ls. This relationship was not observed among females, possibly due to males having greater Ls development and higher body mass, which are important factors influencing the magnitude of the CODD (Freitas et al., 2022) and the braking phase of COD (Dos'Santos et al., 2018). While there are no basketball-specific studies comparing the CODD between genders, similar findings were obtained in both genders in previous research with rugby seven players (Freitas et al., 2021a).

This study is the first to comprehensively analyse the relationship between different movement and strength variables, previously linked to speed tests, and their association with various Ls and COD tests in both male and female players. This approach enables a comprehensive understanding of the performance variables and their relationship with speed tests with diverse angulations according to gender. However, despite its value, this research is not without limitations. Firstly, the cross-sectional design used precludes determining the causality of the results. In addition, we must take into account the characteristics of the sample before generalizing the results to other competitive levels or sports. Therefore, further prospective and experimental

research is recommended to consistently determine gender differences. Therefore, since COD actions are complex and influenced by various factors, future research should explore different pre-COD running distances to modify finishing speed. Considering the vast array of performance variables influencing COD actions, this study had to carefully select the most valid and consistent ones for analysis.

Conclusions

In summary, it is worth emphasizing that the influence of gender must be taken into account when optimizing Ls and COD speed. In this sense, it is recommended to focus on a short SSC and horizontal force direction exercises in men, and a long SSC including maximal strength with vertical force direction exercises in women. As MRA showed, the CMJu involving vertical force direction and a long SSC was the most determinant variable in speed performance for female athletes, explaining the variance of the applied tests between 44.3% and 67.3%. In contrast, the THTu with a horizontal force direction and a short SSC was the most determinant variable in speed performance of male athletes, explaining between 20.1% and 60.6% of the change in their variance. For further individualization of training, it is also recommended to take into account individual strength levels of each male and female athlete. Moreover, coaches should start using the CODD as an isolated measure of COD actions. It was established that male athletes who presented higher linear speed had a greater deficit in multidirectional actions. Thus, we recommend greater focus on eccentric actions, deceleration and technique drills in those male players who have better performance in Ls in order to decrease the CODD (Freitas et al., 2021b; Lazić et al., 2022) and, therefore, improve COD performance.

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STUDY 4

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Strength characteristics in faster change of direction basketball players: A comparison across cutting angles

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Strength characteristics in faster change of direction basketball players: A comparison across cutting angles

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Abstract

Change of directions (COD) involves multidirectional and complex actions, with performance influenced by multiple factors. As lower limb strength is one of the most determinant of COD performance, the present study aimed to (a) explore the differences in strength outcomes across different lower limb muscle actions between faster and slower basketball players in COD actions at different angles and (b) analyse the relationship between isometric, concentric and eccentric strength outcomes and COD performance at different cutting angles. Twenty-five basketball players (44% female) completed a battery of tests, encompassing isokinetic and isometric squat strength assessments, along with COD tests at 45°, 90° and 180°. Players were categorised as '*low-performance*' and '*high-performance*' groups based on execution time in COD, facilitating a comparison between performance groups. Results indicated that concentric strength showed the greatest differences between performance groups at 45° COD (effect size $\geq$ 0.813; $p \leq 0.034$). Isometric and eccentric strength demonstrated a moderate-to-large relationship with 90° COD performance (Rho $\geq$ 0.394; $p \leq 0.045$), and all muscle actions exhibited a large relationship with 180° COD (Rho $\geq$ 0.445; $p \leq 0.030$). Moreover, the fastest players showed higher levels of concentric strength relative to eccentric strength, regardless of the cutting angle. These findings hold practical applications, suggesting that basketball coaches should train a specific kind of muscle action depending on the individual players' COD demands, focusing on improving the rapid eccentric force application while striving to reduce the eccentric/concentric ratio.

KEYWORDS
acceleration, agility, cutting, deceleration, team sport

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Highlights

- Strength is undeniably a key indicator in change of directions (COD) performance. The relationship between strength outcome measures and COD proficiency depends on the cutting angle.
- Cutting angles below 90° emphasise concentric strength, while those above 90° exhibit a stronger reliance on isometric and eccentric strength.
- Rapid eccentric force production strongly correlates with COD performance across all cutting angles. However, the fastest players exhibit higher concentric strength relative to their eccentric strength.

1 | INTRODUCTION

Change of direction (COD) actions, which are vital in basketball, demand precise body control, muscle activation and force production (Spiteri, Newton, Binetti, et al., 2015). This complex and multidirectional skill involves planned deceleration and acceleration in different directions (Nimphius et al., 2016), occurring frequently—over 1000 times per game (Matthew & Delextrat, 2009; Salazar et al., 2020), with 15% of these at maximum intensity (<−3.5 m·s−2) (Svilar et al., 2018). Regardless of a player's position or gender, COD is a crucial physical ability in basketball, providing a physical advantage over opponents, aiding in offencive positioning or enhancing defencive manoeuvers (Power et al., 2022). With the rising intensity of modern basketball (Sugiyama et al., 2021), strength and conditioning coaches must prioritise COD, understanding its physical factors and enhancing athletes' performance in these actions.

Efficient execution of COD relies on distinct types of muscle actions, with athletes needing adequate eccentric strength for initial deceleration, isometric strength during stance and concentric strength for reacceleration in the new direction (Spiteri et al., 2014). Achieving optimal COD at maximum speed involves the crucial interplay of these muscle actions (Castillo-Rodríguez et al., 2012). While prior studies have investigated physical determinants of COD, including eccentric (Jones et al., 2022; Smajla et al., 2022), isometric (Smolarek et al., 2023; Spiteri et al., 2014; Spiteri, Newton, & Nimphius, 2015) and concentric strength (Spiteri et al., 2014; Spiteri, Newton, & Nimphius, 2015), as well as power and reactive strength (Barrera-Domínguez et al., 2020; Castillo-Rodríguez et al., 2012), conflicting conclusions and lack of consensus persist. Divergent findings may stem from variations in sample characteristics, COD assessment protocols employed (i.e., *t*-test vs. 505 test) and muscle strength measurement methods (i.e., isokinetic vs. isoinertial). Notably, the influence of muscle actions on COD likely hinges on the task demands, which are directly affected by cutting angles (Dos'Santos et al., 2018). Thus, the absence of consensus in the scientific literature is justifiable, given the challenge of comparing results across studies using different COD assessment tests.

The analysis of mechanical demands in 180° cutting angles reveals the necessity for athletes to rapidly decelerate at the cut point and then swiftly reaccelerate in the opposite direction. Previous studies emphasise the crucial role of the deceleration phase in COD performance, recognising its instrumental preparation for the final step and the subsequent reacceleration (Dos'Santos et al., 2021a; Dos'Santos et al., 2019). In this phase, athletes experience force peaks reaching up to six times their body mass (Harper et al., 2022), highlighting the significance of eccentric strength in mitigating linear momentum during pre-cutting steps and the braking phase at the final step of the cut (Jones et al., 2017). A strong association between the eccentric strength of knee flexors and extensors and 180° COD performance has been reported (Jones et al., 2017). These sharp cutting actions also extend ground contact time beyond 400 milliseconds during the final step (McBurnie & Dos'Santos, 2022), making isometric strength relevant. Smolarek et al. (2023) discovered significant correlations between peak isometric strength (measured in a mid-thigh pull) and the ability to execute a 180° COD.

In contrast, for shear cuts below 90°, managing the moment of inertia is pivotal, with less emphasis on deceleration (Dos'Santos et al., 2018). Additionally, maintaining high speeds at these wider cutting angles is crucial for higher performance (Hader et al., 2015). While Jones et al. (2022) emphasised the substantial influence of eccentric strength at shear angles ranging from 70° to 90°, Smajla et al. (2022) found only trivial correlations between eccentric strength in an isoinertial flywheel squat and 90° COD performance.

As previously mentioned, distinct muscle actions have been demonstrated to influence COD performance, with all types of muscle actions playing crucial roles in this complex, high-speed action (Spiteri, Newton, Binetti, et al., 2015). Studies assessing full-spectrum strength through dynamic movements show correlations between dynamic strength and COD performance, particularly emphasising the elastic and reactive components of strength at angles of 90° and 180° (Barrera-Domínguez et al., 2020; Castillo-Rodríguez et al., 2012). Strength is undeniably a key indicator in COD performance, yet consensus is lacking on the impact of various strength measures for each muscular action at different cutting angles.

This study sought to achieve two main purposes: (a) to examine the differences in strength measures for different lower limb muscle actions between faster and slower basketball players in COD actions at different angles and (b) to analyse the relationship between isometric, concentric and eccentric strength measures and COD performance at different cutting angles. It was hypothesised that associations between different muscle actions and COD exist, with the strength of these associations varying depending on the specific

cutting angle. Faster players engaged in cutting actions at 45° may require greater concentric strength, those at 90° may demand greater eccentric strength, and in the case of cutting actions at 180°, all muscle actions may hold equal importance.

2 | MATERIALS AND METHODS

2.1 | Design

A cross-sectional experimental design was employed to analyse the effect of specific strength characteristics on different cutting angles and to compare different strength characteristics between "fast" and "slow" COD basketball players at each angle. The evaluation session comprised two main components. Firstly, participants performed the modified 505 COD test at 45°, 90° and 180° (Barrera-Domínguez et al., 2023). Subsequently, assessments of isokinetic strength at 0.60 $m{\cdot}s^{-1}$ were conducted, along with 8-s isometric strength measurements involving knee flexion at 65° and hip flexion at 55°, using functional electromechanical dynamometry (FEMD).

Data collection occurred during the competitive phase of the sports season. The strength assessment was conducted in the (blinded) facility, while the COD tests were executed on the university's basketball court. To familiarise participants with the isokinetic and isometric strength testing procedures using FEMD, a familiarisation session was conducted 1 week before the assessment. All participants completed both the familiarisation and assessment sessions immediately before their basketball training sessions.

2.2 | Participants

A total of 25 basketball players (44% females; age, 23.2 ± 4.69 years; height, 182.5 ± 7.69 cm; body mass, 77.4 ± 11.3 kg), all competing in the (blinded), voluntarily participated in this study. Participants were recruited using convenience sampling and were included if they had been free from lower limb injuries for at least 6 months prior to the assessment, engage in training at least 3 days a week during the season in addition to competitive games and possess a minimum of 10 years of basketball-playing experience.

All participants were informed of potential risks and benefits before the study and provided written consent prior to commencing testing procedures. This study was approved by the (blinded), following the guidelines outlined in the Declaration of Helsinki.

2.3 | Procedures

The familiarisation session lasted 30 min, starting with 5 min of general hip and ankle mobility exercises. Following this, the subjects performed two sets of 30-s bodyweight isometric squats and 10 repetitions of dynamic free squats. Subsequently, familiarisation with FEMD began, involving two sets of 8-s maximum isometric squats. Finally, participants performed two sets of four repetitions (two submaximal and two maximal) of isokinetic squats at a velocity of 0.60 $m{\cdot}s^{-1}$ with subject-specific ranges of motion (ROM). The ROM depended on the length of the lower limb levers of each subject and was individually adjusted to allow them to perform an isokinetic squat from 0° to 90° of knee flexion.

One week after familiarisation, the main evaluation took place. Before the start of the evaluation sessions, a 15-min warm-up was implemented, starting with general activation, including light intensity jogging, a series of dynamic stretching exercises and several acceleration runs, followed by specific potentiation exercises. Additionally, each player was instructed to ensure adequate hydration and rest, abstain from high-intensity training for 24 h preceding the evaluation and control caffeine and food intake at least 3 h before each assessment.

2.3.1 | Modified 505 COD test at 45°, 90° y 180°

The execution time for speed tests was measured using single-beam timing cells (Chronojump BoscoSystem®, Barcelona, Spain). The timing cells were positioned 2 m apart at a height of 1 m, approximately corresponding to the height of the players' hips. Before the test, each player was positioned 0.5 m behind the first gate in a two-point split stance (i.e., standing with the preferred foot forward and placed exactly 0.5 m behind the starting line). Then, each player accelerated to maximum speed, covering 10 m in all tests, with a turning point at the 5-m mark. At this turning point, each athlete executed turns at angles of 45°, 90° and 180° to reach the second gate in the shortest possible time. The COD tests at 45°, 90° and 180° were performed on both sides, with laterality determined by the leg used during the final step when performing the COD mechanics.

2.3.2 | Isometric and isokinetic strength

Isokinetic and isometric strength were assessed during the squat exercise using a FEMD (Myoquality, Spain) (del-Cuerpo et al., 2023; Morenas-Aguilar et al., 2023; Rodriguez-Perea et al., 2021) with high precision, featuring a three-mm displacement accuracy, a load detection sensitivity of 100 g and a sampling frequency of 1000 Hz. The FEMD system comprises a rope connected to the machine body, passing through a floor-mounted pulley located just in front of the machine. To isolate lower limb strength, the player stood with one foot on each side of the pulley, ensuring that the application of force against the rope remained completely vertical (Figure 1). The player then hooked the rope to a waist harness. In the correct position, players applied force to the rope, and a load cell detected the tension on the rope to measure lower limb strength.

Isometric strength assessment involved conducting two sets of 8-s isometric squats with the knee flexed at 65° and the hip at 55°, replicating the joint angles experienced during COD (Dos'Santos et al., 2021b). The rope length was individually adjusted for each

FIGURE 1 Isokinetic and isometric squat set-up. Initial (left) and final (right) position.

player to achieve the specified squat position. Players were instructed to exert maximum and steady force quickly.

For isokinetic strength, participants completed two sets of four maximal repetitions of isokinetic squats at a velocity of 0.60 $m \cdot s^{-1}$. The FEMD system precisely controlled angular velocity using a 2000 W electric motor (Martinez-Garcia et al., 2020). The squat movement ranged from a standing position to a knee flexion of 90° (Figure 1), encompassing the angles experienced by the lower limbs during COD actions (Dos'Santos et al., 2021b). Rope length and distance covered were individually adjusted for each player. Players were instructed to resist the "pull" of the rope as much as possible during the eccentric phase and to exert maximal force during the concentric phase.

A five-minute rest period was maintained between each set using the FEMD system. Mean strength values for each type of muscular action were used to calculate eccentric/isometric (E/I), eccentric/concentric (E/C) and isometric/concentric (I/C) strength ratios. A sampling period of 20 milliseconds was used to analyse the peak rate of force development (pRFD), given its demonstrated reliability in prior studies (Haff et al., 2015).

2.4 | Statistical analyses

Means ± standard deviations (SD) were used for variable descriptions. The relative and absolute reliabilities of the tests were evaluated using the intraclass correlation coefficient (ICC; ICC > 0.9 was considered strong) and the coefficient of variation (CV; CV < 10% was established as an intraday reliability criterion). A median cut-off score was established for the execution time of each COD angulation, thus dividing participants according to their performance in each COD test. High Performance (HP) included participants with a performance above the 50th percentile in each COD test. Low Performance (LP) consisted of players with a performance below the 50th percentile in each COD test. Normality and homogeneity of data were assessed using Shapiro–Wilk and Levene's tests, respectively. Given non-compliance with assumptions, the Mann–Whitney *U*-test was used to analyse the influence of the strength variables across the different COD performance groups. Cohen's *d* was calculated for effect size (ES) interpretation. Thresholds for qualitative descriptors of Cohen's *d* were set at < 0.20 'trivial', 0.20–0.50 'small', 0.50–0.80 'moderate' and >0.80 'large' (Cohen, 1988). Spearman's correlation coefficient assessed relationships between the different strength variables and COD, with the following thresholds indicating magnitude: <0.10 'trivial', 0.10–0.30 'small', 0.30–0.50 'moderate', 0.50–0.70 'large', 0.70–0.90 'very large' and >0.9 'almost perfect' (Hopkins et al., 2009). The alpha level was set at $p < 0.05$. All statistical analyses were conducted using IBM SPSS Statistics for Macintosh (V25.0, IBM Corporation).

3 | RESULTS

Table 1 presents the mean ± SD values for the assessed strength and COD variables, along with the ICC and CV for each variable. The test reliability, both in relative and absolute terms, was confirmed (ICC ≥ 0.905; CV ≤ 7.94).

Table 2 displays a comparison between LP and HP groups for different turning angles with each strength variable. The HP group showed the highest levels of strength for all muscle actions. Concentric strength characteristics showed the largest significant differences between performance groups (ES ≥ 0.813; $p \leq 0.034$) for a shear angle at 45°. At a cutting angle of 90°, the only variable demonstrating significant and substantial differences between

TABLE 1 Descriptive analysis (mean ± SD) of the performance variables analysed.

Variables	Mean ± SD	Minimal–Maximal	ICC	CV (%)
Isometric strength				
Mean force (kg)	175.5 ± 43.3	106.4–265.8	0.969	7.94
Peak force (kg)	203.3 ± 48.4	125.1–296.0	0.940	7.17
Impulse (N·s)	14,032.2 ± 3338.9	8498.1–21,238.5	0.981	4.35
Peak RFD (N/s)	9899.3 ± 6175.3	2992.9–26,935.9	0.973	3.75
Concentric strength at 0.6 $m \cdot s^{-1}$				
Mean force (kg)	67.4 ± 32.3	21.0–129.2	0.976	7.77
Peak force (kg)	134.5 ± 50.8	52.0–236.5	0.977	7.55
Peak RFD (N/s)	6941.5 ± 3044.3	1678.9–12,451.0	0.957	7.61
Eccentric strength at 0.6 $m \cdot s^{-1}$				
Mean force (kg)	165.1 ± 57.7	74.3–269.1	0.982	4.24
Peak force (kg)	246.8 ± 74.2	142.7–381.1	0.986	6.88
Peak RFD (N/s)	12,300.8 ± 3725.2	6514.4–19,987.1	0.919	7.49
Change of direction tests				
COD 45° L (s)	2.01 ± 0.16	1.63–2.51	0.941	2.38
COD 45° R (s)	2.01 ± 0.15	1.57–2.44	0.983	1.45
COD 90° L (s)	2.32 ± 0.18	1.94–2.83	0.935	2.55
COD 90° R (s)	2.32 ± 0.19	1.96–3.08	0.905	3.50
COD 180° L (s)	2.81 ± 0.21	2.54–3.44	0.955	2.25
COD 180° R (s)	2.81 ± 0.22	2.39–3.28	0.956	1.59

Abbreviations: COD, change of direction; CV, coefficient of variation.; ICC, intraclass correlation coefficient; L, left; R, right; RFD, rate of force development; SD, standard deviation.

groups was eccentric pRFD (ES = 0.882; $p = 0.035$). The sharpest COD at 180° revealed the greatest significant differences between groups for all isometric (ES ≥ 1.080; $p \leq 0.015$), concentric (ES ≥ 1.03; $p \leq 0.010$) and eccentric (ES ≥ 0.697; $p \leq 0.050$) strength outcome measures.

The correlation analysis between different strength outcome measures of each muscle action and COD tests is presented in Figure 2. Mean force (MF) and impulse in the isometric squat exhibited moderate negative correlations that were statistically significant with 90° (Rho ≥ 0.394; $p \leq 0.048$) and 180° (Rho ≥ 0.445; $p \leq 0.030$) cutting angles. The MF of the concentric phase of the isokinetic squat demonstrated a substantial negative correlation with 45° (Rho ≥ 0.460; $p \leq 0.022$) and 180° (Rho ≥ 0.551; $p \leq 0.005$) cutting angles. In relation to eccentric strength, it was fast force application, specifically pRFD, that displayed significant negative correlations with all COD angles (Rho ≥ 0.469; $p \leq 0.019$).

Table 3 displays the comparison between LP and HP groups for different turning angles in terms of each strength ratio. Significant large differences were identified in the E/C and I/C ratios (ES ≥ 0.834; $p \leq 0.035$) between performance groups, with the HP group showing the lowest values at a 45° cutting angle. Additionally, the I/C ratio also showed significant large differences between performance groups (ES = 0.994; $p = 0.030$) during the 180° COD test, indicating that those fastest at this cutting angulation resulted in the lowest I/C ratio.

4 | DISCUSSION

The purpose of the present study was to examine differences in strength outcome measures of lower limb muscle actions between faster and slower basketball players in COD actions at different angles. Additionally, the study aimed to analyse the relationship between isometric, concentric and eccentric strength outcome measures and COD performance at different cutting angles. The findings shed light on how the disparities in performance groups for each strength outcome measure were directly influenced by the cutting angle. Specifically, concentric strength measures displayed the most differences at a 45° angle, fast eccentric strength emerged as pivotal for cuts at 90° and all muscle actions showed significant differences at 180° COD. Noteworthy findings of this research included the robust relationship between the pRFD and all COD angulations, the significant relationship between concentric strength and COD at 45° and 180° and the moderate relationship between isometric strength and COD at 90° and 180°. Finally, the strength ratios underscored the importance of possessing high concentric strength levels

TABLE 2 Comparison (mean ± SD) of the different strength characteristics between *low performance* and *high performance* groups classified by each change of the direction test.

	COD 45°		COD 90°		COD 180°		*p value* (ES)		
	LP (*n* = 12)	HP (*n* = 13)	LP (*n* = 12)	HP (*n* = 13)	LP (*n* = 12)	HP (*n* = 13)	45°	90°	180°
Isometric strength									
MF (kg)	166.6 ± 37.3	182.7 ± 46.4	167.0 ± 35.7	182.4 ± 47.5	149.5 ± 23.3	197.2 ± 43.1	*0.277* (0.503)	*0.424* (0.372)	***0.002*** (1.574)
PF (kg)	196.7 ± 43.8	206.8 ± 51.4	194.7 ± 39.5	208.5 ± 53.7	177.0 ± 32.2	223.5 ± 48.5	*0.733* (0.203)	*0.691* (0.193)	***0.015*** (1.080)
Impulse (N·s)	13,312.7 ± 2976.8	14,683.7 ± 3388.1	13,345.9 ± 2855.5	14,655.6 ± 3485.7	12,050.5 ± 1733.3	15,751.8 ± 3239.0	*0.331* (0.440)	*0.424* (0.355)	***0.002*** (1.495)
RFDp (N/s)	8794.4 ± 6741.3	10,834.1 ± 5757.9	10,277.8 ± 5546.3	9578.9 ± 6871.2	7583.5 ± 3772.4	11,858.7 ± 7221.9	*0.246* (0.328)	*0.562* (0.111)	*0.132* (0.723)
Concentric strength at 0.6 $m \cdot s^{-1}$									
MF (kg)	52.6 ± 31.3	81.0 ± 27.6	65.3 ± 38.9	69.3 ± 26.2	49.8 ± 26.7	83.6 ± 29.0	***0.014*** (0.892)	*0.574* (0.116)	***0.002*** (1.299)
PF (kg)	112.3 ± 48.6	155.0 ± 45.1	137.0 ± 60.8	132.2 ± 42.0	110.5 ± 45.5	156.7 ± 46.5	***0.030*** (0.813)	*0.852* (0.007)	***0.010*** (1.032)
RFDp (N/s)	5935.6 ± 2913.7	7869.8 ± 2967.7	6584.7 ± 3328.9	7270.8 ± 2851.7	5858.4 ± 3251.9	7941.2 ± 2566.2	***0.034*** (0.865)	*0.807* (0.222)	*0.221* (0.715)
Eccentric strength at 0.6 $m \cdot s^{-1}$									
MF (kg)	159.4 ± 64.5	170.3 ± 52.6	147.5 ± 62.1	181.3 ± 50.2	133.3 ± 58.7	185.3 ± 50.8	*0.503* (0.205)	*0.137* (0.569)	***0.049*** (0.775)
PF (kg)	235.2 ± 86.7	257.4 ± 62.1	222.8 ± 69.9	268.9 ± 73.6	202.3 ± 77.2	269.4 ± 66.3	*0.347* (0.265)	*0.137* (0.535)	***0.050*** (0.697)
RFDp (N/s)	10,890.8 ± 3261.1	13,606.8 ± 2900.8	10,707.6 ± 2698.8	13,775.9 ± 3920.4	10,214.4 ± 2616.4	14,231.2 ± 2708.1	***0.035*** (0.882)	***0.016*** (1.027)	***0.001*** (1.507)

Note: Bold indicates significant differences between groups $p < 0.05$.

Abbreviations: COD, change of direction; HP, high performance group; LP, low performance group; MF, mean force; PF, peak force; RFDp, rate of force development peak.

compared to other muscular actions for achieving superior performance across various COD angulations.

These findings align with prior research, consistently indicating a strong relationship between isometric (Smolarek et al., 2023; Spiteri et al., 2014; Spiteri, Newton, & Nimphius, 2015), concentric (Spiteri et al., 2014, 2015) and eccentric (Jones et al., 2022; Smajla et al., 2022) strength measures and COD performance. However, these studies only examined the relationship between strength variables at a single cutting angle or within manoeuvrability tests that involved various cutting actions across multiple angles (Nimphius et al., 2018). Consequently, they could not provide a detailed analysis of the effect of each strength outcome measure on various COD angulations.

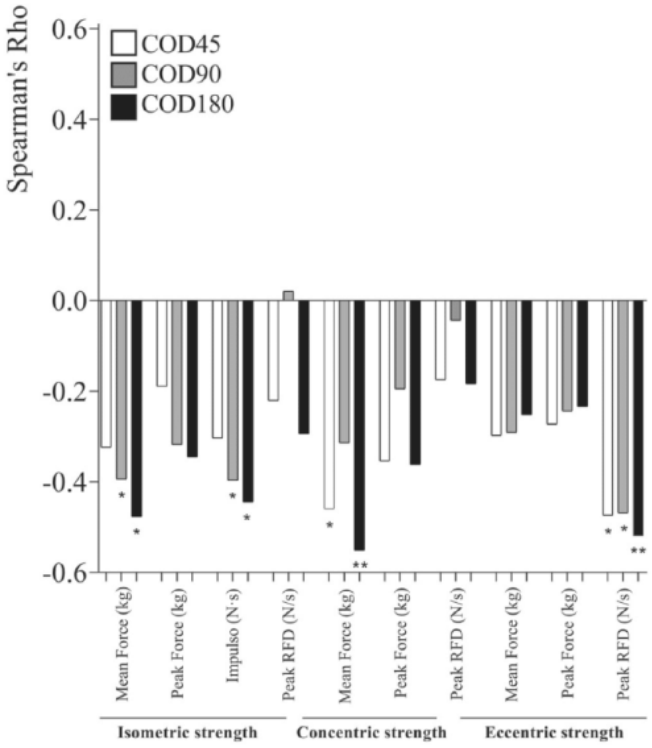

FIGURE 2 Spearman's Rho correlations between different strength outcome measures of each muscle action and change of direction tests. COD, Change of Direction time at 45° (COD45), 90° (COD90) and 180° (COD180) turn; RFD, Rate of Force Development. An asterisk (*) indicates $p < 0.05$; two asterisks (**) indicate $p < 0.001$.

The present study reinforces the existing literature's assertion that strength is an indispensable component for successful COD performance (Barrera-Domínguez et al., 2020; Young et al., 2002). Furthermore, it sheds light on the specific strength characteristics of each cutting angle. In this regard, for wide cutting angles of 45°, the concentric strength outcome measures had the greatest influence on COD performance. This could be explained by the emphasis on velocity in these shear angles (Bourgeois et al., 2017). Achieving optimal performance at 45° COD requires a primary focus on maintaining high speeds (Hader et al., 2015), characterised by ground contact times of less than 150 milliseconds and minimal braking forces (McBurnie & Dos'Santos, 2022). Thus, it makes sense that concentric strength is of great relevance in 45° COD.

Nevertheless, when performing COD with sharper cutting angles, the strength requirements undergo significant changes, and other strength outcome measures become increasingly influential on COD performance. Prior research has indicated that the mechanical characteristics of 90° and 180° cuts result in longer ground contact times in the final step, ranging from 250 to 500 milliseconds (McBurnie & Dos'Santos, 2022). The findings from the present study showed a strong relationship between isometric strength and COD performance at sharp angles. This relationship can be attributed to the need for the lower limbs to maintain isometrically longer reaction forces in the final step while the rest of the body undergoes reorganisation and redirection towards a new direction of displacement (Dos'Santos et al., 2021a).

In addition, it is known that 180° COD actions emphasise force-oriented characteristics (Bourgeois et al., 2017), demanding substantial braking and reacceleration forces for higher performance. The current results align with previous literature and show that the sharpest angles of 180° COD are the most force-demanding, with all assessed strength outcome measures serving as determinants in 180° COD. Finally, it is worth noting that among all the strength outcome measures obtained, eccentric pRFD showed the strongest relationship with COD and was the sole variable that exerted a significant impact on all cutting angles. COD actions are executed at maximal intensities and speeds with high external load demands, as demonstrated in recent studies that have recorded values of knee joint

TABLE 3 Comparison (mean ± SD) of the different strength ratios between *low performance* and *high performance* groups classified by each change of the direction test.

	COD 45°		COD 90°		COD 180°		*p value* (ES)		
	LP (n = 12)	HP (n = 13)	LP (n = 12)	HP (n = 13)	LP (n = 12)	HP (n = 13)	45°	90°	180°
Strength ratios									
E/I	1.04 ± 0.49	0.97 ± 0.38	0.92 ± 0.38	1.07 ± 0.47	1.06 ± 0.52	0.96 ± 0.34	*0.910* (0.162)	*0.361* (0.350)	*0.820* (0.214)
E/C	3.53 ± 1.37	2.45 ± 1.20	2.91 ± 1.58	3.02 ± 1.22	3.53 ± 1.58	2.44 ± 0.94	***0.035*** (0.834)	*0.650* (0.078)	*0.087* (0.743)
I/C	4.15 ± 2.04	2.59 ± 0.86	3.60 ± 2.03	3.06 ± 1.35	3.95 ± 1.81	2.76 ± 1.41	***0.026*** (1.026)	*0.649* (0.317)	***0.030*** (0.994)

Note: Bold indicates significant differences between groups $p < 0.05$.

Abbreviations: C, concentric; COD, change of direction; E, eccentric; ES, effect size; HP, high performance group; I, isometric; LP, low performance group.

angular velocities ranging from 469 to 493°/s during the deceleration phase before COD (Nedergaard et al., 2014). These elevated knee joint angular velocities underscore the paramount importance of rapid eccentric force production capacity and pre-activation of the knee extensors to facilitate early pRFD occurrence within the first 40 milliseconds of stance (data not shown).

Previous studies have highlighted the crucial role of eccentric muscle action in COD performance (Jones et al., 2017, 2022; Smajla et al., 2022), primarily due to substantial peaks in eccentric strength during braking actions. These peaks, reaching 168% higher than propulsive forces (Harper et al., 2022), emphasise the importance of eccentric strength. However, existing research often isolated eccentric muscle action without considering its interplay with other muscle actions or the specific COD tests performed. Our comprehensive study examined various strength outcome measures and scrutinised strength ratios across all muscle actions. Surprisingly, the swiftest players in COD exhibited higher concentric strength relative to eccentric and isometric strength, reflected in lower E/C and I/C ratios. This trend was evident in both sharper (180°) and shear (45°) cuts. These underscore the importance of possessing high concentric strength levels compared to other muscular actions for achieving superior performance in various COD angles. Although the capacity to rapidly apply eccentric strength during maximum deceleration at the COD is crucial (Harper et al., 2022), players demonstrating rapid eccentric force production with minimal disparities between eccentric and concentric strength excel across cutting angles. This highlights the multifaceted nature of COD performance, emphasising the importance of strength ratios for a more comprehensive assessment.

To the best of our knowledge, this study represents the first comprehensive analysis of the impact of different muscle actions assessed with FEMD on different cutting angles in basketball players. Even though the findings provide valuable insights into COD performance, it is essential to acknowledge several limitations inherent in our study. Firstly, all squats evaluated were performed bilaterally, while actual COD actions in basketball involve bilateral asymmetric or unilateral actions. Unilateral squat assessment with FEMD may be more specific and better simulate COD execution, which might lead to greater correlations, but may also show worse ICC and CV values. Secondly, the sample size is relatively small, which may restrict the generalisability of the findings to a larger population. Furthermore, it is important to note that due to the cross-sectional nature of our study, we cannot establish a cause-and-effect relationship. Nonetheless, it is worth mentioning that Barrera-Domínguez et al. (2023) reported improvements in COD performance at different angles in basketball players after an 8-week of individualised training program designed to enhance all strength outcome measures in the squat. This further reinforces the present research findings, adding valuable insights to the existing literature regarding the impact of diverse strength measures on COD. These insights may prove beneficial for coaches in devising more effective training programmes to enhance their athletes' COD performance.

5 | CONCLUSION

In conclusion, strength emerges as a pivotal factor influencing COD performance, and this study sheds light on intriguing discoveries in this domain. The results unequivocally demonstrated that the relationship between strength outcome measures and COD proficiency depends on the cutting angle. Specifically, cutting angles below 90° emphasise concentric strength, while those above 90° exhibit a stronger reliance on isometric and eccentric strength. Furthermore, rapid eccentric force production strongly correlates with COD performance across all cutting angles. However, the fastest players exhibit higher concentric strength relative to their eccentric strength. These findings are crucial for coaches seeking to improve their players' COD performance. Coaches should analyse the individual COD requirements, considering angle variations, and design tailored training programmes that focus on augmenting rapid eccentric force while aiming to reduce the E/C ratio. This strategic approach could optimise basketball players' COD abilities.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they do not have any conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, F.J.B.-D., upon reasonable request.

PATIENT CONSENT STATEMENT

Informed consent was obtained from all participants included in the study.

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Influence of functional movement, jump and linear speed on change of direction speed in female basketball players: Novel vs. traditional approaches

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Basketball Strength and Conditioning: A Look at Current Trends

Influence of Functional Movement, Jumping Ability and Linear Speed on Change of Direction Speed in Female Basketball Players: Novel vs. Traditional Approaches

by
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There is extensive discourse surrounding the factors influencing performance in change of direction (COD) actions in basketball, given the wide range of tests and methods that exist in the scientific literature for assessing this ability. This study analysed and compared relationships between functional movement, jumping and linear speed performance using two distinct methods of measuring COD performance in female basketball players, while also distinguishing between cut-off angles. Fifty female semi-professional basketball players (age: 23.7 ± 3.81 years, body height: 175.5 ± 7.69 cm; body mass: 64.4 ± 7.88 kg) participated in the assessment, involving various performance and COD tests. COD tests were categorised for each method and angulation into "low performance" and "high performance" groups, facilitating a Bayesian comparative analysis. For the traditional method of measurement (execution time) vertical (ES ≥ 0.66; BF_{10} ≥ 3.50) and horizontal (ES ≥ 0.97; BF_{10} ≥ 44.4) variables exhibited significant differences between performance groups across all cutting angles, with faster players performing better in all tests. For the novel approach (COD Deficit) differences between performance groups were only found for horizontal variables, while these differences disappeared for vertical variables. These findings suggest the need for caution when considering the determinants of COD performance, as these relationships are directly dependent on the COD method used. Therefore, female basketball coaches are encouraged to adopt the COD Deficit for assessing this ability, as it isolates COD from other abilities.

Keywords: *agility; multidirectional speed; key performance indicator; team sport; performance*

Introduction

Changes of direction (COD) and speed constitute actions that recur more than a thousand times during a women's basketball game (Matthew and Delextrat, 2009), responding to the game's specific demands (Sekulic et al., 2017). In basketball, 15.1% of COD actions are executed at maximum intensities (<−3.5 $m \cdot s^{-2}$) (Svilar et al., 2018). These high-intensity movements play a pivotal role in determining the final outcome of the match, given the fast-paced nature of the game and the brief duration of the decisive actions in both offensive and defensive scenarios. Consequently, enhancing COD abilities is deemed essential for gaining a physical edge over opponents in basketball (Brini et al., 2020), irrespective of the playing position and gender (Power et al., 2022). In addition, throughout a basketball game, COD are executed at a multitude of different angles, spanning from 0° to 180° (Gonzalo-Skok et al., 2023). For all these reasons, basketball coaches must be cognizant of the critical requirements for improving this skill and fostering the multidirectional speed development of their players.

COD represents a complex and multi-directional action, defined as the ability to decelerate and accelerate in a planned manner toward a new direction (Nimphius et al., 2018). Despite existing scientific literature highlighting the significance of ankle dorsiflexion, dynamic balance, linear speed, jumping ability, and the

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COD technique itself as determinants of COD performance (Barrera-Domínguez et al., 2020; Chaouachi et al., 2009; Hewit et al., 2013), a consensus remains elusive, leading to considerable controversy regarding which factors truly determine COD performance. In this regard, although prior studies with male basketball players have identified a relationship between quantitative movement tests, such as ankle dorsiflexion and dynamic balance, with COD (Gonzalo-Skok et al., 2015), others have failed to observe such a relationship (Barrera-Domínguez et al., 2020). Regarding speed, studies involving female basketball players demonstrate a robust association between linear speed and COD actions (Michael et al., 2021). However, conflicting findings exist, with some studies not observing this correlation (Nimphius et al., 2013, 2016). In terms of jumping, previous research suggests that plyometric exercises with a short stretch-shortening cycle are generally the most specific to COD actions (Falch et al., 2020a). Nevertheless, this relationship may not occur in female basketball players, where long stretch-shortening cycle and strength exercises might be more specific to COD performance (Barrera-Domínguez et al., 2024a).

The discrepancies in previous studies could be explained in different ways. On the one hand, the utilization of more than 48 different COD tests in studies with basketball players has been noted (Sugiyama et al., 2021). Specific characteristics of the different COD tests (i.e., approach distances, angulations, and numbers of cuts) may lead to different magnitudes of physical and technical requirements for each test (Nimphius et al., 2018), introducing a potential limitation when comparing data between studies. As COD performance is directly dependent on the cutting angle (Dos'Santos et al., 2018), the use of tests with different cutting angles directly affects the performance and test-influencing variables, adding complexity to data interpretation and comparison (Falch et al., 2020b; Nimphius et al., 2018). Consequently, it is not advisable to compare results between studies employing different COD tests. To enhance standardization, it is strongly recommended to employ several COD tests with a single cut at different angles and at the shortest possible approach distance (at least 5 m), aiming to minimise the influence of other physical qualities on the test and to create a "COD angle profile" of each player (Gonzalo-Skok et al., 2023; Nimphius et al., 2016). On the other hand, two distinct methods are currently employed to measure performance in COD tests. The traditional approach involves assessing total time or average velocity in the COD test, while the novel method, known as the change of direction deficit (CODD), seeks to quantify the time an athlete spends in the cutting action itself. CODD expresses the difference between the time it takes to complete a COD test and the time taken to cover the same distance in a straight line as a percentage. These data provide insight into the athlete's efficiency in executing COD actions relative to their linear speed (Freitas et al., 2021b). The use of total time or average velocity in the test may encompass other physical capabilities influencing the final result, such as linear speed, anaerobic capacity, and movement specificity for the test (Nimphius et al., 2013, 2016). In this sense, previous studies indicate that linear speed can contribute to as much as 74.8% of the total time in a COD test (Delextrat et al., 2017). Consequently, CODD has been proposed as a potentially more valid variable for evaluating COD performance (Freitas et al., 2021b; Nimphius et al., 2013, 2016), as it accurately reflects the targeted physical quality (i.e., COD performance), eliminating the influence of other physical qualities on the test result.

Women's competitive sport has been on the rise in recent years, which contrasts with the current underrepresentation of women in research within sport and exercise sciences (Anderson et al., 2023). Therefore, observing the lack of consensus in the scientific literature (Michael et al., 2021; Nimphius et al., 2013, 2016) regarding the most determining physical factors in COD actions for female basketball players, a study is needed that analyses the relationship between the different performance variables and COD performance using both prevalent methods for evaluating performance in these actions, total test time and CODD. Therefore, the present study aimed to analyse and compare the relationships among functional movement, jump and linear speed performance using two different methods of measuring COD performance in female basketball players, with a focus on differentiating between cut-off angles. It was hypothesized that measuring COD performance using total test time would result in a significant relationship between

functional movement, linear speed, jumping ability and COD performance. However, using the CODD as a "gold-standard" method for assessing COD performance, the observed relationship between the analysed performance variables and COD might diminish.

Methods

Participants

Fifty highly trained, national level female basketball players (age: 23.7 ± 3.81 years, body height: 175.5 ± 7.69 cm; body mass: 64.4 ± 7.88 kg) competing at the same level in the Spanish N1 Female League were recruited to voluntarily partake in this study. The sample size was calculated using G*Power software (version 3.1.9.6, Kiel, Germany). The number of participants to be included in the study was calculated based on the statistical method used to identify the differences between groups (independent *t*-test). This calculation was based on a large effect size (f) of 0.8, an alpha level of 0.05, and power value of 0.80 (Faul et al., 2007). Inclusion criteria for participants encompassed a minimum of 6 months without lower limb injury prior to the assessment, consistent training of at least 3 days a week throughout the season, in addition to participation in competitive games, and a minimum of 10 years of basketball playing experience. All participants were thoroughly briefed of the possible risks and benefits of study participation, and before the beginning of testing, they provided written consent. This research was approved by the Andalusian Biomedical Research Ethics Committee (protocol code FBD_UHU2020; approval date: 08 October 2020) in adherence to the principles outlined in the Declaration of Helsinki.

Design and Procedures

A cross-sectional experimental design was employed to analyse and compare the relationships between functional movement, linear speed and jumping ability using two distinct methods of measuring COD performance in female basketball players, with consideration given to different cut-off angles. COD tests included a single cut and the shortest possible approach distance, to minimise the influence of other physical qualities on the test (Gonzalo-Skok et al., 2023; Nimphius et al., 2016). Furthermore, COD tests were performed at different angulations as performance in these actions is directly dependent on the cutting angle (Dos'Santos et al., 2018). All players were tested in a trained state because data collection was carried out during the last phase of the competitive season.

Participants underwent the evaluation during two separate testing sessions, with a 48-h interval between them. All assessments took place on a basketball court just before each training session, scheduled between 19:00 and 21:00, under consistent conditions. A familiarization protocol with submaximal attempts of the proposed tests was executed the previous week. Prior to the evaluation sessions, a 10-min warm-up was conducted, commencing with a general activation including light-intensity jogging, a series of dynamic stretching exercises, and several accelerations, followed by specific potentiation exercises. Additionally, participants were instructed to attend the testing sessions with adequate hydration and rest, refraining from high-intensity training in the preceding 24 h. Moreover, they were advised to regulate their caffeine and food intake at least 3 h before each evaluation.

Measures

The first testing session was dedicated to quantitative movement tests: a weight-bearing dorsiflexion test (WB-DF) and a Y-Balance Test (YBT), as well as vertical jump tests: a unilateral Countermovement Jump (uCMJ) and a unilateral Drop Jump (uDJ). The second session included all horizontal tests: a 10-m sprint and CODs at different angles (a 505 modified test at 45°, 90° and 180°), and a unilateral Triple Hop Test (uTHT). All players performed a total of three attempts of each test with a two-minute rest interval in between. The mean of all attempts for each test was used for further analysis.

Weight-Bearing Dorsiflexion Test (WB-DF)

The WB-DF was carried out with My ROM App (Apple Inc., Cupertino, CA, USA) (Balsalobre-Fernández et al., 2019) by placing the mobile device on the anterior tibial crest, just below the tibial tuberosity, and provided the results in degrees. Each player placed their hands on their hips, as well as the foot to be measured in front and the opposite foot resting just behind. In this position, participants were instructed to lunge forward until their knee reached the maximum range of movement. The heel was required to always

remain in contact with the floor (Figure 1A). Players were barefoot for the measurement.

Y-Balance Test (YBT)

Dynamic balance was assessed by the YBT using the OctoBalance device (OctoBalance, Check your Motion, Albacete, Spain). While maintaining a balanced position on one foot on the platform, each player had to reach the maximum possible distance in three directions: anterior, posterolateral and posteromedial (Figure 1B). All attempts were supervised by researchers and were considered valid if 1) the heel rested on the back edge of the platform and the second metatarsal was on the front line, 2) the hands were placed on the hips, and 3) the reaching foot only stayed on the platform (Onofrei et al., 2019).

Unilateral Countermovement Jump (uCMJ) and unilateral Drop Jump (uDJ)

Jump height in uCMJ and uDJ tests was determined using a Chronojump contact platform (Chronojump BoscoSystem®, Barcelona, Spain) (De Blas et al., 2012). Before testing, participants started with an initial position with one foot on the mat for the uCMJ and from a 25-cm step for the uDJ, then each athlete landed with the same foot on the mat. Athletes were instructed to achieve their maximum jump height with the minimum contact time. The jump was considered valid if 1) the hands were not separated from the hips at any time, 2) the knees were not bent during the flight time, and 3) the athlete landed with only one foot on the same point from which they jumped, holding the position for at least 2 s. In addition, the uDJ was used to calculate the reactive strength index (RSI) of each leg using the flight time/contact time ratio for each jump (Markwick et al., 2015).

Triple Hop Test Unilateral

The elastic-reactive force in a horizontal orientation was evaluated through the horizontal triple jump test using a metric tape measure (Hamilton et al., 2008). The test started when the player stood with one leg supported just behind the starting line. After performing three consecutive maximum forward jumps with the same leg, the investigator measured the total distance jumped from the take-off line to the nearest point of landing contact (i.e., back of the heels). Arm swinging was allowed, and attempts were considered failed and thus, then repeated if: 1) the test was not completed as previously described, 2) balance was lost during any part of the test, or 3) the final position could not be maintained on one leg for at least two seconds.

Linear (10-m Sprint) and COD (505 Modified at 45º, 90º and 180º) Speed Test

Execution time for speed tests was measured by Chronojump single beam timing cells (Chronojump BoscoSystem®, Barcelona, Spain). The timing cells were placed 2 m from each other with a height of 1.10 m (approximately the height of the players' hips). Before the start of the test, each player was positioned 0.5 m behind the first gate, in a two-point split stance (i.e., starting position with the preferred foot forward and placed exactly 0.5 m behind the starting line). Then, each player accelerated at maximum speed to the second gate located 10 m away for all the tests, in a straight line for the linear test and with a turning point at 5 m where each athlete performed a COD45º, COD90º and COD180º to reach the second gate in the shortest possible time. COD at 45°, 90° and 180° were performed on both sides and laterality was defined by the leg on which participants set on the court when performing the COD mechanics (Cuthbert et al., 2019). The CODD for each angulation (45º, 90º and 180º) was calculated using the formula: ([COD test time – 10-m sprint time] / 10-m sprint time) * 100 (Freitas et al., 2021b); all time variables were reported in seconds.

Statistical Analysis

The assumption of normality was verified using the Shapiro-Wilk test. Means ± standard deviations (SD) were used to describe variables. The relative and absolute reliability of the tests was evaluated by the intraclass correlation coefficient (ICC) and the coefficient of variation (CV). A median cut-off score was established for each method of determining COD performance and for each COD angulation, thus separating participants according to their performance to each angulation based on the method used. The *High Performance* (HP) group included athletes with a performance above the 50th percentile in each COD test. The *Low Performance* (LP) group consisted of players with a performance below the 50th percentile in each COD test. The Bayesian student's *t*-test for independent samples was used to assess differences between performance groups with regard to both methods,

execution time and CODD. Evidence for the alternative hypothesis (H_1) was set as BF_{10} >1 and evidence for null hypothesis (H_0) was set as BF10 <1. BF_{10} was reported to indicate the strength of the evidence for each analysis. The BF_{10} was interpreted using the following evidence categories: 1 < BF_{10} < 3 = anecdotal evidence for H_1; BF_{10} ≥ 3 = moderate; BF_{10} ≥ 10 = strong; BF_{10} ≥ 30 = very strong; BF_{10} ≥ 100 = extreme (Lee and Wagenmakers, 2013). To explore the physical determinants of execution time and CODD, bayesian regression analyses were conducted. R squared was evaluated as < 0.04 trivial, 0.04–0.25 small, 0.25–0.64 moderate, and > 0.64 strong effect (Cohen, 1988). JASP software, version 0.18.1 (Amsterdam, Netherland) for Macintosh, was used for all statistical analyses.

Results

Table 1 displays mean ± SD values of the assessed variables, along with the ICC and the CV for each. The relative and absolute reliability of the tests was confirmed (ICC ≥ 0.86; CV ≤ 9.89).

The comparison between LP and HP groups in execution time during the COD test for each evaluated performance variable is presented in Table 2. When test execution time served as a measure of COD performance, moderate to extreme evidence supporting differences between groups in vertical jump variables were observed with large effect sizes (ES; ES ≥ 0.66; BF_{10} ≥ 3.50) for all cutting angles. Horizontal variables (sprint and uTHT) exhibited very strong to extreme differences between groups and a larger ES (ES ≥ 0.97; BF_{10} ≥ 44.4) for each angulation, with faster players performing better in all tests. However, no differences were found in functional movement variables between LP and HP groups based on the time of execution of the COD tests. On the other hand, Table 3 outlines differences between each performance variable when CODD was considered as the measure of the COD performance ranking. In that instance, all previously observed differences between performance groups for vertical strength variables disappeared. For CODD45º, moderate evidence supporting differences between groups were found in the linear sprint (BF_{10} = 6.35; ES = 0.72), with players who being more efficient in COD, were slower in linear speed. However, for CODD90° and CODD180°, these differences between groups were found exclusively in the execution time of the COD tests at their respective angles (BF_{10} ≥ 10.1; ES ≥ 0.78), with the most efficient players in COD being the fastest in these actions.

The results of a linear regression analysis, elucidating the variance and properties of each physical variable assessed based on both methods of measuring COD performance are reported in Table 4. All vertical and horizontal strength variables examined showed a significant linear relationship with COD (BF_M ≥ 7.897) at every angulation, being linear speed the one that best explained the variance in COD performance (R^2 ≥ 0.471; BF_M > 100) when execution time was taken as a reference measure. Moreover, a one second improvement in linear speed was associated with 0.681, 1.043 and 1.255 s of COD improvement at 45º, 90º and 180º, respectively. This finding contrasts with the relationships found between the strength variables assessed and the CODD. Specifically, only the time in the COD tests at their respective angles showed a significant relationship (R^2 ≥ 0.409; BF_M > 100) with CODD90º and CODD180º, and the time in the linear speed test was related to CODD at 45º (R^2 = 0.249; BF_M ≥ 56.50).

Discussion

Identifying the key factors influencing COD performance is crucial for strength and conditioning coaches who seek to enhance athletes' efficacy in these decisive actions during a basketball game. However, prior to understanding the determinants of COD, it is imperative to analyse the best method for assessing COD performance. Accordingly, the present study undertook an analysis and comparison of the association of functional movement variables, linear velocity and jumping ability considering two distinct methods for measuring COD performance in female basketball players, differentiating between cut-off angles. The main finding of this study is that variables frequently related to COD performance such as dynamic balance (Lockie et al., 2016), linear velocity (Michael et al., 2021; Young et al., 2015), and jumping ability (Barrera-Domínguez et al., 2020; Spiteri et al., 2015), demonstrated a relationship with COD performance when assessed through the traditional method (i.e., execution time in the test). However, this relationship disappeared when

COD performance was assessed with a novel approach (i.e., CODD). Furthermore, CODD (90º and 180º) exhibited no relationship with linear speed. Consequently, it would be recommended to use this novel method as the preferred approach for evaluating performance in these actions, effectively isolating the COD capacity from other physical abilities that might influence test outcomes.

Table 1. Descriptive analysis (Mean ± SD) and within session reliability of each performance variable analysed.

Variables	Mean ± SD	Q1	Q3	ICC	CV
Functional Movement					
WB-DF R (◦)	42.6 ± 5.97	37.8	47.0	0.99	1.08
WB-DF L (◦)	42.5 ± 5.64	37.6	46.8	0.98	1.29
YBT R (cm)	62.2 ± 8.76	54.9	68.0	0.92	2.97
YBT L (cm)	62.6 ± 8.70	55.3	68.7	0.89	3.81
Vertical Force-Vector					
uCMJ R (cm)	11.1 ± 3.31	9.36	13.3	0.98	5.41
uCMJ L (cm)	11.1 ± 3.47	8.90	12.6	0.88	9.67
uDJ R (cm)	11.0 ± 2.93	8.93	13.7	0.86	9.89
uDJ L (cm)	10.9 ± 3.07	8.88	12.8	0.93	7.12
RSI R	0.68 ± 0.18	0.56	0.78	0.92	8.75
RSI L	0.67 ± 0.17	0.57	0.75	0.95	7.86
Horizontal Force-Vector					
uTHT R (m)	4.61 ± 0.54	4.22	5.03	0.93	3.82
uTHT L (m)	4.64 ± 0.59	4.23	4.93	0.93	3.89
10-m sprint (s)	2.01 ± 0.12	1.91	2.09	0.97	1.35
Change of Direction Test					
COD45º R (s)	2.14 ± 0.12	2.03	2.21	0.95	1.36
COD45º L (s)	2.13 ± 0.14	2.02	2.23	0.91	3.16
COD90º R (s)	2.42 ± 0.20	2.25	2.55	0.88	3.48
COD90º L (s)	2.42 ± 0.21	2.27	2.57	0.87	3.65
COD180º R (s)	2.95 ± 0.25	2.76	3.14	0.97	1.55
COD180º L (s)	2.95 ± 0.26	2.77	3.11	0.96	1.86

Abbreviations: WB-DF: weight-bearing dorsiflexion; R: right; L: left; º: degree; YBT: Y-balance test including all directions; cm: centimeters; uCMJ: unilateral countermovement jump; uDJ: unilateral drop jump; RSI: reactive strength index; uTHT: unilateral triple hop test; m: meter; s: seconds; COD: change of direction; SD: standard deviation; Q1: quartile 1; Q3: quartile 3; ICC: intraclass correlation coefficient; CV: coefficient of variation

Table 2. Differences in performance of quantitative movements and strength in different force-vectors between slow (LP) and fast (HP) basketball players in 505 modified tests at 45º, 90º and 180º.

Variables	LP (n = 25)	HP (n = 25)	Mean Difference (CL 90%)	BF_{10}	ES (CI 95%)	Evidence
	Mean ± SD	Mean ± SD				
			COD 45º			
Quantitative Movement						
WB-DF (º)	41.1 ± 6.19	43.3 ± 4.89	–2.12 (–4.93; 0.70)	0.56	–0.30 (–0.87; 0.22)	Anecdotal
YBT (cm)	61.2 ± 7.68	63.2 ± 9.57	–1.96 (–6.62; 2.71)	0.37	–0.17 (–0.74; 0.37)	Anecdotal
Vertical Force-Vector						
uCMJ (cm)	9.22 ± 3.09	12.9 ± 2.58	–3.71 (–5.20; –2.22)	152.4	–1.18 (–1.88; –0.49)	**Extreme**
uDJ (cm)	9.41 ± 2.56	12.3 ± 2.78	–2.91 (–4.34; –1.49)	24.1	–0.94 (–1.62; –0.29)	**Strong**
RSI	0.59 ± 0.13	0.72 ± 0.17	–0.13 (–0.21; –0.05)	4.64	–0.71 (–1.36; –0.10)	**Moderate**
Horizontal Force-Vector						
uTHT (m)	4.29 ± 0.37	4.92 ± 0.49	–0.63 (–0.85; –0.41)	923.2	–1.31 (–1.98; –0.64)	**Extreme**
10-m sprint (s)	2.09 ± 0.11	1.93 ± 0.09	0.16 (0.11; 0.21)	4300	1.47 (0.78; 2.16)	**Extreme**
CODD 45º (%)	7.11 ± 4.18	5.38 ± 4.61	1.73 (–0.48; 3.93)	0.59	0.31 (–0.21; 0.88)	Anecdotal
			COD 90º			
Quantitative Movement						
WB-DF (º)	42.0 ± 6.32	42.5 ± 5.00	–0.49 (–3.36; 2.38)	0.31	–0.07 (–0.60; 0.46)	Moderate
YBT (cm)	63.3 ± 9.21	61.6 ± 8.49	1.60 (–3.07; 6.27)	0.35	0.14 (–0.40; 0.70)	Anecdotal
Vertical Force-Vector						
uCMJ (cm)	9.35 ± 3.31	1282 ± 2.52	–3.47 (–5.00; –1.94)	58.5	–1.06 (–1.75; –0.39)	**Very Strong**
uDJ (cm)	9.60 ± 2.94	12.2 ± 2.65	–2.58 (–4.05; –1.11)	8.29	–0.79 (–1.45; –0.17)	**Moderate**
RSI	0.59 ± 0.17	0.72 ± 0.14	–0.13 (–0.21; –0.04)	4.05	–0.68 (–1.33; –0.08)	**Moderate**
Horizontal Force-Vector						
uTHT (m)	4.31 ± 0.40	4.90 ± 0.50	–0.59 (–0.82; –0.36)	267.2	–1.17 (–1.84; –0.52)	**Extreme**
10-m sprint (s)	2.08 ± 0.11	1.95 ± 0.02	0.13 (0.07; 0.18)	77.3	1.03 (0.40; 1.68)	**Very Strong**
CODD 90 º (%)	24.6 ± 6.51	16.4 ± 4.69	8.20 (5.36; 11.0)	1088	1.35 (0.66; 2.00)	**Extreme**
			COD 180º			
Quantitative Movement						
WB-DF (º)	41.9 ± 6.24	42.5 ± 4.98	–0.59 (–3.45; 2.27)	0.31	–0.08 (–0.62; 0.44)	Moderate
YBT (cm)	61.2 ± 9.61	63.3 ± 8.02	–2.06 (–6.70; 2.58)	0.38	–0.18 (–0.75; 0.36)	Anecdotal
Vertical Force-Vector						
uCMJ (cm)	9.69 ± 3.31	12.7 ± 2.74	–2.99 (–4.59; –1.40)	12.8	–0.85 (–1.52; –0.22)	**Strong**
uDJ (cm)	9.84 ± 2.98	12.1 ± 2.72	–2.25 (–3.75; –0.75)	3.50	–0.66 (–1.30; –0.06)	**Moderate**
RSI	0.66 ± 0.22	0.67 ± 0.10	–0.01 (–0.10; 0.08)	0.31	–0.05 (–0.60; 0.49)	Moderate
Horizontal Force-Vector						
uTHT (m)	4.35 ± 0.44	4.87 ± 0.51	–0.51 (–0.75; –0.27)	38.7	–0.95 (–1.59; –0.33)	**Very Strong**
10-m sprint (s)	2.08 ± 0.12	1.95 ± 0.11	0.12 (0.07; 0.18)	44.4	0.97 (0.34; 1.61)	**Very Strong**
CODD 180º (%)	52.1 ± 7.09	41.5 ± 7.29	10.5 (6.92; 14.1)	1232	1.34 (0.67; 2.02)	**Extreme**

Abbreviations: WB-DF: weight-bearing dorsiflexion; º: degree; YBT: Y-balance test; cm: centimeters; uCMJ: unilateral countermovement jump; uDJ: unilateral drop jump; RSI: reactive strength index; uTHT: unilateral triple hop test; m: meter; s: seconds; CODD: change of direction deficit; COD: change of direction; LP: low performance; HP: high performance; SD: standard deviation; CL: confidence limits; ES: effect size; CI: credible interval. Bold evidences the alternative hypothesis (H1)

Table 3. Differences in performance of quantitative movements and strength in different force-vectors between less (LP) and more (HP) efficient basketball players in 505 modified tests at 45º, 90º and 180º.

Variables	LP (n = 25)	HP (n = 25)	Mean Difference (CL 90%)	BF_{10}	ES (CI 95%)	Evidence
	Mean ± SD	Mean ± SD				
			CODD 45º			
Quantitative Movement						
WB-DF (º)	41.5 ± 5.31	43.0 ± 5.86	–1.57 (–4.41; 1.27)	0.42	–0.22 (–0.78; 0.30)	Anecdotal
YBT (cm)	61.5 ± 7.23	63.1 ± 10.1	–1.64 (–6.28; 3.00)	0.35	–0.14 (–0.70; 0.39)	Anecdotal
Vertical Force-Vector						
uCMJ (cm)	11.1 ± 3.44	11.5 ± 3.32	–0.33 (–2.11; 1.45)	0.32	–0.07 (–0.63; 0.46)	Moderate
uDJ (cm)	11.3 ± 3.03	10.8 ± 3.08	0.52 (–1.09; 2.13)	0.34	0.13 (–0.40; 0.69)	Anecdotal
RSI	0.63 ± 0.14	0.69 ± 0.19	–0.06 (–0.15; 0.03)	0.52	–0.29 (–0.87; 0.26)	Anecdotal
Horizontal Force-Vector						
uTHT (m)	4.59 ± 0.53	4.65 ± 0.56	–0.59 (–0.33; 0.21)	0.31	–0.08 (–0.62; 0.43)	Moderate
10-m sprint (s)	1.96 ± 0.11	2.06 ± 0.13	–0.10 (–0.16; –0.04)	6.35	–0.72 (–1.33; –0.14)	**Moderate**
COD 45º (s)	2.15 ± 0.12	2.12 ± 0.12	0.03 (–0.03; 0.09)	0.39	0.20 (–0.32; 0.74)	Anecdotal
			CODD 90º			
Quantitative Movement						
WB-DF (º)	42.4 ± 5.35	42.1 ± 5.91	0.21 (–2.65; 3.08)	0.30	0.03 (–0.50; 0.56)	Moderate
YBT (cm)	62.0 ± 7.86	62.7 ± 6.69	–0.67 (–5.33; 3.99)	0.31	–0.06 (–0.61; 0.48)	Moderate
Vertical Force-Vector						
uCMJ (cm)	10.9 ± 3.11	11.7 ± 3.6	–0.82 (–2.59; 0.94)	0.39	–0.19 (–0.76; 0.35)	Anecdotal
uDJ (cm)	11.4 ± 3.06	10.7 ± 3.03	0.64 (–0.96; 2.25)	0.37	0.16 (–0.37; 0.72)	Anecdotal
RSI	0.65 ± 0.15	0.68 ± 0.18	–0.03 (–0.12; 0.06)	0.36	–0.15 (–0.71; 0.39)	Anecdotal
Horizontal Force-Vector						
uTHT (m)	4.52 ± 0.43	4.71 ± 0.62	–0.19 (–0.46; 0.08)	0.52	–0.28 (–0.84; 0.24)	Anecdotal
10-m sprint (s)	2.00 ± 0.12	2.03 ± 0.13	–0.03 (–0.10; 0.03)	0.40	–0.20 (–0.75; 0.32)	Anecdotal
COD 90º (s)	2.51 ± 0.20	2.34 ± 0.16	0.16 (0.07; 0.26)	10.1	0.78 (0.19; 1.40)	**Strong**
			CODD 180º			
Quantitative Movement						
WB-DF (º)	41.7 ± 5.47	42.8 ± 5.79	–1.06 (–3.91; 1.80)	0.35	–0.14 (–0.69; 0.38)	Anecdotal
YBT (cm)	60.7 ± 8.31	64.0 ± 9.06	–3.32 (–7.89; 1.26)	0.55	–0.30 (–0.88; 0.24)	Anecdotal
Vertical Force-Vector						
uCMJ (cm)	10.9 ± 2.95	11.7 ± 3.75	–0.71 (–2.48; 1.06)	0.37	–0.16 (–0.73; 0.37)	Anecdotal
uDJ (cm)	11.2 ± 2.76	10.9 ± 3.36	0.23 (–1.38; 1.84)	0.31	0.06 (–0.48; 0.60)	Moderate
RSI	0.68 ± 0.20	0.65 ± 0.13	0.03 (–0.05; 0.12)	0.36	0.15 (–0.38; 0.72)	Anecdotal
Horizontal Force-Vector						
uTHT (m)	4.47 ± 0.45	4.77 ± 0.59	–0.30 (–0.57; –0.04)	1.33	–0.48 (–1.06; 0.06)	**Anecdotal**
10-m sprint (s)	2.00 ± 0.11	2.02 ± 0.14	–0.02 (–0.09; 0.04)	0.34	–0.13 (–0.67; 0.38)	Moderate
COD 180º (s)	3.07 ± 0.21	2.82 ± 0.22	0.25 (0.14; 0.36)	87.1	1.05 (0.41; 1.70)	**Very Strong**

Abbreviations: WB-DF: weight-bearing dorsiflexion; º: degree; YBT: Y-balance test; cm: centimeters; uCMJ: unilateral countermovement jump; uDJ: unilateral drop jump; RSI: reactive strength index; uTHT: unilateral triple hop test; m: meter; s: seconds; COD: change of direction; CODD: change of direction deficit; LP: low performance; HP: high performance; SD: standard deviation; CL: confidence limits; ES: effect size; CI: credible interval. Bold evidences the alternative hypothesis (H1)

Table 4. Bayesian linear regression analysis showing the properties of each physical variable assessed in both COD performance measurement methods.

Independent variable	P (M|data)	Mean (95% CI)	BF_M	R^2	P (M|data)	Mean (95% CI)	BF_M	R^2
	COD 45º (s)				CODD 45º (%)			
uCMJ	0.995	–0.018 (–0.03; –0.01)	>100	0.319	0.235	0.004 (–0.16; 0.27)	0.307	<0.001
uDJ	0.992	–0.019 (–0.03; –0.01)	>100	0.302	0.314	0.058 (–0.08; 0.48)	0.457	0.025
RSI	0.930	–0.258 (–0.44; 0.00)	13.30	0.206	0.300	–0.910 (–7.81; 2.75)	0.428	0.021
uTHT	1.000	–0.001 (–0.01; –0.00)	>100	0.429	0.236	<0.001 (–0.02; 0.01)	0.308	0.003
10-m sprint	1.000	0.681 (0.51; 0.86)	>100	0.574	0.983	–15.22 (–25.9; –5.13)	56.50	0.249
CODD/COD 45	0.354	0.001 (–0.01; 0.01)	0.549	0.035	0.354	1.993 (–2.68; 12.6)	0.549	0.035
	COD 90º (s)				CODD 90º (%)			
uCMJ	0.995	–0.029 (–0.05; –0.02)	>100	0.318	0.414	–0.162 (–0.79; 0.16)	0.708	0.052
uDJ	0.968	–0.026 (–0.05; –0.01)	29.82	0.243	0.240	–0.021 (–0.45; 0.37)	0.317	0.002
RSI	0.661	–0.207 (–0.60; 0.01)	1.952	0.109	0.282	–1.195 (–11.3; 5.27)	0.393	0.016
uTHT	1.000	–0.002 (–0.01; –0.00)	>100	0.481	0.861	–0.038 (–0.07; 0.00)	6.430	0.157
10-m sprint	1.000	1.043 (0.70; 1.35)	>100	0.501	0.253	–0.984 (–13.8; 5.51)	0.339	0.008
CODD/COD 90	1.000	0.017 (0.01; 0.02)	>100	0.409	1.000	21.09 (13.1; 29.3)	>100	0.409
	COD 180º (s)				CODD 180º (%)			
uCMJ	0.965	–0.030 (–0.05; 0.00)	27.55	0.240	0.306	–0.100 (–0.83; 0.20)	0.442	0.023
uDJ	0.888	–0.026 (–0.048; 0.00)	7.897	0.181	0.235	0.008 (–0.49; 0.58)	0.307	<0.001
RSI	0.321	–0.061 (–0.45; 0.11)	0.472	0.027	0.254	0.898 (–4.75; 13.9)	0.341	0.007
uTHT	1.000	–0.003 (–0.01; –0.00)	>100	0.389	0.600	–0.024 (–0.08; 0.00)	1.499	0.087
10-m sprint	1.000	1.255 (0.81; 1.66)	>100	0.471	0.259	–1.417 (–15.9; 8.64)	0.350	0.010
CODD/COD 180	1.000	0.017 (0.01; 0.02)	>100	0.430	1.000	22.22 (14.4; 31.1)	>100	0.430

Abbreviations: uCMJ: unilateral countermovement jump; uDJ: unilateral drop jump; RSI: reactive strength index; uTHT: unilateral triple hop test; COD: change of direction; CODD: change of direction deficit

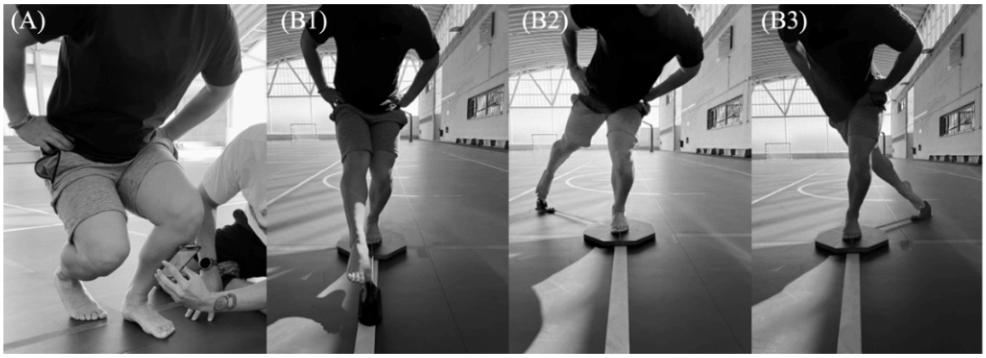

Figure 1. Weight-bearing dorsiflexion test (A) conducted using My ROM App (Apple Inc., Cupertino, CA, USA). Dynamic balance assessment by the Y-balance test (B): anterior reach (B1), posterolateral (B2) and posteromedial (B3) using the OctoBalance device (OctoBalance, Check your Motion, Albacete, Spain).

Previous research on COD in sport sciences has highlighted the complexity of COD actions which depend on a multitude of technical and physical factors (Sheppard and Young, 2006; Young et al., 2002). However, these findings and conclusions may be due to the way COD has been assessed. Frequently, maneuverability tests have been used. Tests where a variety of movements and COD at different angles are performed, with execution time often employed as the primary metric for assessing the tests results (Nimphius et al., 2018). The execution time in such tests could be influenced by linear speed, anaerobic capacity or the specificity of the movements, potentially masking the player's real ability to perform a COD. In this regard, previous studies (Nimphius et al., 2013, 2016) indicate that the time spent exclusively on COD in these tests is less than 30% of the total test time, allowing athletes with high linear sprinting ability to compensate for potential COD deficiencies (Sayers, 2015). Controlling performance through execution time might not explain a player's COD performance, leading to a need for caution in interpreting previous studies that analysed the determinants of COD performance using the execution time of a maneuverability test as a measure of performance.

In the present study, COD was evaluated using a simplified approach involving a single cut at different angulations. Even with this simplification, significant differences between methods emerged when identifying COD determinants. The results of this study showed a relationship between the traditional method of measuring COD through execution time with the linear speed and jumps regardless of the cutting angle, consistent with findings in previous research (Sheppard and Young, 2006; Young et al., 2002). The RSI showed a strong relationship with COD performance at wide angles, but it was the only variable that showed no relationship with the execution time in COD180º. This may be due to the fact that at these sharper angles, the ground contact times are longer (>400 ms) (McBurnie and Dos'Santos, 2022), with other force variables being more decisive in this instance (Barrera-Domínguez et al., 2024b).

Although COD performance is significantly related to neuromuscular performance as indicated by previous scientific literature (Pereira et al., 2018) and the results so far, when the novel method of measuring COD performance (i.e., CODD) was used as a reference, all previously observed relationships between vertical jump variables and COD disappeared. Large relationships were found between CODD and vertical jump performance in female handball players (Pereira et al., 2018), but in the current study with female basketball players such a relationship between the vertical jump and CODD was not observed. This could be explained due to the sport played by the sample or the different COD tests assessed. Finally, although previous research has found relationships between functional movement variables and COD performance in male basketball players (Gonzalo-Skok et al., 2015), the results of the current study showed no differences between performance groups in any of the COD performance methods examined. Although CODs are complex actions that are executed unilaterally and require adequate lower limb mobility and stability (Gonzalo-Skok et al., 2015), the findings of this study along with previous research (Barrera-Domínguez et al., 2020) may indicate a limited contribution of these functional movement variables to COD performance at any cutting angulation.

On the other hand, previous studies that have used CODD as a metric for assessing COD performance in female samples across different team sports (Freitas et al., 2022; Pereira et al., 2018) have reported significant associations between CODD and linear speed. However, others have not found this relationship between CODD and linear speed (Nimphius et al., 2013, 2016), indicating that CODD is a validated measure which isolates COD from other abilities that may influence the test results and provides more information about the trade-off between linear and multidirectional speed, asymmetries (Barrera-Domínguez, Jones, et al., 2024; Dos'Santos et al., 2019) and the effect of fatigue on these actions (Scanlan et al., 2021). Despite this controversy in the above findings, the current study's results present some additional evidence on the issue, being potentially explained by the specific COD angulation assessed. Performance in COD actions is directly dependent on the angulation of the cut (Dos'Santos et al., 2018). Given the inclusion of different simple COD tests, each featuring a single cut at different angulations in the present study, it was found that CODD at wider angulations exhibited a stronger

relationship with linear speed, whereas this relationship was not evident for sharper angles. This, along with the use of different COD assessment tests in previous studies, would explain the abovementioned controversy.

In the context of wider angulations, COD actions should prioritise maintaining maximum velocity while minimizing horizontal braking forces (Bourgeois et al., 2017). This suggests that athletes with higher linear speed could benefit from cutting angulations of less than 60° (Dos'Santos et al., 2018). Conversely, for CODD involving sharper cuts, this relationship with linear velocity disappeared. Such cuts are more force demanding, as the inertia of the movement must be drastically reduced in order to perform the COD efficiently (Bourgeois et al., 2017). Previous studies comparing between genders (Freitas et al., 2021a) have suggested that linearly faster and more powerful male athletes might obtain higher CODD before sharper cuts, given their need to manage greater sprint momentum prior to COD. However, this pattern was not observed in females, as they reached lower linear speeds and, consequently, lower sprint momentums. The present findings align with these observations, revealing no relationship between linear velocity and CODD in a female sample for sharper angulations. Thus, the use of CODD to measure COD performance in female basketball players could be recommended, as it isolates the COD action from other abilities that may influence the tests results.

Before concluding, some limitations should be considered when interpreting the findings of the current study. Firstly, due to the cross-sectional design of the study, a cause-effect relationship cannot be deduced. Secondly, it should be considered that the sample was composed exclusively of amateur female basketball players, thus it is recommended to be cautious when applying the data to other samples. Furthermore, given that we assessed strength variables frequently associated with the execution time in COD tests, these variables did not show large differences or associations with the novel approach. Therefore, it is recommended in future research to analyse other strength and biomechanical variables that may affect the efficiency of COD actions.

Conclusions

Although a multitude of tests and methods are currently available for assessing COD performance, the findings of this research indicate to practitioners that using CODD to assess this skill through simple COD tests with a single cut at various angles to create an individual "COD angle profile" may be the best way to isolate the COD action. Thus, strength and conditioning coaches could have a complete speed profile for each athlete and analyse the effect of the cut angle on performance of each female basketball player. In addition, it is advisable to exercise caution when considering factors frequently linked to COD performance, given that most prior studies have used test execution time to determine these relationships. As elucidated throughout this study, such relationships are directly dependent on the COD method and angulation assessed, thus generalizations are not advisable. Therefore, coaches and sport scientists are encouraged to use CODD and standardise COD assessments to determine in future research which factors most determine performance in this task.

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4.1.6. Results chapter 1

Table 10 summarises and categorises the relationships between the multiple dependent variables assessed (i.e., anthropometric variables, functional movement variables, strength in its different manifestations and muscle actions, and speed) and COD performance according to cutting angle in male and female basketball players.

Table 10. Correlation coefficients between anthropometry, functional movement, strength, and linear speed variables, with change of direction actions based on cutting angle and gender. Summary of the findings from the different studies of chapter 1.

Variables	COD 45º (s)		COD 90º (s)		COD 180º (s)	
	Male	Female	Male	Female	Male	Female
Anthropometric						
Body mass (kg)	−0.024[1]	0.164[5]	0.069[1]	0.022[5]	0.034[1]	0.143[5]
Body height (cm)	0.037[1]	−0.138[5]	0.042[1]	−0.148[5]	0.037[1]	−0.090[5]
BMI (kg/m^2)	0.165[1]	0.330[5]	−0.075[1]	0.168[5]	−0.048[1]	0.260[5]
Lean mass (kg)	−0.076[1]	–	−0.300[1]	–	−0.374[1]	–
Fat mass (%)	0.527[1**]	–	0.246[1]	–	0.384[1]	–
Functional movement						
WB-DF (º)	−0.128[1]	−0.180[5]	−0.008[1]	−0.037[5]	−0.011[1]	−0.029[5]
	−0.003[3]	−0.533[3**]	−0.152[3]	−0.282[3]	−0.217[3]	−0.299[3]
SEBT (cm)	−0.187[1]	–	−0.187[1]	–	−0.262[1]	–
YBT (cm)	−0.144[1]	−0.065[5]	−0.430[1*]	−0.037[5]	−0.231[1]	−0.048[5]
	−0.181[3]	−0.573[3**]	−0.015[3]	−0.607[3**]	0.018[3]	−0.625[3**]
Strength						
CMJ (cm)	−0.668[1**]	−0.462[5*]	−0.340[1]	−0.485[5*]	−0.462[1*]	−0.465[5*]
CMJu (cm)	−0.401[3]	−0.750[3**]	−0.417[3]	−0.792[3**]	−0.538[3*]	−0.684[3**]
DJu (cm)	−0.632[1**]	−0.550[5**]	−0.532[1**]	−0.493[5*]	−0.451[1*]	−0.426[5*]
	−0.488[3*]	−0.666[3**]	−0.455[3*]	−0.701[3**]	−0.511[3*]	−0.642[3**]
RSI	−0.446[1*]	−0.454[5**]	−0.465[1*]	−0.331[5*]	−0.579[1**]	−0.165[5]
	−0.252[3]	−0.493[3**]	−0.379[3]	−0.533[3**]	−0.318[3]	−0.307[3]
THTu (cm)	−0.295[1]	−0.655[5**]	−0.311[1]	−0.693[5**]	−0.036[1]	−0.624[5**]
	−0.397[3]	−0.679[3**]	−0.561[3**]	−0.655[3**]	−0.512[3*]	−0.640[3**]
F–V Imbalance	0.255[1]	−0.116[5]	0.603[1**]	0.065[5]	0.589[1**]	0.016[5]
F–V V0	0.219[1]	−0.177[5]	0.379[1]	−0.035[5]	0.530[1**]	−0.056[5]
F–V F0	−0.344[1]	−0.238[5]	−0.711[1**]	−0.165[5]	−0.621[1**]	−0.250[5]
F–V Pmax	0.097[1]	−0.310[5]	0.193[1]	−0.132[5]	0.342[1]	−0.194[5]

Abbreviations: BMI, Body mass index; WB-DF, Weight-bearing dorsiflexion; SEBT, Star excursion balance test; YBT, Y-balance test; CMJ, Countermovement jump; CMJu, Countermovement jump unilateral; DJu, Drop jump unilateral; RSI, Reactive strength index; THT, Triple hop test; F–V, Vertical force–velocity profile; V0, theoretical maximal unloaded velocity; F0, Theoretical maximal force; Pmax, Maximal power; Iso, Isometric; Con, Concentric; Ecc, Eccentric; MF, Mean force; PF, Peak force; RFD, Rate of force development; RHF, Ratio of the horizontal component of force during sprinting; COD, Change of direction. An asterisk (*) indicate significant correlation $p < 0.05$; and two asterisk (**) indicate significant correlation $p < 0.001$. Green indicates positive correlation. Red indicates negative correlation. Yellow indicate no correlation. [1] Data extracted from study 1 with male basketball players. [2] Data extracted from study 2 with male basketball and handball players. [3] Data extracted from study 3 with separate male and female basketball players. [4] Data extracted from study 4 with a mix of male and female basketball player. [5] Data extracted from study 5 with female basketball players.

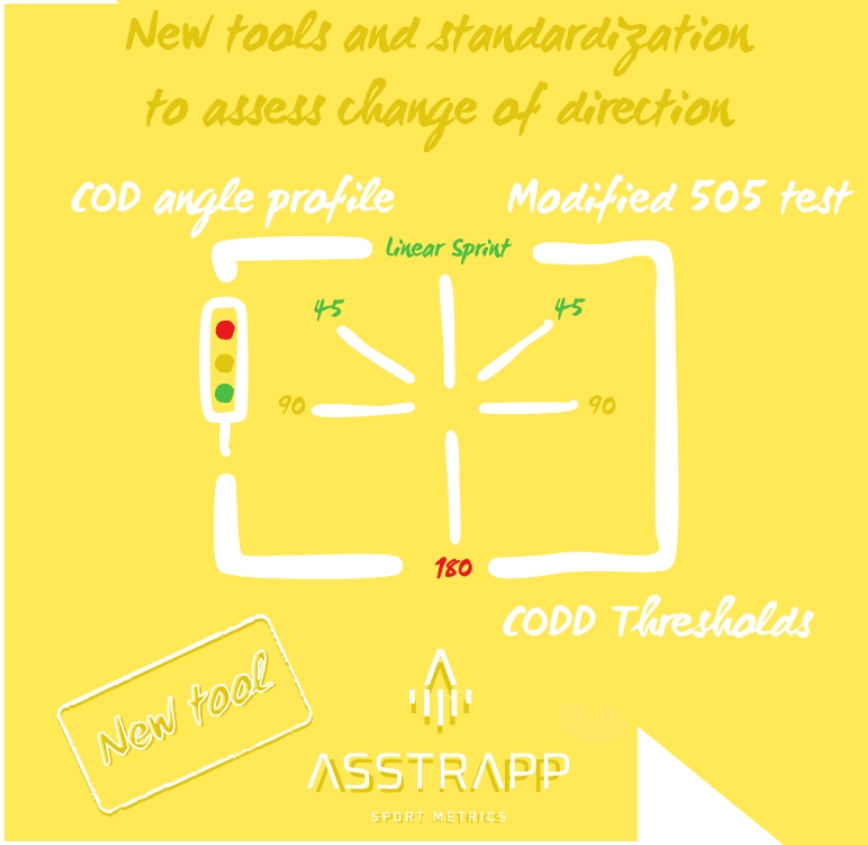
Table 10 (continued).

Variables	COD 45º (s)		COD 90º (s)		COD 180º (s)	
	Male	Female	Male	Female	Male	Female
Strength						
Iso MF (kg)	−0.324[4]		−0.394[4*]		−0.477[4*]	
Iso PF (kg)	−0.189[4]		−0.318[4]		−0.345[4]	
Iso Impulse (N·s)	−0.304[4]		−0.397[4*]		−0.445[4*]	
Iso RFD (N/s)	−0.221[4]		0.021[4]		−0.294[4]	
Con MF (kg)	−0.460[4*]		−0.314[4]		−0.551[4*]	
Con PF (kg)	−0.354[4]		−0.195[4]		−0.362[4]	
Con RFD (N/s)	−0.175[4]		−0.044[4]		−0.184[4]	
Ecc MF (kg)	−0.298[4]		−0.291[4]		−0.252[4]	
Ecc PF (kg)	−0.273[4]		−0.244[4]		−0.234[4]	
Ecc RFD (N/s)	−0.474[4*]		−0.469[4*]		−0.519[4*]	
Linear speed						
5 metres sprint (s)	0.176[1]	–	0.227[1]	–	0.476[1*]	–
10 metres sprint (s)	0.153[1]	0.758[5**]	0.233[1]	0.707[5**]	0.461[1*]	0.686[5**]
30 metres sprint (s)	0.355[1*]	–	0.441[1*]	–	0.537[1**]	–
RHF	−0.339[1]	–	−0.433[1*]	–	−0.470[1*]	–

Abbreviations: BMI, Body mass index; WB-DF, Weight-bearing dorsiflexion; SEBT, Star excursion balance test; YBT, Y-balance test; CMJ, Countermovement jump; CMJu, Countermovement jump unilateral; DJu, Drop jump unilateral; RSI, Reactive strength index; THT, Triple hop test; F–V, Vertical force–velocity profile; V0, theoretical maximal unloaded velocity; F0, Theoretical maximal force; Pmax, Maximal power; Iso, Isometric; Con, Concentric; Ecc, Eccentric; MF, Mean force; PF, Peak force; RFD, Rate of force development; RHF, Ratio of the horizontal component of force during sprinting; COD, Change of direction. An asterisk (*) indicate significant correlation p < 0.05; and two asterisk (**) indicate significant correlation p < 0.001. Green indicates positive correlation. Red indicates negative correlation. Yellow indicates no correlation. [1] Data extracted from study 1 with male basketball players. [2] Data extracted from study 2 with male basketball and handball players. [3] Data extracted from study 3 with separate male and female basketball players. [4] Data extracted from study 4 with a mix of male and female basketball player. [5] Data extracted from study 5 with female basketball players.

CHAPTER 2

New tools and standardization to assess change of direction



Study 6

Barrera-Domínguez, F. J., Jones, P. A., Almagro, B. J., & Molina-López, J. **(2024)**. Determination of change of direction deficit thresholds across a spectrum of angles in basketball players. *Journal of Sports Sciences*, 42 (7), 621-628.

Study 7

Barrera-Domínguez, F. J., Jones, P. A., Almagro, B. J., & Molina-López, J. **(2025)**. Validity and inter-device reliability of an artificial intelligence app for real-time assessment of 505 change of direction tests. *European Journal of Sport Science*, 25 (2), e12252.

STUDY 6

Journal of Sport Sciences (2024) — IF JCR 2.30 (Q2)

Determination of change of direction deficit thresholds across a spectrum of angles in basketball players

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Determination of change of direction deficit thresholds across a spectrum of angles in basketball players

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ABSTRACT

Change of direction deficit (CODD) offers valuable insights into a player's balance between linear and multidirectional speed. However, there are still no established reference values for CODD. The objectives of this study were to determine CODD thresholds for various change of direction angles in basketball players according to gender and analyse the relationships between CODD and execution time in speed tests. One hundred and thirty basketball players (46% female; age: 23.7 ± 5.29 years; height: 189.1 ± 11.1 cm; body mass: 84.3 ± 15.7 kg) undertook 10-m linear and change of direction speed test at 45º, 90º and 180º. A k-means cluster analysis was conducted to standardise CODD thresholds and a one-way analysis of variance to identify the differences between clusters. The results revealed angulation-specific CODD thresholds, ranging from 3% to 8%, 17% to 25% and 43% to 51% for 45º, 90º and 180º cutting angles, respectively for the pooled sample. Furthermore, differences inter-clusters ($p < 0.05$) were observed for execution time at all cutting angles for both genders. Therefore, strength and conditioning coaches are encouraged to assess CODD as a highly valid variable for evaluating change of direction performance and to use current CODD thresholds to tailor training programmes according to each athlete's needs.

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Multidirectional speed; agility; sprint; assessment; team sport; performance

1. Introduction

In team sports, high-intensity actions such as jumps, sprints and changes of direction (COD), are influential in the final outcome of a game (Delextrat et al., 2017). Among all these actions, the COD is the most frequently performed during a basketball game regardless of the playing position or gender (Salazar et al., 2020). COD are defined as the ability to decelerate and accelerate in different directions in a planned manner (Nimphius et al., 2016). Previous research indicates that basketball players perform a COD every 1–3 seconds (Klusemann et al., 2013; Scanlan et al., 2011), and that 15.1% of these actions are performed at maximum intensity (>3.5 $m \cdot s^{-2}$) (Svilar et al., 2018). In addition, basketball players must be able to perform a COD at a wide range of angles (between 0º and 180°) during a game regardless of their playing position (Gonzalo-Skok et al., 2023; Power et al., 2022). In this regard, the cutting angle is one of the most decisive variables in the performance of these actions in order to evade an opponent (Dos'Santos et al., 2018). Therefore, it is strongly recommended to evaluate the athletes through several tests with a single COD at various angles to create a "COD angle profile" of each player (Gonzalo-Skok et al., 2023). Given the high prevalence of COD during team sports competition (Salazar et al., 2020; W. Young et al., 2022), COD actions should be considered as a key performance indicator for basketball players. Thus, proper assessment and data interpretation of this skill is particularly relevant for strength and conditioning coaches.

COD assessment in team sports has been extensively studied in the previous research (Mancha-Triguero et al., 2019; Nimphius et al., 2018; Stojanović et al., 2019), and there are a variety of 48 different tests to analyse the COD performance of basketball players (Sugiyama et al., 2021). Even so, the "Gold-Standard" COD test does not exist and is unlikely to exist due to the unpredictable nature and wide variety of on-court movements performed in basketball across a wide spectrum of angles and approach distances to the cut (Gonzalo-Skok et al., 2023). Given the wide variety of available tests to assess COD and the lack of consensus on the "perfect" COD assessment, many investigations used different COD tests. This may make the results not comparable between studies, as test performance will depend directly on the characteristics of the test such as distance covered, the number of cuts and their angulation (Dos'Santos et al., 2018). This adds a degree of complexity in attempting to advance scientific knowledge about this skill and it was recommended to standardise COD tests (Gonzalo-Skok et al., 2023).

Frequently in the scientific literature, COD assessments have involved determining the time to complete multiple COD at different angles that simulate sport-specific distances and displacements (Nimphius et al., 2018). However, given the wide range of physical qualities involved in these tests (e.g., linear sprinting ability, anaerobic capacity, and movement specificity for the test), the result of the COD test could be masked by another ability (Nimphius et al., 2016). In particular, 74.8% of the variance in these COD tests is explained by linear sprint speed (Delextrat et al., 2017). This may be because the vast majority of tests currently used to measure COD performance

are tests in which more than 70% of the time is spent on linear speed actions and do not isolate the COD action itself (Nimphius et al., 2013, 2016). To avoid this limitation, previous studies have developed the concept of change of direction deficit (CODD). The CODD seeks to most effectively isolate the COD action from the player's linear sprinting ability (Nimphius et al., 2013). Originally, this variable was calculated as the difference between the time in COD and linear speed test (Nimphius et al., 2013), but more recently a percentage change has been advocated to standardise the measurement between the two speed tests (Freitas, Pereira, et al., 2021). In both ways, CODD expresses the amount of time a subject has spent on the COD during the test and indicates the athlete's efficiency in these actions (Freitas, Pereira, et al., 2021; Nimphius et al., 2013, 2016). A lower CODD indicates a great efficiency in changing direction compared to its linear speed, and vice versa, a higher CODD indicates greater reliance on acceleration and linear speed ability but an inefficient COD technique or possess deficiencies in specific muscle strength qualities that results in a worse COD performance (Freitas et al., 2019; Loturco et al., 2022; Pereira et al., 2018). Additionally, previous studies (Freitas, Alcaraz, et al., 2021) have indicated that male athletes showed higher CODD compared to female athletes, suggesting the need to identify different CODD thresholds according to gender.

On the other hand, strength and conditioning coaches should select tests in their assessments that allow them to monitor the evolution of a player, rank the athlete in comparison to others and prescribe an individualised training programme in order to improve performance in the assessed skill (Weakley et al., 2023). In this sense, using time as an outcome variable to measure COD performance may hide other physical qualities required within the test and falls short of providing information for individualising training programmes (Nimphius et al., 2016). In contrast, the use of CODD makes it possible to determine the player's efficiency in COD and to analyse their weaknesses in these actions to improve them. Previous studies showed that faster linear speed and more powerful athletes tend to exhibit higher CODD (Freitas, Alcaraz, et al., 2021; Loturco et al., 2022; Pereira et al., 2018), this may be linked to the difficulties of handling higher velocities prior to COD (i.e., higher sprint momentum and subsequent braking forces) (Freitas et al., 2019; Freitas, Alcaraz, et al., 2021). Therefore, it was recommended that high CODD athletes should train on COD technique and the ability to handle higher braking forces and, conversely, low CODD athletes should train on acceleration and high speed, whilst still maintaining technique and required muscle strength qualities (Freitas, Alcaraz, et al., 2021; Harper et al., 2022; McBurnie et al., 2021). Thus, the current research suggests that athletes may be classified based on CODD as "Multidirectional Speed Dominant" (MSD; Low CODD), "Linear Speed Dominant" (LSD; High CODD) or fall in between ("balanced"; Moderate CODD – a trade-off between multidirectional and linear speed dominant). However, to the authors' knowledge there are no previous studies that provide cut-off points for classification of CODD, and this may be useful to individualise COD training.

For the above reasons, the present work aimed to determine the CODD thresholds for different COD angulations in basketball players according to gender. In this regard, it was hypothesised that CODD would increase as the cutting angle increases, so the balanced CODD thresholds should be specific to each COD angulation. Additionally, as a secondary purpose, the relationships between CODD and execution time in speed tests based on gender were analysed.

2. Materials and methods

2.1. Participants

A total of 130 trained basketball players (46% female; age: 23.7 ± 5.29 years; height: 189.1 ± 11.1 cm; body mass: 84.3 ± 15.7 kg) volunteered to participate in this study were included. The sample size was calculated for our primary aim using G*Power software (version 3.1.9.6, Kiel, Germany). To the best of our knowledge, there were no available information on CODD thresholds in basketball players. Therefore, the number of participants to be included in the study was calculated based on the statistical method used to identify the differences between groups (a one-factor ANOVA). This calculation was based on a moderate effect size (f) of 0.3, an alpha level of 0.05, and power value of 0.85 (Faul et al., 2007).

All players had their regular basketball training at least 3 days a week for 2 hours and played one federated game per week during the season. They played in the Spanish N1 League and had at least 10 years of experience playing basketball. None of the athletes included in the study had suffered an injury in the 6 months prior to the study. All of them were previously informed of the possible risks and benefits of participating in the study and gave their written consent before the start of the test evaluation. This research was approved by the Andalusian Biomedical Research Ethics Committee (reference number: FBD_UHU2020) in accordance with the rules established in the Declaration of Helsinki.

2.2. Study design and procedures

A cross-sectional experimental design was used to calculate the CODD for each athlete and determine CODD thresholds for each COD angulation. Data collection was carried out during the last month of the competitive season. All participants completed the assessment in a single testing session after a familiarisation session with the proposed tests in the previous week. Prior to the speed and COD testing, all players conducted a 15-minute warm-up, including low-intensity movements (high-knees, butt kicks, cariocas) (5 minutes); dynamic stretches (lunges, diver, lateral squat) (5 minutes); and moderate to high-intensity activities such as jumps, accelerations, decelerations, linear sprints and changes of direction (5 minutes). Testing was performed in the following order: 10-m linear sprinting, 45° COD, 90° COD and 180° COD. Players executed two warm-up trials (in each direction during COD tests) at 70% and 90% maximum effort before their maximum effort trials. The testing session took place during the regular training schedule, just before the regular basketball training between match day plus 2 and 4. All tests were conducted on the frequent training and competition basketball courts, and the players wore sports clothes and their usual basketball shoes. Moreover, each player

was instructed to attend the testing sessions with adequate hydration and rest, and to control their caffeine and food intake at least 3 hours before each evaluation.

2.2.1. Linear speed: 10 metres test

Execution time was recorded with single-beam electronic timing gates (ETGs, Chronojump BoscoSystem®, Barcelona, Spain). ETGs were placed 2 m from each other at a height of 1 m (approximately the height of the players' hips). Each player was positioned 0.5 m behind the first timing gate whilst adopting a 2-point split stance. Then, each player accelerated at maximum linear speed to the second gate 10 m away (Figure 1). This test was performed three times with a 2-minute rest between trials, and an average of the three attempts were selected for analysis.

2.2.2. Change of direction speed: 505 modified tests at 45º, 90º and 180º

Execution time was recorded with single-beam ETG (Chronojump BoscoSystem®, Barcelona, Spain). ETGs were placed 2 m from each other at a height of 1 m (approximately the height of the players' hips). Each player was positioned 0.5 m behind the first timing gate whilst adopting a 2-point split stance. Then, each player accelerated at a maximum speed 5 m ahead and performed a 45° or 90° side-step cut, or 180° turn before accelerating further 5 m to the finish line (Figure 1). The COD performance at 45°, 90° and 180° left and right directions was defined by the leg on which the subjects set on the court when performing the COD. This test was performed three times with a 2-minute rest between attempts, and an average of the three attempts was used for statistical analysis. The

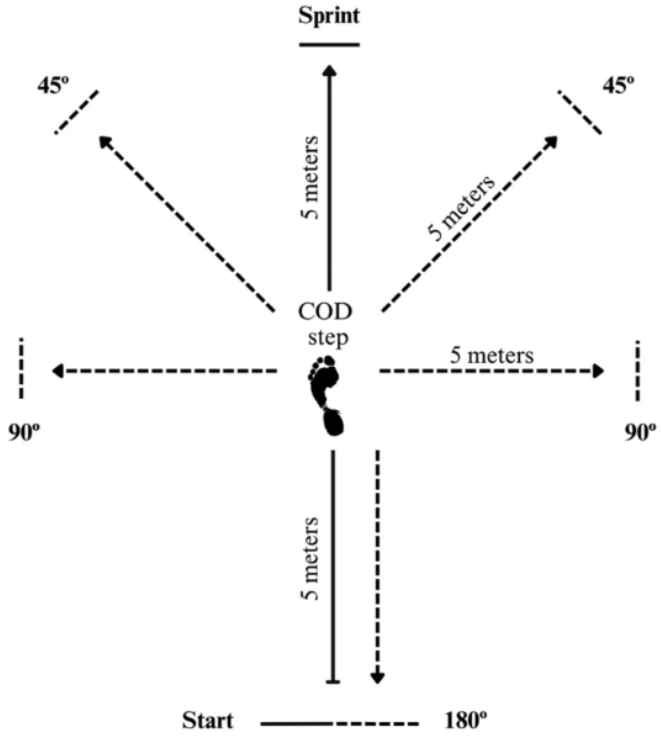

Figure 1. Schematic presentation of the linear speed test (10 m) and the change of direction speed test (5 + 5 m at 45º, 90º and 180º cut).

CODD for each angulation was calculated as follows (Freitas, Pereira, et al., 2021):

$$CODD\% = \frac{COD\ time - 10\ metres\ tets\ time}{10\ metres\ test\ time} x100$$

2.3. Statistical analyses

Means ± standard deviations (SD) were used to describe the variables. The assumption of normality of the data was verified using the Shapiro–Wilk test. Homoscedasticity was determined with the Levene test. A two-way random, absolute agreement intraclass correlation coefficient (ICC) determined the relative test–retest reliability of the measures. Relative reliability was deemed as excellent when ICC >0.9 (Koo & Li, 2016). Absolute reliability of test measures was computed using the coefficient of variation (CV) and the typical error of measurement (TEM). CV was calculated as: (SD/average)*100; and values ≤5% were deemed acceptable as a criterion for intraday reliability (Atkinson & Nevill, 1998). The TEM was calculated as: SD*∏(1-ICC); and was deemed acceptable if the TEM value was less than 10% the mean cumulative test–retest scores (Fox et al., 2014). Student's *t*-test for independent samples was used to assess the influence of gender on tests. Cohen's d was computed, with thresholds for qualitative descriptors set at <0.20 "trivial", 0.20–0.50 "small", 0.50–0.80 "moderate", and >0.80 "large" (Cohen, 1988). A Pearson product-moment test with 95% confidence intervals (CI) was performed to determine the correlations (r) between the performance at different linear speed and COD tests with CODD. The magnitude of Pearson's correlation was interpreted as trivial (<0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), and almost perfect (0.9–1.0) (Hopkins et al., 2009). Coefficient of determination ($R^2 \times 100$) was also calculated and interpreted as trivial (<0.04), small (0.04–0.25), moderate (0.25–0.64), and strong effect (>0.64) (Hopkins et al., 2009). Then, a k-means cluster analysis was used to establish cut-off CODD scores based on COD execution time and rank athletes according to their CODD for each cutting angle. A non-hierarchical k-means cluster analysis was used for each angulation (Hartigan & Wong, 1979), obtaining the final cluster solution and including a total of three clusters for each angulation. Finally, a one-factor ANOVA was used to identify the differences between clusters, and the effect size (ES) was determined using the partial eta-square. ES was considered trivial (<0.01), small (0.01–0.06), moderate (0.06–0.14), large (>0.14) (Lenhard & Lenhard, 2016). Additionally, the Bonferroni post-hoc for multiple comparisons was performed to identify cluster significant changes. Statistical significance was set at $p < 0.05$. All statistical analysis was performed using IBM SPSS Statistics for Macintosh, Version 25.0 (Armonk, NY: IBM Corp.).

3. Results

Table 1 presents the mean performance of the linear speed and COD tests analysed differentiating between genders, alongside the ICC, CV, and TEM for each variable. Male players showed a better performance for all speed variables analysed (ES ≥ 1.03; $p < 0.01$), except for CODD90º and CODD180º.

Table 1. Descriptive analysis (mean ± SD) of the performance variables analysed differentiating between genders and within session reliability.

	MALE ($n = 70$)		FEMALE ($n = 60$)					
Variables	Mean	SD	Mean	SD	p value (ES)	ICC	CV (%)	TEM (%)
Linear Sprint (s)	1.85	0.10	2.01	0.10	<0.01 (1.66)	0.99	0.75	0.42
COD 45º L (s)	1.91	0.12	2.12	0.13	<0.01 (1.72)	0.91	1.06	2.39
COD 45º R (s)	1.90	0.11	2.13	0.11	<0.01 (2.19)	0.94	0.80	1.98
COD 45º (s)	1.91	0.10	2.13	0.11	<0.01 (2.10)			
COD 90º L (s)	2.24	0.15	2.41	0.19	<0.01 (1.04)	0.93	1.16	2.13
COD 90º R (s)	2.24	0.16	2.41	0.19	<0.01 (1.03)	0.91	0.72	2.57
COD 90º (s)	2.24	0.14	2.41	0.18	<0.01 (1.10)			
COD 180º L (s)	2.70	0.14	2.94	0.21	<0.01 (1.32)	0.97	0.64	1.41
COD 180º R (s)	2.70	0.15	2.94	0.22	<0.01 (1.31)	0.96	0.58	1.55
COD 180º (s)	2.69	0.15	2.94	0.21	<0.01 (1.39)			
CODD 45º (%)	3.11	4.02	5.71	4.29	<0.01 (0.63)			
CODD 90º (%)	20.9	5.70	19.8	6.93	0.32 (0.18)			
CODD 180º (%)	46.1	6.43	46.0	8.24	0.80 (0.04)			

Abbreviations: COD, Change of Direction; CODD, Change of Direction Deficit; L, Left; R, Right; s, Seconds; %, Percentage SD, Standard Deviation; ES, Effect Size; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; TEM, Typical Error of Measurement.

Table 2. Relationships between CODD at several angulations with linear speed and COD execution time differentiating between genders and for the pooled sample.

	LS		COD 45º		COD 90º		COD 180º	
Variables	r	R^2	r	R^2	r	R^2	r	R^2
Male								
CODD 45º	0.31*	9.90%	0.43**	18.2%	0.05	0.20%	0.01	0.10%
CODD 90º	0.18	3.10%	0.12	1.50%	0.60**	36.1%	0.21	4.20%
CODD 180º	0.47**	21.7%	0.15	2.40%	0.08	0.50%	0.55**	29.7%
Female								
CODD 45º	0.42**	17.4%	0.38**	14.4%	0.24	5.70%	0.14	1.90%
CODD 90º	0.08	0.60%	0.46**	21.3%	0.73**	53.5%	0.50**	24.9%
CODD 180º	0.17	2.70%	0.27*	7.40%	0.42**	17.6%	0.69**	48.2%
Pooled sample								
CODD 45º	0.08	0.60%	0.48**	23.3%	0.27*	7.20%	0.23*	5.40%
CODD 90º	0.15	2.30%	0.14	2.00%	0.55**	29.8%	0.26*	6.60%
CODD 180º	0.24*	5.70%	0.04	0.20%	0.21*	4.20%	0.52**	27.4%

Abbreviations: LS, Linear Speed; COD, Change of Direction; CODD, Change of Direction Deficit. Significant relationship: *$p < 0.05$; **$p < 0.001$.

Table 2 depicts the relationships between CODD at several angulations with linear speed and COD execution time, indicating the correlation coefficients between these variables for the pooled sample and differentiating between genders. The correlations between the CODD and execution time in the COD tests were demonstrated to be angle-specific, with the most significant correlations observed when comparing CODD and execution time in the COD at the same angles. Significant large correlations and moderate coefficient of determination were observed at 45º ($r = 0.48$ [CI 95% = 0.34–0.61]; $R^2 = 23.3\%$), 90º ($r = 0.55$ [CI 95% = 0.42–0.66]; $R^2 = 29.8\%$), and 180º ($r = 0.52$ [CI 95% = 0.39–0.64]; $R^2 = 27.4\%$) for the pooled sample. Furthermore, the relationships between CODD and execution time were significantly higher and steadier in the female gender.

The results of the k-means cluster analysis are shown in Table 3, setting the CODD thresholds for each cut-off angle in the pooled sample and differentiating between genders to classify the athletes into MSD, Balanced or LSD. This analysis showed that CODD thresholds are different and specific for each COD angle, and the cut-off points were higher for sharper angles. Moreover, the cut-off points showed to be different between genders mainly at CODD45°.

Table 4 shows comparative analysis between clusters on linear speed and angulation-specific COD performance differentiating between genders. The analysis showed moderate to large significant inter-group differences (ES ≥ 0.08; $p < 0.05$) for all COD angulations regardless of gender. However, the linear speed performance showed no significant inter-group differences at CODD90º cluster for males and CODD180º cluster for females. A post-hoc Bonferroni analysis revealed differences in both genders between the LSD group and the other clusters ($p < 0.05$) in the execution time of COD, being the players of this group the ones who obtained the highest execution time in COD tests regardless of the cutting

Table 3. K-means clustering results showing the CODD thresholds according to the cut-off angle and gender.

Variables	MSD	Balanced	LSD
Male			
CODD 45º (%)	−4.19 to 1.06	1.44 to 5.61	6.47 to 13.3
CODD 90º (%)	5.08 to 15.7	16.2 to 23.3	23.7 to 33.3
CODD 180º (%)	31.0 to 42.4	43.3 to 49.4	50.9 to 61.3
Female			
CODD 45º (%)	−2.48 to 3.42	3.74 to 9.68	10.3 to 12.8
CODD 90º (%)	5.89 to 16.0	16.4 to 26.4	28.3 to 42.1
CODD 180º (%)	26.0 to 42.3	43.0 to 53.6	54.4 to 70.0
Pooled sample			
CODD 45º (%)	−4.19 to 2.49	2.62 to 8.13	8.37 to 16.1
CODD 90º (%)	5.08 to 17.0	17.1 to 25.0	25.1 to 42.1
CODD 180º (%)	26.0 to 42.4	43.0 to 51.0	51.3 to 70.0

Abbreviations: CODD, Change of Direction Deficit; %, Percentage MSD; Multidirectional Speed Dominant; LSD, Linear Speed Dominant.

Table 4. Comparative analysis between CODD subgroups (MSD, balanced and LSD) according to cutting angle (45º, 90º and 180º) and gender with the execution time of linear sprint and changes of direction.

Variables	MSD	Balanced	LSD	*p valor*	ES (η^2)	Descriptor
Male						
CODD 45º	**n = 23**	**n = 29**	**n = 18**			
Sprint (s)	$1.90 \pm 0.10^{a,b}$	1.81 ± 0.08^{a}	1.83 ± 0.07^{b}	***<0.01***	0.17	Large
COD 45º (s)	1.87 ± 0.11^{b}	1.88 ± 0.09^{c}	$1.98 \pm 0.08^{b,c}$	***<0.01***	0.19	Large
CODD 90º	**n = 13**	**n = 33**	**n = 24**			
Sprint (s)	1.90 ± 0.08	1.83 ± 0.10	1.84 ± 0.08	*0.17*	0.05	Small
COD 90º (s)	2.12 ± 0.11^{b}	2.20 ± 0.13^{c}	$2.33 \pm 0.10^{b,c}$	***<0.01***	0.31	Large
CODD 180º	**n = 24**	**n = 27**	**n = 19**			
Sprint (s)	$1.90 \pm 0.08^{a,b}$	1.84 ± 0.09^{a}	1.79 ± 0.07^{b}	***<0.01***	0.23	Large
COD 180º (s)	2.65 ± 0.12	2.68 ± 0.16	2.76 ± 0.14	***0.04***	0.08	Moderate
Female						
CODD 45º	**n = 17**	**n = 34**	**n = 9**			
Sprint (s)	$2.08 \pm 0.05^{a,b}$	2.00 ± 0.10^{a}	1.92 ± 0.11^{b}	***<0.01***	0.22	Large
COD 45º (s)	2.09 ± 0.06	2.13 ± 0.11	2.17 ± 0.13	*0.15*	0.06	Moderate
CODD 90º	**n = 16**	**n = 36**	**n = 8**			
Sprint (s)	2.06 ± 0.07	1.98 ± 0.10	2.05 ± 0.11	***0.04***	0.11	Moderate
COD 90º (s)	2.31 ± 0.10^{b}	2.39 ± 0.14^{c}	$2.73 \pm 0.15^{b,c}$	***<0.01***	0.47	Large
CODD 180º	**n = 20**	**n = 31**	**n = 9**			
Sprint (s)	2.04 ± 0.09	2.01 ± 0.11	1.97 ± 0.10	*0.28*	0.04	Small
COD 180º (s)	$2.79 \pm 0.13^{a,b}$	$2.97 \pm 0.17^{a,c}$	$3.15 \pm 0.24^{b,c}$	***<0.01***	0.33	Large

Abbreviations: COD, Change of Direction; CODD, Change of Direction Deficit; s, Seconds; MSD; Multidirectional Speed Dominant; LSD, Linear Speed Dominant; ES, Effect Size; η^2, partial eta square. Significant intra-groups differences: [a](between MSD-Balanced; $p < 0.05$), [b](between MSD-LSD; $p < 0.05$), [c](between Balanced-LSD; $p < 0.05$). Bold indicates significant differences inter-groups at $p < 0.01$.

angle. In contrast, it was the MSD group that showed differences with the other clusters ($p < 0.05$) in the execution time of linear speed, being this group the ones that showed the lowest performance in linear speed test. The balanced group showed the best trade-off between linear speed and COD performance.

4. Discussion

This is the first study that aims to determine the CODD thresholds for different COD angulations in basketball players according to gender. Additionally, the relationship between the execution time to perform the linear sprint and COD tests, and the CODD for each angulation were analysed for the pooled sample and differentiating between genders. The K-mean cluster analysis undertaken revealed the CODD thresholds. Furthermore, it was observed that these thresholds are angulation specific. These findings hold the potential to empower strength and conditioning coaches to effectively identify their athletes' strengths and weaknesses in COD actions based on the specific cutting angle. Subsequently, coaches can design individualised training programmes tailored to each athlete's CODD. Another noteworthy finding in this research is the great relationship between CODD variables and COD execution time for each cutting angle. This corroborates the conclusions of prior studies (Freitas, Pereira, et al., 2021; Gonzalo-Skok & Bishop, 2023; Nimphius et al., 2013, 2016), and supports the validity of CODD as a performance measure for COD actions. This variable precisely reflects the physical quality to be measured, the COD while mitigating the influence of other physical qualities that might otherwise impact test results.

Although a strong relationship between the performance of linear speed and COD actions has traditionally been observed in basketball players (Michael et al., 2021), this relationship disappeared when CODD was used as a measure of COD performance (Nimphius et al., 2013, 2016). This may be explained by the fact that CODD exactly measures the time an athlete dedicates to the COD action itself during the test, thereby reducing the impact of other physical capabilities on the test outcome. In line with these previous studies, our study results corroborate the absence of a significant relationship between linear sprint performance and COD actions in basketball players so that both physical skills should be considered entirely distinct (D. B. Young & Henry, 2015). It is relevant to take into account that the number and angle of cuts, and the distance covered in both speed tests included in the CODD equation could condition the final result (Gonzalo-Skok & Bishop, 2023). On the other hand, it is worth noting that our study identifies a moderate to high positive relationship between CODD and execution time in the COD tests, a finding consistent with prior research (Lazić et al., 2022; Nimphius et al., 2013, 2016). These results underscore the validity of employing CODD as a COD performance metric independent of linear velocity. In practice, if an athlete enhances their linear velocity without concurrent improvement in COD performance, the time taken in a COD test might decrease (indicating better COD ability), yet the CODD would not show improvement, or it could even increase. Therefore, CODD emerges as more sensitive to detect changes in COD performance and is recommended as a minimum requirement for evaluating COD ability.

A priority for coaches when evaluating their athletes is to accurately identify their athletes' strengths and weaknesses (Weakley et al., 2023). In this regard, the use of CODD offers more than a specific measure of COD actions; it provides additional advantages. CODD serves as a variable that aids in identifying the optimal and individual balance between linear speed and COD performance for athletes seeking to enhance their linear and multidirectional speed (Nimphius et al., 2013, 2016). However, since the concept of CODD is relatively new and performance in COD actions are complex and depends on the cutting angle (Dos'Santos et al., 2018), reference values for CODD in various angulations have not been established so far. The present study has disclosed that players exhibiting CODD within the approximate ranges of 3–8%, 17–25%, and 43–51%

for angulations of 45º, 90º, and 180º, respectively, manifest a balanced CODD (Table 3). This balance provides the best trade-off between linear speed and COD performance. Conversely, players falling below this range in any of the mentioned angulations would be categorised as MSD players (i.e., they have a high COD ability but have a low linear performance). On the other hand, athletes exceeding this CODD range for each angulation would be classified as LSD players (i.e., they have a high linear speed performance, but are inefficient in COD actions). Although previous studies have shown differences between genders for CODD (Freitas, Alcaraz, et al., 2021), no significant differences were found between genders for CODD in the current research, except for the CODD45°. Therefore, CODD thresholds might be slightly different according to gender as shown in Table 3.

Notably, the classification based on CODD presented significant differences in inter-groups in COD performance across different angulations in both genders (Table 4). Regardless of cutting angle and gender, athletes with high CODD (i.e., LSD players) achieved better performance at linear speed and showed lower performance in COD. Additionally, females showed lower CODD at the different cutting angles as they were considerably less in the LSD group ($n = 27$) than in MSD ($n = 53$) and Balanced ($n = 101$) (which is not the case for males with 61, 60 and 89 for LSD, MSD, and Balanced, respectively). While no prior evidence exists for comparing CODD cut-off points, our findings were aligned with previous studies (Freitas, Alcaraz, et al., 2021) in which rugby sevens male athletes, who were faster and more powerful in linear speed compared to females, exhibited reduced efficiency in COD actions and the highest CODD, irrespective of the cutting angle. This was attributed to male athletes having to manage higher cutting approach speeds, sprint momentum, and braking forces (Freitas, Alcaraz, et al., 2021). The present research, alongside the CODD thresholds, provided novel results with respect to previous studies since it analysed the behaviour of linear speed and COD according to each CODD threshold proposed for both genders. In this regard, the results revealed that the MSD athletes were the fastest in COD, but their performance was the lowest in linear speed. Furthermore, it was the balanced group that showed the best trade-off between linear speed and COD performance across all cutting angles in both genders. Hence, since both linear and multidirectional speed is an essential physical ability in basketball, strength and conditioning coaches would be advised to take these CODD thresholds into account to improve the speed profile and performance of their players whether male or female.

Despite the interesting and novel findings found in the present study, some limitations should be considered when interpreting the results. First, our sample exclusively comprised non-professional basketball players, which implies that the standardised values in this study can serve as a reference but should be applied cautiously when extrapolated to different competitive levels or sports. Second, the use of k-means cluster analysis to compute CODD thresholds represents a novel approach, and to our knowledge, this study marks the initial endeavour to standardise CODD values for the purpose of athlete classification. Moreover, other covariates could not be analysed in the cluster analysis due to the sample size. Therefore, it is recommended that similar studies be conducted in the future with larger samples, to analyse the influence of anthropometric variables or playing position and to pool more information around this very interesting COD measurement tool and thus be able to get the most out of it. Finally, the cross-sectional design provided a single time-point measurement for capturing player performance, so it was not possible to analyse the fluctuations of this variable over time. In this context, it would be advisable to conduct intervention studies to see how this variable may change after individualised training programmes.

5. Conclusions

Briefly, strength and conditioning coaches should understand that basketball is becoming more and more physically demanding, a greater number of linear and multidirectional actions occur at maximum intensity and these actions may determine the final outcome of the game (Salazar et al., 2020). Thus, coaches must place a strong emphasis on achieving balanced development of linear speed and COD capabilities. For this purpose, it is recommended to use the CODD as standardised measurement tool, offering insights into a player's efficiency in COD and shedding light on the trade-off between linear speed and COD for each individual athlete. Interestingly, the current research analysed and established normative data for CODD, providing sports scientists and coaches with invaluable information to craft more effective training programmes tailored to the specific needs and attributes of each athlete. Therefore, the measurement of CODD as the most valid variable for assessing COD performance and endorse the use of the cut-off thresholds unveiled in this study is strongly recommended. CODD provides extensive information on the relationship between linear speed and COD for each athlete, identifying individual strengths and weaknesses in this skill. Furthermore, the CODD thresholds found allow to classify basketball players, to share and compare standardised data with other samples, to improve the management and performance monitoring of each player and, most importantly, to propose training programmes targeting the individual weaknesses and needs of the athlete.

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Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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STUDY 7

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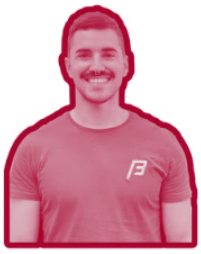
Validity and inter-device reliability of an artificial intelligence app for real-time assessment of 505 change of direction tests



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Validity and Inter-Device Reliability of an Artificial Intelligence App for Real-Time Assessment of 505 Change of Direction Tests

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ABSTRACT

The present study aimed to explore the validity and inter-device reliability of a novel artificial intelligence app (Asstrapp) for real-time measurement of the traditional (tra505) and modified-505 (mod505) change of direction (COD) tests. Twenty-five male Sports Science students (age, 23.5 ± 3.27 years; body height, 178 ± 9.76 cm; body mass, 79.4 ± 14.7 kg) completed 12 trials each, consisting of six tra505 and six mod505 trials. Completion times were simultaneously recorded via single-beam electronic timing gates (ETG) and two different iPhones (APP1 and APP2). In total 300 trials were collected across the two tests, using all three devices, to establish the reliability and validity of the app. The coefficient of variation indicated a similar level of dispersion between the ETG (≤ 2.73%), APP1 (≤ 2.39%) and APP2 (≤ 2.52%). Intraclass correlation coefficients (ICC) revealed excellent reliability among the three timing devices (ICC ≥ 0.99) and Asstrapp relative reliability was excellent for both APP1 (ICC ≥ 0.91) and APP2 (ICC ≥ 0.91). There was a practically perfect correlation and agreement between ETG and Asstrapp (APP1: $r = 0.97$; APP2: $r = 0.97$) for both COD tests. However, small but significant differences were found between smartphones and ETG for tra505 (ES ≤ 0.33; $p < 0.05$). Collectively, these findings support the use of Asstrapp for real-time assessment of both 505 COD tests.

1 | Introduction

Changes of direction (COD) are key performance metrics in many field and court sports and are often decisive in key moments in a match, such as scoring a goal (Taylor et al. 2017). Previous studies have revealed that professional football players execute over 726 cuts during a match (Bloomfield, Polman and O'Donoghue 2007). Moreover, most movements preceding a goal situation involve decelerations and turns (Martínez-Hernández, Quinn and Jones 2023). In basketball, players typically perform a COD every 1–3 s within a game (Klusemann et al. 2013), being the action that is most frequently performed regardless of playing position or gender (Salazar, Castellano and Svilar 2020). This relevance of COD is also evident in handball, where more than 60% of the maximum intensity actions involve a COD (Povoas et al. 2012). Beyond team sports, COD actions also play an important role in racket sports (Schneider, Rothschild and Uthoff 2023). With COD being such a decisive

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Summary

- Asstrapp is a mobile application specifically designed to measure the total time in sporting tests automatically and was able to provide a valid and reliable measurement in both 505 COD tests compared to the gold-standard.
- Asstrapp demonstrated perfect validity and agreement in inter-smartphone measurements in both COD tests, tra505 and mod505.
- It is important to consider the characteristics of the COD test when selecting a measurement device. Particularly for tests involving a flying start, such as the tra505 test, where caution should be exercised when using single-beam ETG.

physical quality in competition across a wide range of sports as it has been noted, it is not surprising that the COD assessment is frequently included in the sports testing battery that sport scientists and coaches perform on their athletes (Nimphius et al. 2018).

The assessment of COD has been extensively studied, resulting in the development of over 48 different tests to analyse COD performance (Sugiyama et al. 2021). Nevertheless, the most commonly used test is the traditional (tra505, flying start) or modified 505 (mod505, stationary start) COD test with a 180-degree cut (Ryan et al. 2021b). Additionally, a multitude of technological tools have been used in scientific literature to measure performance in these COD tests, with electronic timing gates (ETG) being widely accepted as time-based gold standard instruments (Altmann et al. 2018). However, this technology has some drawbacks, such as its high cost, which may prevent its accessibility to coaches and institutions with budget constraints, making it difficult to use in athletes' daily practice. As a more affordable and portable alternative, coaches may resort to using a stopwatch in daily practice. Nevertheless, previous research has indicated that manual timing exhibits large absolute errors during linear sprinting and COD tasks (Chen et al. 2021), so its use has not been recommended for the assessment of these maximum speed actions.

In order to overcome all these aforementioned limitations, a plethora of smartphone applications (apps) have appeared as a cost-effective and portable alternative to traditional laboratory equipment for assessing sports performance. Although not all apps have undergone empirical tests of validity and reliability, previous research has shown that these tools can be valid and reliable for assessing physical capacities such as jumping actions, barbell velocity in strength exercises and speed in sprint and COD tests (Pérez-Castilla et al. 2019; Romero-Franco et al. 2017; Silva et al. 2021; Turan et al. 2022). This reliability is attributed to the high-speed cameras integrated in current smartphones. However, these apps have typically lacked real-time feedback, requiring coaches to manually assess their athletes afterwards, resulting in time-consuming evaluations that cannot facilitate real-time decision-making in sports training. Advances in artificial intelligence (AI) and computer vision offer the potential to overcome this limitation by enabling smartphones to autonomously identify measurement targets, analyse them and provide test results in real time. Due to the novelty of this technology, there are limited validation and reliability studies employing AI in sports testing. Nonetheless, recent research has validated AI apps for tasks such as tracking the bar path in weightlifting movements (Balsalobre-Fernández et al. 2020), assessing joint range of motion (Carrasco-Uribarren et al. 2023), measuring barbell velocity in strength exercises (Taber et al. 2023) or determining cricket bowling line and length (Tissera et al. 2024). However, to the best of the authors' knowledge, no studies have yet assessed the validity and reliability of any AI or computer vision app in COD tests.

Therefore, the main purpose of this research was to examine the validity and reliability of Asstrapp in the tra505 and mod505 COD tests. Additionally, each mobile device model has different features and characteristics that might affect the results of Asstrapp's measurements. Inter-smartphones validity and reliability were analysed by comparing Asstrapp on two different mobile phones. Based on previous literature that analysed the validity of AI apps to measure several physical capacities, it hypothesised that Asstrapp may be a valid and reliable alternative for the measurement of total time in the tra505 and mod505 when compared with ETG.

2 | Materials and Methods

2.1 | Design

A reliability and validity study were carried out following the guidelines for reliability studies (Kottner et al. 2011). Testing took place in the human performance laboratory on an indoor track (Mondo, SportsFlex, 10 mm; Mondo America, Inc., Mondo, Summit, NJ) in a single session. Prior to starting the tests, a 15-min warm-up was conducted; which began with a general activation including light intensity jogging, two sets of dynamic stretching (four knee hug-moving, four walking quad stretches, two inchworms and two world's greatest stretch on each side) and three sets of acceleration-deceleration drills, followed by three submaximal mod505 trials. After that, participants began to perform the tra505 and mod505. Moreover, each participant was instructed to attend the testing sessions adequately hydrated and rested, with no high intensity training in the previous 24 h and to control their caffeine and food intake for at least 3 h before evaluation.

Each participant completed a total of 12 attempts. First, six mod505 and then, six tra505 trials. Each trial was interspersed with 3 min of rest. All attempts were timed simultaneously in three ways: using sets of single-beam ETG; and on the other hand, using two different iPhones. Times were recorded to the nearest 0.001 s. A total of 300 trials were collected with each tool in both COD tests for further analysis.

2.2 | Participants

The sample size was calculated based on an effect size of 0.5, an alpha level of 0.05 and power value of 0.80 (Faul et al. 2007) using G*Power software (version 3.1.9.6, Kiel, Germany). Twenty-five

male Sports Science students (age, 23.5 ± 3.27 years; body height, 178 ± 9.76 cm; body mass, 79.4 ± 14.7 kg) from the School of Health & Society at the University of Salford were selected to voluntarily participate in this study. All participants met the following inclusion criteria: at least 1 year of sport training experience, no injuries in the last 6 months, no health problems, practice a sport besides the sports science degree at university and age ranged from 20 to 30 years. All of them were previously informed of the possible risks and benefits of participating in the study and, before the beginning of the testing, they gave their written consent. This research was approved by the Andalusian Biomedical Research Ethics Committee (reference number: TES_COD_23) and University of Salford Ethics Committee (reference number: HSR2324_001) in accordance with the guidelines established in the Declaration of Helsinki.

2.3 | Procedures

Traditional and Modified 505 COD Setup. A schematic of the testing set-up is provided in Figure 1. Participants performed six mod505 trials and six tra505 trials. Each test was performed on both sides (first three right leg trials and then, three left leg trials for each test). The starting position was standardized for all participants. Each participant was positioned 0.5 m behind the start line, in a two-point split stance, to try to avoid early triggering of the timing gates. For the tra505 and mod505, the starting line was 15 and 5 m from the turning point, respectively (Figure 1). Both tests seek to assess an individual's ability to sprint 5 m, perform a 180° COD and re-accelerate 5 m to the finish line; but the trad505 has 10 m flying start and the mod505 has a standing start just behind the start line (Ryan et al. 2021a). If the participant slid or turned prematurely the trial was discarded and subsequently another trial was performed after 3 min of rest.

Electronic Timing Gate (ETG) device. A set of single-beam Brower ETG (Draper, UT) at a frequency of 480 Hz were used as the gold standard to measure the execution time of the attempts. The ETC was placed at the start/finish line, 2 m apart from each other and at a height of 1 m (approximately the height of the participants' hips) to ensure only one body part breaks the beam. The timing cells system can send radio transmissions up to 250 m and is accurate to the thousandth of a second, making it a highly precise timing tool (Shalfawi et al. 2014).

Asstrapp Smartphone App. Two iPhones, one basic and one pro, were used to analyse Asstrapp's reliability. The app (Asstrapp, Version 3.0) was installed on an iPhone 11 (APP1) and an iPhone 15 Pro (APP2) both running iOS 17.1 (Apple Inc., Cupertino, USA). Videos were captured with the on-board camera of the iPhones using Asstrapp, recording at HD 1080p resolution and 60 Hz sample rate; so, the software automatically analysed them and provided real-time feedback. Each iPhone was placed in a landscape orientation on a tripod at 1 m high and 4 m away from the start/finish line, perpendicular to the direction of movement of the test (Figure 1). In this way it ensures that the participant's full body is focussed within the Asstrapp measurement screen as it passes through the start/finish line. The centre of the Asstrapp measurement screen must coincide precisely with the start/finish line, so that the software automatically detects the start/finish of the test when the participant's hip crosses the start/finish line.

The app was developed by using Apple's open-source Swift 5 programming language in Xcode 16 for macOS (Apple Inc., Cupertino, USA). Live object recognition features were included using Apple's computer-vision framework Vision 2.0 (Apple Inc., Cupertino, USA) for real-time detection and tracking of humans. Specific, technical details of this framework can be found following this link: https://developer.apple.com/documentation/vision. This computer vision system is based on a pre-trained model, provided by Apple (Apple Inc., Cupertino, USA), to detect and track multiple body points, facilitating accurate tracking of the person's movement throughout the test. Specifically, the framework was integrated into Asstrapp to detect the person's hip point, so that it can detect when the person crosses the start/finish line of the test without the movement of the limbs influencing the test result. Additionally, the app automatically stores the collected data on a server by calling an Application Programming Interface built in Hypertext Pre-Processor.

2.4 | Statistical Analyses

Means ± standard deviations (SD) were used to describe variables. Normality and homogeneity were verified using Shapiro-Wilk and Levene's tests, respectively. The intraclass correlation coefficient (ICC, two-way random, absolute agreement) with 95% confidence intervals (CI) was used to analyse the within session relative reliability of the total time measures in the COD tests using each device and mobile phone app. ICCs were also used to explore the agreement between ETG and mobile phone app. ICCs were interpreted as follow: ICC < 0.50 = 'poor', 0.50–0.75 = 'moderate', 0.75–0.90 = 'good', > 0.90 = 'excellent' (Koo and Li 2016). The coefficient of variation (CV) was calculated as: (SD/average) × 100 and used to analyse the stability of timing systems, with a CV < 5% considered as acceptable for the absolute within-session reliability of each device (Atkinson and Nevill 1998). A linear regression with Pearson's (r) correlation coefficient with 95% CI, the standard error of the estimate (SEE) and the correction equations were analysed to assess the concurrent validity of Asstrapp, in comparison with the ETG. Also, the possibility of collinearity between devices was tested by the variance inflation factor (VIF; VIF < 10), tolerance (> 0.2) and verified by the Durbin–Watson test. The strength of the r coefficients was interpreted as follows: r < 0.10 = 'trivial', 0.10–0.29 = 'small', 0.30–0.49 = 'moderate', 0.50–0.69 = 'high', 0.70–0.89 = 'very high' and > 0.90 = 'practically perfect' (Hopkins et al. 2009). Paired samples t-test and Bland–Altman plots were used to identify potential systematic bias, reported via mean bias, standard deviations and the analysis of the regression line on the Bland-Altman plots (Bland and Altman 1986). Cohen's d was used to assess the mean differences between the measures obtained with each instrument; thresholds for qualitative descriptors of Cohen's d were set at, < 0.20 'trivial', 0.20–0.50 'small', 0.50–0.80 'moderate' and > 0.80 'large' (Cohen 1988). Statistical significance was set at $p < 0.05$. All statistical analysis was performed using Jamovi 2.3.21 for macOS.

3 | Results

Reliability statistics of the ETG, APP1 and APP2 is shown in Table 1. Both tra505 and mod505 demonstrated highly acceptable levels of stability across different timing systems (tra505 CV: ETG = 2.23%; APP1 = 2.15%; and APP2 = 2.13%; and mod505 CV: ETG = 2.73%; APP1 = 2.39%; and APP2 = 2.52%). No significant differences were detected in CV values between trad505 trials (ES ≤ 0.089; $p \geq 0.631$) and mod505 trials (ES ≤ 0.171; $p \geq 0.356$) measured with ETG, APP1 and APP2. The reproducibility of data provided by each measuring devices for the assessment of trad505 and mod505 showed good to excellent within-device agreement (Table 1). Additionally, excellent agreement was observed between ETG, APP1 and APP2 for the measurement of total time in tra505 COD tests (ICC = 0.987 [95% CI = 0.982–0.990]) and mod505 (ICC = 0.993

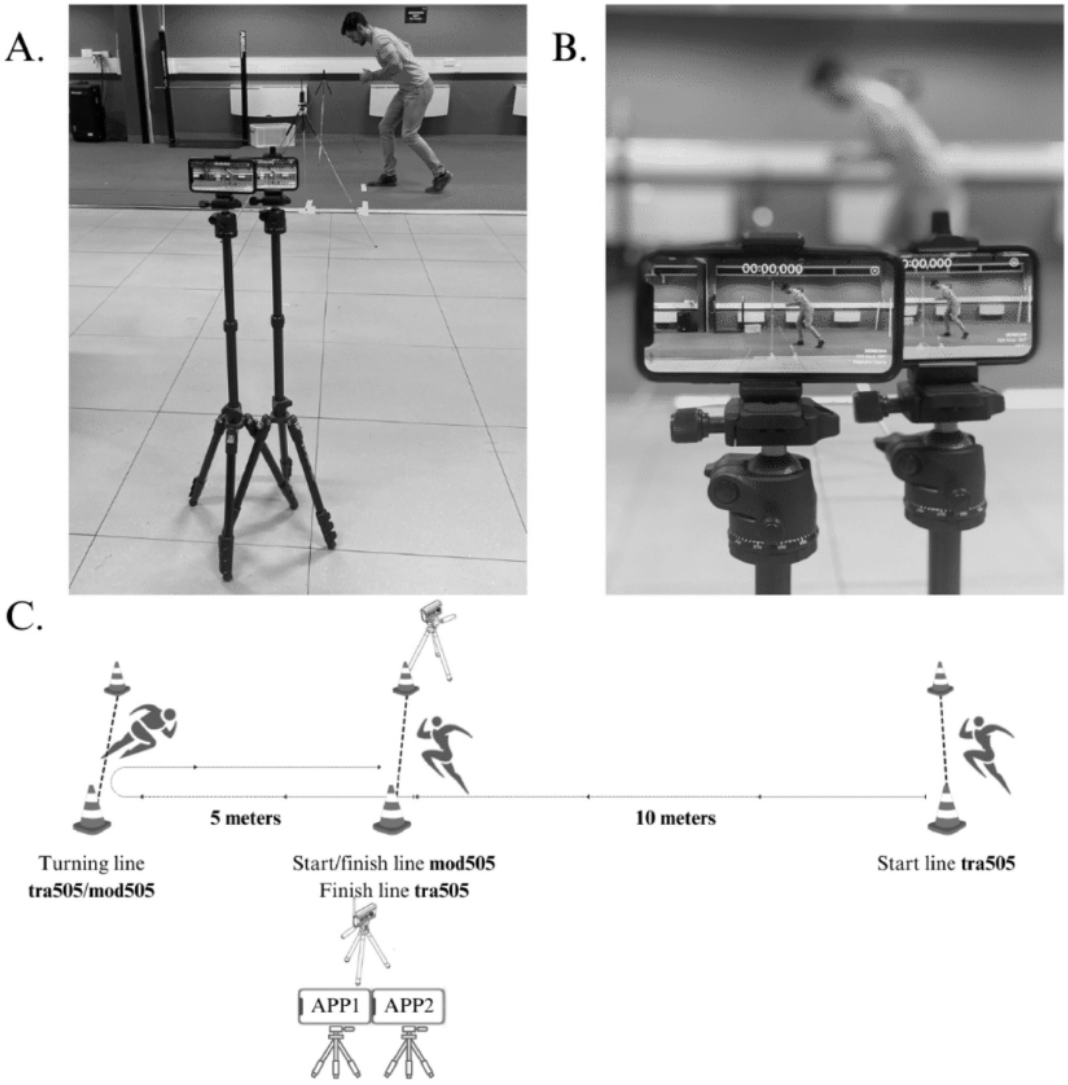

FIGURE 1 | Illustration of the tra505 and mod505 COD tests, showing where the ETG, APP1 and APP2 were placed. (A) Overall assessment set-up in the human performance lab, with the ETG and Asstrapp AI app on two different iPhones; (B) Fitting of the Asstrapp measurement screen with test start/finish line; and (C) Schematic diagram of the tra505 and mod505 COD tests set-up.

TABLE 1 | Two-way random intraclass correlation coefficient and coefficient of variation with 95% confidence intervals assessing within session reliability of each device.

	Tra505		Mod505	
	ICC (95% CI)	CV (95% CI)	ICC (95% CI)	CV (95% CI)
ETC	0.893 (0.811; 0.944)	2.229 (1.597; 2.861)	0.920 (0.858; 0.958)	2.729 (2.018; 3.440)
APP1	0.919 (0.856; 0.957)	2.151 (1.578; 2.724)	0.933 (0.882; 0.965)	2.387 (1.769; 3.005)
APP2	0.918 (0.856; 0.957)	2.135 (1.585; 2683)	0.925 (0.867; 0.960)	2.520 (1.864; 3.176)

Abbreviations: APP1, Asstrapp on an iPhone 11; APP2, Asstrapp on an iPhone 15 Pro; CI, confidence intervals; CV, coefficient of variation; ETC, electronic timing gate; ICC, intraclass correlation coefficient; Mod505, modified 505 change of direction test; Tra505, traditional 505 change of direction test.

[95% CI = 0.991–0.004]). Moreover, Asstrapp showed excellent inter-smartphones' reliability for tra505 (ICC = 0.971 [95% CI = 0.955–0.984]) and mod505 (ICC = 0.978 [95% CI = 0.965–0.999]).

Figure 2 shows scatter plot graphs of the linear regression analysis with Pearson's *r* correlation for the trad505 and mod505 tests comparing between measuring devices. Asstrapp demonstrated practically perfect validity in comparison with ETG for mod505

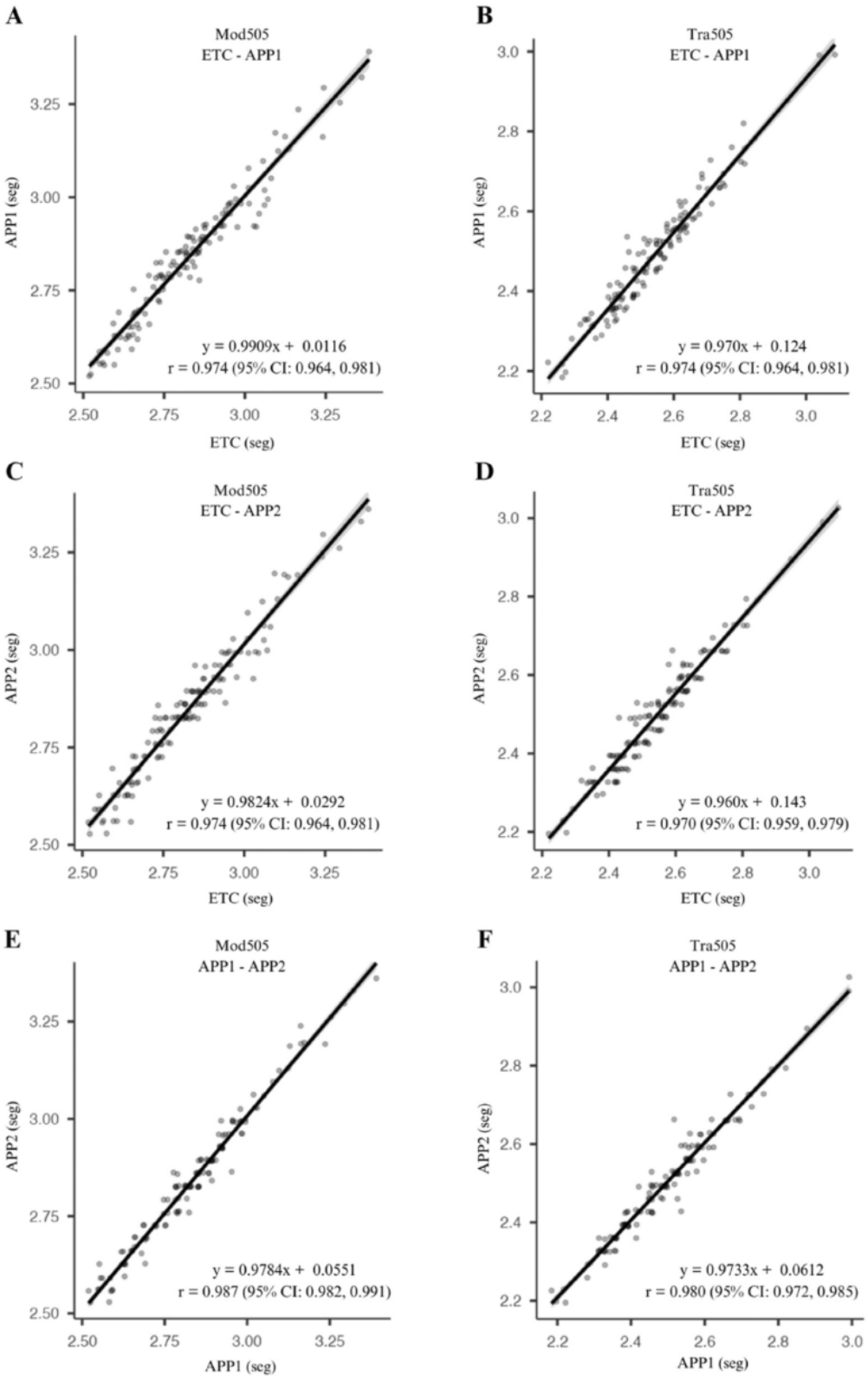

FIGURE 2 | Linear regression inter-devices for the measurement of total time in the mod505 ((A) ETC—APP1; (C) ETC—APP2; (E) APP1—APP2) and tra505 ((B) ETC—APP1; (D) ETC—APP2; (F) APP1—APP2) COD tests.

(APP1: $r = 0.974$; SEE = 0.019s; and correction equation = $0.991x + 0.012$; $p < 0.001$; and APP2: $r = 0.974$; SEE = 0.019s; and correction equation = $0.982x + 0.029$; $p < 0.001$); and for trad505 (APP1: $r = 0.974$; SEE = 0.018s; and correction equation = $0.970x + 0.124$; $p < 0.001$; and APP2: $r = 0.970$; SEE = 0.020s; and correction equation = $0.960x + 0.143$; $p < 0.001$). Furthermore, it also showed a perfect validity inter-smartphone when comparing the results for mod505 ($r = 0.987$; SEE = 0.013s; and correction equation = $0.978x + 0.055$; $p < 0.001$); and for trad505 ($r = 0.980$; SEE = 0.016s; and correction equation = $0.973x + 0.061$; $p < 0.001$). No collinearity was observed in the linear regression analysis (tolerance ≥ 0.98, VIF ≤ 1.05 and $d \geq 2.02$ for both COD tests).

The comparison of mean results between devices is presented in Table 2. Non-significant differences were found between devices in the mod505 tests and the pooled data from the COD tests evaluated (ES ≤ 0.117; $p \geq 0.320$). However, tra505 showed small significant differences between smartphones and ETG (ES ≤ 0.329; $p < 0.014$), although no significant differences were observed in tra505 between smartphones devices using Asstrapp (ES = 0.035; $p = 0.764$).

Figure 3 shows Bland–Altman plots to detect potential systematic bias. Mean bias estimate for mod505 between ETG-APP1 was −0.014s (95% CI: −0.021, −0.008s); ETG-APP2 was −0.021s (95% CI: −0.027, −0.014s); and APP1-APP2 was −0.006s (95% CI: −0.011, −0.002s). For trad505 the mean bias estimate between ETG-APP1 was 0.049s (95% CI: 0.044, 0.055s); ETG-APP2 was 0.044s (95% CI: 0.038, 0.051s); and between APP1-APP2 was −0.005s (95% CI: −0.10, −0.001s). These results indicate perfect agreement between all instruments across different COD tests.

4 | Discussion

The main purpose of the present study was to examine the validity and reliability of a novel AI app in the tra505 and mod505 COD tests. Additionally, inter-smartphones validity and reliability were analysed by comparing Asstrapp on two different mobiles. Results showed that Asstrapp is a highly valid and reliable tool for measuring tra505 and mod505 COD tests. Thus, Asstrapp could be a very cost-effective and automatic alternative for COD performance assessment. This could make COD performance assessment quicker and more accessible for strength and conditioning coaches and trainers.

Although the use of laboratory instruments is highly sensitive, accurate and considered gold-standard, the use of mobile apps in sports testing is currently on the rise and has many advantages such as being affordable for all professionals, as well as their easy use and portability, among others. This makes them increasingly useful for sports researchers and physical trainers if they have been shown to be valid and reliable (Peart, Balsalobre-Fernández and Shaw 2019). From a reliability standpoint, the results of the present study showed that Asstrapp exhibits excellent relative within-session reliability (APP1, ICC ≥ 0.911; APP2, ICC ≥ 0.905; Table 1) when measuring execution time in both COD tests analysed. Moreover, the ICC was

TABLE 2 | Comparison (mean ± SD) and Cohen's *d* effect size with 95% confidence intervals denoting practical differences between measurement devices in tra505, mod505 and pooled data.

	ETC	APP1	APP2	ETC—APP1			ETC—APP2			APP1—APP2		
	Mean ± SD	Mean ± SD	Mean ± SD	*p*	ES (95% CI)	Descriptor	*p*	ES (95% CI)	Descriptor	*p*	ES (95% CI)	Descriptor
Tra505 (s)	2.539 ± 0.15	2.489 ± 0.15	2.491 ± 0.15	0.006	0.329 (0.096; 0.561)	Small	0.014	0.292 (0.059; 0.524)	Small	0.764	−0.035 (−0.266; 0.196)	Trivial
Mod505 (s)	2.831 ± 0.17	2.845 ± 0.17	2.852 ± 0.17	0.493	−0.081 (−0.312; 0.150)	Trivial	0.320	−0.117 (−0.349; 0.114)	Trivial	0.753	−0.037 (−0.268; 0.194)	Trivial
Pooled (s)	2.685 ± 0.22	2.667 ± 0.24	2.673 ± 0.24	0.356	0.077 (−0.086; 0.240)	Trivial	0.541	0.051 (−0.112; 0.214)	Trivial	0.768	−0.025 (−0.188; 0.139)	Trivial

Abbreviations: APP1, Asstrapp on an iPhone 11; APP2, Asstrapp on an iPhone 15 Pro; CI, confidence intervals; ES, effect size; ETC, electronic timing gate; Mod505, modified 505 change of direction test; s, seconds; SD, standard deviation; Tra505, tradicional 505 change of direction test.

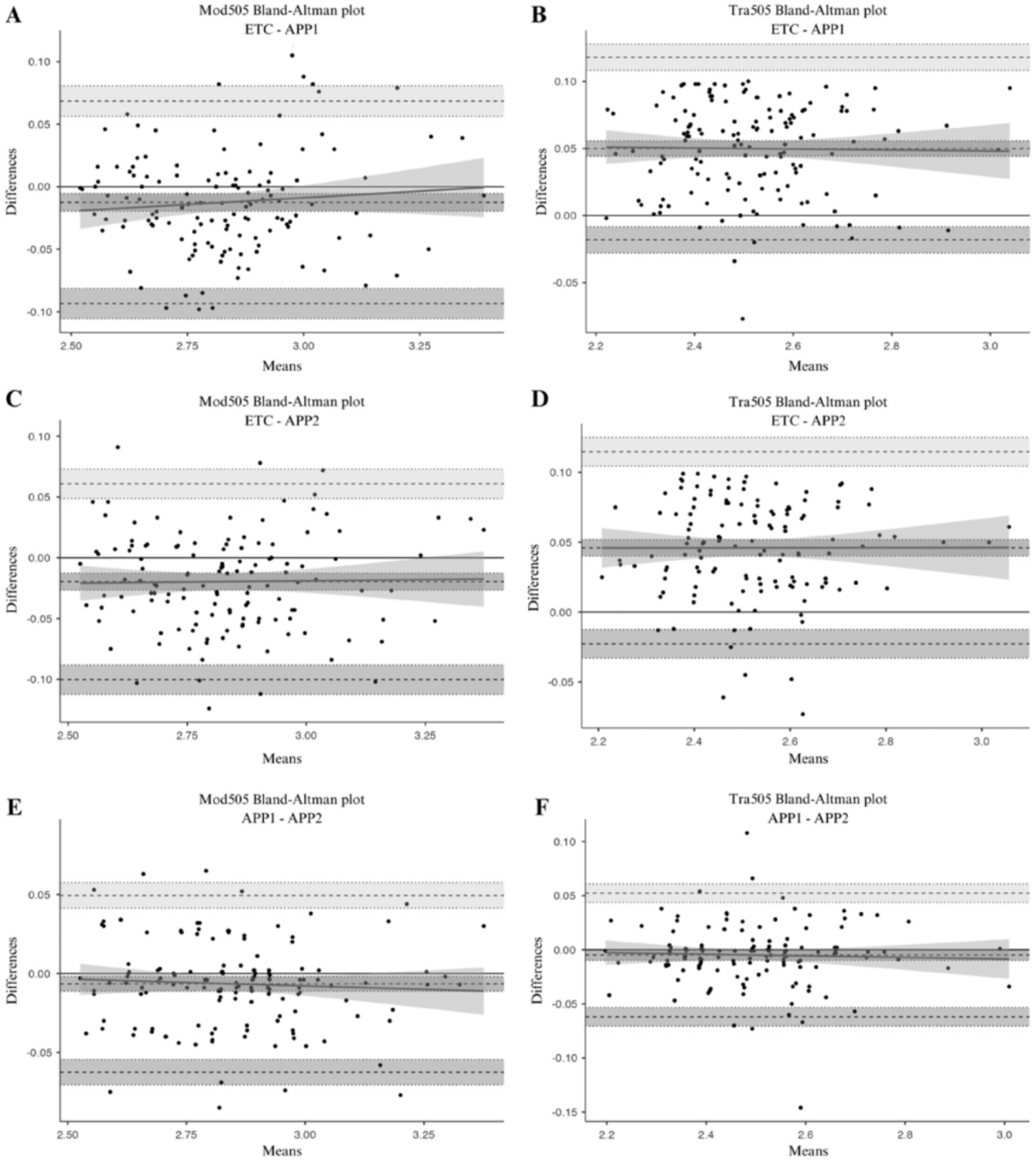

FIGURE 3 | Bland–Altman plot showing levels of agreement in the measurement inter-devices for mod505 ((A) ETC—APP1; (C) ETC—APP2; (E) APP1—APP2) and trad505 ((B) ETC—APP1; (D) ETC—APP2; (F) APP1—APP2) COD test. Including the mean bias estimate bias (with 95% CI), both lower and upper limits of agreement (with 95% CI) and the regression line of the residual (blue line with 95% CI).

also used to compare agreement between the ETG and Asstrapp showing almost perfect inter-devices reliability (ICC ≥ 0.987). These ICC values are higher than those found for other apps in previous studies (ICC = 0.671–0.840) (Balsalobre-Fernández et al. 2019). Additionally, the absolute reliability values assessed through the CV showed that the results of all measuring tools were acceptable and stable, with the CV being very similar to inter-devices and smartphones in the different COD tests (Table 1). The CV found are in line with previous studies analysing the reliability of a video-based app assessing mod505 (CV = 3.2%) (Balsalobre-Fernández et al. 2019) and tra505 (CV = 6.3%) (Chen et al. 2021). Therefore, professionals and Asstrapp users may be confident that the results provided by the app to measure the execution time of COD tests are reliable.

Due to the growing use of apps in sports testing, previous research has already shown that current smartphone technology makes it possible to validate the execution time in COD tests ($r = 0.964$; 95% CI = 0.95–1.00) using slow-motion video-based apps (Balsalobre-Fernández et al. 2019). However, scientifically validated apps to assess COD performance rely on external observers so far and although these apps have been tested for inter-observer validity (Chen et al. 2021), the measurement is not done automatically. So, no instant feedback is provided and professionals must invest significant time in video analysis. The app analysed in the present study uses AI to automatically give the COD test result. With the help of a machine learning model that has been programmed to detect people in motion, the AI-based smartphone app itself is able to detect when a person crosses the start and finish line of a COD test. This allows Asstrapp to do the same task as an ETG by calculating the time it takes for a participant to complete any COD test automatically and providing real-time feedback. The current research results reveal a very high concurrent validity of Asstrapp compared to ETG, showing an almost perfect association inter-devices ($r \geq 0.970$; $r^2 \geq 0.942$) and the slope coefficient was very close to the identity line (slope ≥ 0.960) for both COD tests assessed. Furthermore, a practically perfect validity was also observed in inter-smartphones using Asstrapp, showing an even stronger association ($r \geq 0.980$; $r2 \geq 0.960$). This agreement in the results reported inter-devices and inter-smartphones was also supported by Bland-Altman plots. Simply put, the values measured for both inter-devices and inter-smartphones were very consistent in both COD tests assessed, confirming the validity of Asstrapp. On the other hand, including measures from the same participant in a regression could lead to collinearity of the data, producing an overestimation of the model (Naclerio and Larumbe-Zabala 2017). But even though six attempts from each participant were included, this did not affect the fit of the linear regression model as no collinearity was observed in the sample data.

Finally, although all previous analysis denotes a very high validity of Asstrapp to measure execution time in COD tests, it is recommended to be cautious with the measurement instrument used according to the COD test assessed. Because small significant differences in tra505 execution time were observed between ETG and Asstrapp on both mobiles. These differences inter-devices were only found for the trad505 and no differences were found for the mod505 test and the pooled results. This finding may be explained by several reasons. Firstly, the sampling frequency inter-devices was different. Furthermore, the ETC used could be activated by cutting the single-beam through either limb of the athlete while running, while Asstrapp's AI is programmed so that only the person's hip activates the system when it crosses the start and finish test line to avoid any early start-finish cut-off, errors in the measurement and providing very similar inter-smartphone results. These differences in sampling frequency and tool activation methods may explain the difference observed just in tra505, which is a test with a flying start and higher speeds. Although the ETG was adjusted as recommended by previous scientific literature (Haugen, Tønnessen and Seiler 2015), showed a longer execution time for each tra505 trial (+0.049 vs. APP1; +0.044 vs. APP2). However, results showed stable inter-device differences in all tra505 trials. These differences were similar to those found in previous studies (Haugen et al. 2014) comparing a single-beam versus a dual-beam ETG system (+0.03 to +0.05 vs. dual-beam ETG). This could be explained because the activation method of the Asstrapp timing system is likely to be more similar to the dual-beam ETG system. These previous reasons could explain the small differences observed between Asstrapp and single-beam ETG in the tra505, whereby the result provided by Asstrapp's AI may be the one that best fits the reality.

Despite the novelty and usefulness of the findings for strength and conditioning coaches, there are some limitations in this study that should be acknowledged. Mainly, as the present research has highlighted, the validity data of Asstrapp could vary depending on the COD test analysed. Although there are many COD tests, only mod505 and tra505 have been analysed in this study, so caution is advised when using the app to assess other COD tests. Secondly, it should be noted that Asstrapp is currently only available for iOS and although this validation study has been conducted with two different iOS models to analyse validity and reliability inter-smartphone, it would recommend developing an equivalent AI software for smartphones with Android operating system, thus encouraging the COD assessment to all sport professionals.

5 | Conclusion

Accuracy and stability of measurement are indispensable characteristics for timing devices in COD testing. The findings of the present study showed that the Asstrapp is a highly valid and reliable tool for measuring the execution time of the mod505 and tra505 COD tests. Moreover, Asstrapp is an affordable and accessible sports testing instrument for all coaches, a user-friendly and quick-to-use tool, it is more portable than traditional laboratory instruments and has the advantage that it offers immediate feedback. For all these reasons, this app is recommended to any sports professional to assess, quantify and train COD.

Author Contributions

Research concept and study design: F.J.B.-D. and J.M.-L. Literature review: F.J.B.-D. and P.A.J. Data collection: F.J.B.-D. and P.A.J. Data analysis and interpretation: F.J.B.-D., B.J.A. and J.M.-L. Statistical analyses: F.J.B.-D., B.J.A. and J.M.-L. Writing of the manuscript: F.J.B.-D. and P.A.J. and Reviewing/editing a draft of the manuscript: P.A.J., B.J.A. and J.M.-L.

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Ethics Statement

This study was conducted following the principles of the Declaration of Helsinki and approved by the Andalusian Biomedical Research Ethics Committee (reference number: TES_COD_23) and University of Salford ethics committee (reference number: HSR2324-001).

Conflicts of Interest

The first author of the present investigation is the creator of the app mentioned. To guarantee data independency, data were collected and analysed by independent researchers not related with the app's development (specifically, the second, third and last authors of the present manuscript).

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, F.J.B.-D., upon reasonable request.

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Study 8

Barrera-Domínguez, F. J., Martínez-García, D., Jerez-Mayorga, D., Chirosa-Ríos, L. J., Almagro, B. J., & Molina-López, J. **(2024)**. Vertical Versus Horizontal Training for Improving the Change of Direction Speed in Adult Basketball Players: A Systematic Review and Meta-analysis. *Journal of Strength & Conditioning Research*, 38 (4), 791-803.

Study 9

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Study 10

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Study 11

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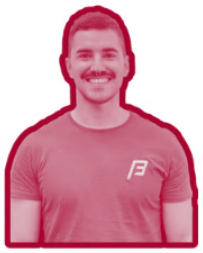
CHAPTER 3

New approach to individualized change of direction training

STUDY 8

Journal of Strength and Conditioning Research (2024) — IF JCR 2.50 (Q2)

Vertical versus horizontal training for improving the change of direction speed in adult basketball players: A systematic review and meta-analysis



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Vertical Versus Horizontal Training for Improving the Change of Direction Speed in Adult Basketball Players: A Systematic Review and Meta-analysis

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Abstract

Barrera-Domínguez, FJ, Martínez-García, D, Jerez-Mayorga, D, Chirosa-Ríos, LJ, Almagro, BJ, and Molina-López, J. Vertical versus horizontal training for improving the change of direction speed in adult basketball players: a systematic review and meta-analysis. *J Strength Cond Res* XX(X): 000–000, 2023—The ability to perform changes of direction (COD) is a complex skill that involves the application of multiple force-orientations, and its execution at maximum speed is crucial in basketball players. The present study aimed to synthesize findings from previous interventions classified according to force-orientation (vertical, horizontal, or mixed) and determine their magnitude of the effect on COD performance in basketball players. A systematic review of the literature was performed in several databases (Web of Science, Scopus, SPORTDiscus, and PubMed) following the PRISMA statement and reviewed the quality of the included papers according to the Cochrane Collaboration Guidelines Assessment. Sixteen articles with a total of 21 reports were included to analyze the role of force-orientations in COD performance. For the meta-analysis, the standardized mean differences with 95% confidence intervals (CIs) were calculated to determine the chronic changes induced by training and performed an effect size (ES) analysis with a random-effects model. The results showed that all force-orientations generated improvements in COD performance (ES = −0.47 [95% CI −0.57, −0.36], $Z = 8.74$ [$p < 0.01$]). It was a mixed force-orientation that produced the greatest changes (ES = −0.91 [95% CI −1.27, −0.55], $Z = 4.96$ [$p < 0.01$]), followed by vertical training (ES = −0.45 [95% CI −0.70, −0.20], $Z = 3.51$ [$p < 0.01$]). Horizontal training was the least studied and showed the smallest change (ES = −0.10 [95% CI −0.14, −0.07], $Z = 5{,}71$ [$p < 0.01$]). This meta-analysis demonstrates that mixed vertical and horizontally oriented training may be the most optimal because it offers a greater variety of multidirectional stimuli that better prepares the athlete to deal with complex COD in real-game situations.

Key Words: team sport, agility, multidirectional speed, plyometric, strength, force orientation

Introduction

Basketball is a multidirectional team sport of intermittent nature (14), which alternates high-intensity actions and low-intensity periods, with a work:rest ratio between 1:3.5 and 1:4.3 (26). Consequently, the game requires explosive actions such as accelerations, decelerations, changes of direction (CODs), and jumps, both with and without the ball (79,83). Among these actions, COD actions are the most frequently performed (84) and are fundamental to achieving success in decisive moments of the game, such as scoring, assisting, or gaining an advantage over the opponent, regardless of the player's position (78) and gender (72). Given the importance of these actions and the unpredictable nature of basketball, players should be able to generate force at specific speeds in multiple directions (90). Therefore, basketball coaches must emphasize creating fast, efficient and robust players who can perform a COD rapidly in any direction (53) through the implementation of accurate and effective training programs.

Changes of direction are defined as the ability to decelerate and accelerate in a planned manner to a different direction (59). Previous research (13,18,38,69) concludes that COD is a complex multidirectional skill that is influenced by and interacts with different sport skills such as technique, dynamic balance, linear speed, and lower limb strength. Rate of force development (RFD) is the ability to generate and apply large amounts of force in a short period and is considered to play the most important role in COD (11,13,88). It is also important to highlight that the physical and biomechanical demands of COD are mainly dependent on the velocity of approach and the cutting angle (30), which implies that as the velocity of approach or the intended cutting angle increases, more deceleration and braking are required to change the inertia, leading to increased force requirements. Furthermore, it has been observed that the direction of force application against the ground also varies according to the cutting angle (53). According to the principle of specificity (66) and transfer of training (35), previous research (10,17,56,73,75,90) highlights the importance of combining different force orientations to

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improve performance in these actions in basketball players because it is mainly a multidirectional sport (26).

In the scientific literature, there are several reviews about training methods that improve the performance of basketball players (74,77), but given the complexity of the COD actions, there is still no consensus on the method and the combination of the different training variables that maximize the improvements sought in the COD. Different training methods, such as plyometric training (PT), strength training, sprint training, or a combination of these training forms, have been shown to be effective in improving COD (63). Of these, PT is the most studied and has shown the greatest improvement in basketball players (8). Although the positive effect of this type of training on COD depends on many factors, such improvements could be explained by high strength, power, and RFD development and by improving the ability to use the stretch-shortening cycle (SSC) in basketball-specific ballistic actions (3,5). However, there are also studies that find no change in COD performance in basketball players after a period of PT (31). Therefore, in addition to the training method used, it is of vital importance for the improvement of COD to manage other training characteristics such as specificity (8,35), time to apply force, or the orientation of force application (30,43,53).

To maximize transfer and achieve greater performance improvements through training, training should be as specific as possible to the targeted action, paying close attention to the movement pattern, speed, and direction of force application (35,87). Previous research has shown that training oriented vertically or horizontally can lead to greater improvements in specific tasks corresponding to the force-orientation being trained (10,35). For instance, Aztarain-Cardiel et al. (10) showed that training with vertical jumps was the most effective in improving performance in an abalakov jump (i.e., vertical) and that training with horizontal jumps was the most effective in improving performance in a broad jump. However, a recent meta-analysis suggests that horizontally oriented PT is equally effective as vertical training for improving performance in vertical actions and has a greater impact on improving performance in horizontal tasks (56). Even so, previous reviews (90) indicate that the effects of training with a focus on horizontal and vertical force-orientation have not been adequately investigated or compared, and that such knowledge is crucial for coaches and trainers. Thus, there is still no consensus in the scientific literature on the most effective force-orientation approach for implementing specific training to improve COD performance.

It is widely acknowledged that most COD actions involve the integration of multiple force-orientations (10,53), and there remains limited evidence on how to work these multidirectional COD actions effectively. Based on the background outlined above, the present meta-analysis aims to achieve 3 main objectives. First, to describe the effect of different training interventions that focus on COD performance in adult basketball players of both genders and classify them according to the force-orientation in which the training was conducted (vertical, horizontal, or mixed). Second, to determine the magnitude of the effect on COD, considering the specific force-orientation primarily trained in the intervention. Third, to provide practical recommendations around specific force-orientation training to support programming decisions for coaches and trainers.

Methods

Procedures

A systematic review was conducted to synthesize the effect of different training interventions on COD performance in adult basketball players depending on the orientation of force application (vertical, horizontal, or mixed) on November 10 to December 20, 2022. A protocol was registered on the International Prospective Register of Systematic Reviews (PROSPERO) registration number CRD42022374206 before commencing the review. The reporting flow diagram of this systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (67) (Figure 1).

Literature Search

Randomized controlled trials (RCTs) were identified by searching 4 main electronic databases: Web of Science, Scopus, SPORTDiscus, and PubMed. The bibliographic search combined the different terms of the medical subject heading (MeSH) with specific keywords, such as "Athletic performance," "Change of direction," "Agility," "COD," "Multidirectional speed," "Resistance training," "Strength training," "Weight training," "Eccentric training," "Contrast training," "Complex training," "Combined training," "Plyometric," "Power training," "Neuromuscular training," "Sprint," and "Basketball." These search terms were combined with 2 Boolean operators: AND and OR. Additionally, the bibliographies of other previous related reviews and the studies ultimately selected were examined to find new studies. Other possible scientific evidence related to the subject was identified by contacting the authors of the published articles via email.

Study Selection

The articles retrieved from the initial search were entered into the Rayyan QCRI application, which assisted in the article selection process, optimized evaluation time, and allowed for collaborative work (available for free at http://rayyan.qcri.org; accessed December 22, 2022) (65). Duplicate references were removed. Next, articles were identified by 2 independent investigators (F.J.B.-D. and D.J.-M.) who reviewed titles and abstracts to identify relevant articles to the systematic review. The eligibility criteria were then assessed by reading the full text of the articles, and the reference list was checked for any relevant articles that could be included. Any disagreements were resolved by consensus or by consultation with a third author (D.M.-G.). The authors were familiar with the existing literature and were not biased toward any of the studies selected for inclusion in the review.

Inclusion and Exclusion Criteria

The PICOS model was used to define the inclusion criteria (55). Eligibility for each investigation was measured according to the following criteria: (a) studies with a control group and subjects randomly assigned to each group; (b) interventions of at least 4 weeks; (c) carried out only on male and female federated basketball players over 18 years old; (d) supervised training program that includes strength, power, plyometric, or speed or agility exercises in any force orientation; (e) including COD assessments as a dependent variable; and (f) published in Spanish or English. Articles that met the inclusion criteria were identified, and their full-text versions were obtained.

Articles with one or more of the following criteria were excluded: (a) a sample of wheelchair basketball players; (b) interventions involving the use of legal or illegal ergogenic aids or

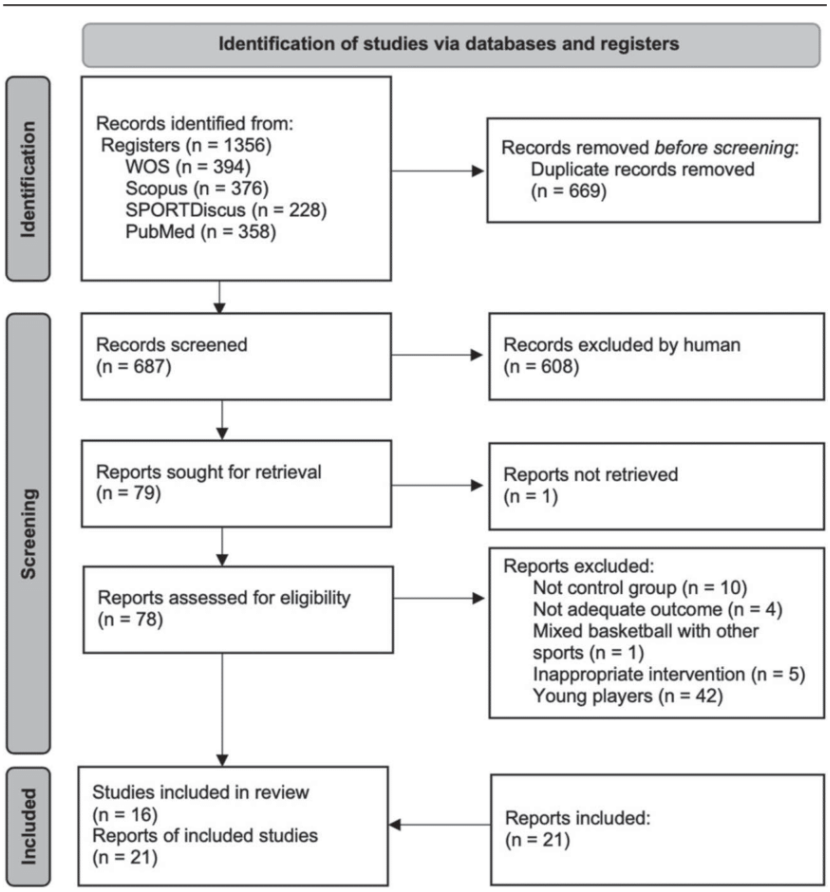

Figure 1. Flow diagram of search results and study selection through the different stages of the systematic review based on PRISMA guidelines.

supplements; and (c) interventions only based on small side games, vibration exercises, or upper-body or core strength.

Data Extraction

Two independent data extractors (F.J.B.-D. and D.M.-G.) followed a previously established protocol to extract the data (52). If differences or inconsistencies were found, a third reviewer (D.J.-M.) discussed the study data until an agreement was reached about the data validity. The following information was collected from the included studies: (a) author's name and year of publication; (b) study design; (c) sample size; (d) characteristics of the participants (competitive level, age and gender); (e) intervention (type, exercises, force orientation, frequency, duration, and season period); (f) assessment test; (g) results of interventions and percentage of change pre-post intervention; and (h) limitations, suggestions, applications, and conclusions described in the studies.

Assessment of Methodological Quality

Two independent authors (F.J.B.-D. and D.M.-G.) assessed the methodological quality and risk of bias (RoB) of the studies. A third evaluator (J.M.-L.) assessed the study RoB if differences or inconsistencies were found until an agreement on the RoB was made. According to the Cochrane Collaboration Guidelines Assessment (40), the items assessed were divided into 7 different domains: random sequence generation (section bias), allocation concealment (section bias), blinding of participants and personnel (performance bias), blinding of outcome assessment (detection bias), incomplete outcome data (attrition bias), selective reporting (report bias), and other types of bias. Each item was characterized as "low" if criteria for a low RoB were met (plausible bias unlikely to seriously alter the results) or "high" if criteria for a high RoB were met (plausible bias that seriously weakens confidence in the results). If the RoB was unknown, it was considered "unclear" (plausible bias that raises some doubts about the results). The summary of the RoB for the included studies is presented in Figure 2 and the individual RoB of each included study can be found in Supplemental Digital Content 1 (see Figure 1, http://links.lww.com/JSCR/A448).

Data Analysis and Synthesis

Data extracted from each publication were included in a Microsoft Excel spreadsheet (Microsoft, Redmond, WA). In cases where studies only reported data in charts, WebPlotDigitizer version 4.4 was used to obtain functional capacity performance values. *Review Manager (RevMan) version 5.4.5* was used to create all forest plots for statistical analyses. The Cochran Q statistic (22) was used to assess heterogeneity between studies, which is a measure of differences in main effects between studies. Publication bias was assessed through the visual assessment of funnel plots and Egger's regression test (82) to identify the presence of highly influential studies that might have biased the analysis. Additionally, the I^2 statistic was used to assess heterogeneity, with an I^2 value greater than 50% considered to indicate high heterogeneity.

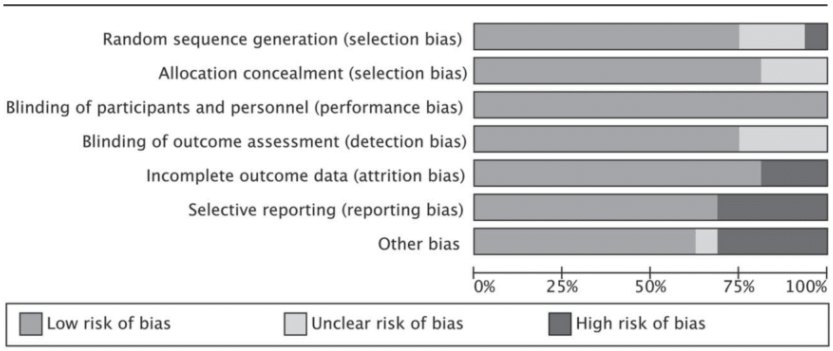

Figure 2. Summary of the risk of bias assessment.

The included studies were divided into 3 groups based on the force orientation used in the intervention: vertical orientation training (VT) included studies involving vertical jump, squat, deadlift, or other exercises in which the weight movement (body mass or extra load) is vertical; horizontal orientation training (HT) included studies involving horizontal or lateral jump, sprint, COD exercises; and mixed training (MT) included studies that combined both vertical and horizontal orientation in their intervention (10,16,56). To calculate the specific effects of the training program according to the force orientation on the COD performance tests, the postintervention mean values and *SDs* of both groups were used for each included study.

The standardized mean difference (SMD) between groups was conducted with *RevMan* using a random-effects model estimated with the DerSimonian and Laird method (27). The random-effects model is used when the assumption is that the effect across studies is randomly distributed around a central value. Data were required to be presented in one of the following formats: (a) mean and *SD* (preintervention and postintervention); (b) 95% confidence interval (CI) data for the postintervention change for each group; or if this was not available, (c) actual *p*-values for the postintervention change for each group; or if only the level of statistical significance was available, (d) default *p*-values (e.g., $p \leq 0.05$ becomes $p = 0.049$; $p \leq 0.01$ becomes $p = 0.0099$; and not significant p becomes $p \geq 0.05$). Forest plots were generated to demonstrate study-specific posttraining velocity differences and ES within a 95% CI. The combination of estimates allowed for the evaluation of a pooled effect, which took into account the estimated variance associated with the study and the estimated component of variance because of variation between studies, by adding the reciprocal sums of the 2 variances. The study-specific weight was derived as the inverse of the square of the respective standard errors. ES values of ≤0.2, ≤0.5, ≤0.8, and ≥0.8 were considered trivial, small, moderate, and large, respectively (23).

Furthermore, additional meta-analyses were conducted to assess the potential effects of moderator variables. Subgroup analyses were performed considering covariables with the potential bias that might influence the outcome of intervention as intervention duration (weeks), frequency (days·wk^{-1}), resistance training type, and assessment COD test. This approach provides a more accurate perspective on the issue addressed. For duration of the intervention and frequency, median split was used to form the subgroups and the analyses was conducted differentiating to force-orientation. For resistance training type, the classifications were PT according to force-orientation, strength training, COD training, or combined training. For the assessment COD test analyses, all COD tests used in the included studies were considered, independent of the force orientation of the intervention.

Results

Main Search

After the search process, 1,356 studies were identified for inclusion in the review, comprising 358 from PubMed, 376 from Scopus, 394 from Web of Science, and 228 from SPORTDiscus. Figure 1 provides a visual representation of the study selection process. Duplicate studies were eliminated ($n = 669$). In the first filter, which involved reviewing the title and abstract of each study, 608 studies were excluded, and 79 studies were selected for full-text review. After reviewing the full text of all studies, 65 studies were excluded because they did not meet all the inclusion criteria or the full text could not be retrieved, leaving a total of 16 studies included in the review and meta-analysis process. The pool of these studies included 192 participants (23% female) in 21 experimental groups and 168 participants (29% female) in 16 control groups. The summary of subject characteristics is shown in Table 1.

Methodological Quality

Publication bias could be observed on the funnel plot (Figure 3). Egger's test was significant ($t = -0.482$, $p = 0.004$). The funnel plot showed that the majority of data points reside within the funnel, except for 2 experimental groups in the MT subgroup (16,85). Therefore, complementary analyses were carried out to calculate the SMD without such studies. Moreover, the summary RoB are presented in Figure 2 and the individual RoB for each included study can be found in Supplemental Digital Content 1 (see Figure 1, http://links.lww.com/JSCR/A448). Low RoB was detected after the analysis following the Cochrane Collaboration Guidelines assessment. The main sources of bias were as follows: (a) selection bias (lack of or inadequate random sequence generation and allocation concealment of participants), which was rated as high risk in 1 study (85) and unclear in 3 studies (19,20,41); (b) attrition bias (incomplete outcome data), which was rated as high risk in 3 studies (19,48,62); (c) reporting bias (selective reporting), which was rated as high risk in 5 studies (1,3,5,6,19) because of authors not showing all data of interest in their studies; and (d) other biases, which were rated as unclear in one study (1) and high risk in 5 studies (3,5,41,71,85). Some of the included studies did not take into account other variables that may affect the final outcome of the intervention, such as initial

Table 1

Characteristics of the subjects of the studies included in the systematic review with meta-analysis.*

Reference	Subjects (*n*)	Sex	Age (y)	Level	Training experience
Alp (1)	*N* = 24; EG = 12, CG = 12	M	EG, 20.2 ± 1.5; CG, 21.2 ± 1.9	Collegiate	N/A
Arazi et al. (3)	*N* = 18; EG1 = 6, EG2 = 6, CG = 6	M	EG1, 18.0 ± 0.6; EG2, 18.1 ± 1.3; CG, 20.4 ± 0.6	Semi-prof	5.66 ± 2.58 y BE
Arede et al. (4)	*N* = 20; EG = 10, CG = 10	M	19.4 ± 4.3	Federated amateur	>1 y strength train
Asadi et al. (6)	*N* = 16; EG = 8, CG = 8	M	EG, 19.1 ± 0.8; CG, 20.0 ± 0.7	Semi-prof	5.62 ± 2.13 y BE
Asadi (5)	*N* = 20; EG = 10, CG = 10	M	EG, 19.1 ± 0.8; CG, 20.0 ± 0.7	1° province div.	N/A
Asadi et al. (9)	*N* = 16; EG = 8, CG = 8	M	18.5 ± 0.8	National level	7.5 ± 2.1 y BE
Aztarain-Cardiel et al. (10)	*N* = 40; EG1 = 11, EG2 = 9, EG3 = 10, CG = 7	M	EG1, 21.2 ± 2.0; EG2, 23.1 ± 3.7; EG3, 21.5 ± 2.0; CG, 21.0 ± 5.8	Federated amateur	N/A
Brini et al. (15)	*N* = 16; EG = 8, CG = 8	M	22.1 ± 2.8	Prof (2° national div.)	11.8 ± 3.9 y BE
Brini et al. (16)	*N* = 52; EG1 = 13, EG2 = 13, EG3 = 13, CG = 13	M	EG1, 26.0 ± 2.4; EG2, 25.7 ± 1.8; EG3, 26.1 ± 1.8; CG, 26.3 ± 2.1	Prof (1° national div.)	11.4 ± 3.6 y BE
Cherni et al. (19)	*N* = 26; EG = 13, CG = 12	F	EG, 20.9 ± 2.6; CG, 21.0 ± 3.0	Elite national level	10.8 ± 4.8 y BE
Cherni et al. (20)	*N* = 27; EG = 15, CG = 12	F	EG, 20.9 ± 2.4; CG, 21.0 ± 3.0	Elite national level	10.8 ± 4.8 y BE
Hoffman et al. (41)	*N* = 15; EG = 6, CG = 9	M	EG, 19.2 ± 1.8; CG, 18.8 ± 0.7	Collegiate	No strength experience
Maggioni et al. (48)	*N* = 24; EG = 9, CG = 9	M	19.0 ± 1.0	Collegiate	10.0 ± 2.0 y BE
Nuhmani (62)	*N* = 59; EG = 23, CG = 25	F	EG, 20.3 ± 2.3; CG, 20.0 ± 2.1	Federated amateur	N/A
Poomsalood et al. (71)	*N* = 10; EG = 5, CG = 5	M	EG, 19.6 ± 1.3; CG, 19.2 ± 0.8	Collegiate	N/A
Usgu et al. (85)	*N* = 28; EG = 14, CG = 14	M	EG, 26.6 ± 5.9; CG, 22.4 ± 4.2	EG, Prof (1° div.) CG, Prof (2° div.)	N/A

*EG = experimental group; CG = control group; M = male; F = female; Prof = professionals; Div = division; BE = basketball experience; N/A = not available.

differences between groups, validity of the measurement instruments used in the assessment, or did not balance the total workload between the 2 groups, which could result in improvements simply because of a higher workload in the experimental group.

Training Intervention Description

The characteristics and effects of all interventions included in this study are described in Table 2. The control group for all interventions was limited to regular basketball practice only, except for one in the MT group (85), in which the workload was equalized between both groups by adding traditional vertical strength training in the control group. PT was the most frequently used because it was used in 16 experimental groups (76%). Two interventions combined PT with strength training (62,85), and one combined it with COD training (16). The in-season period was when the highest number of interventions was carried out (81%) with a duration of 4–20 weeks, with 8 weeks being the most frequently used duration (38%). The training frequency used in all studies was 2 (71%) to 3 (29%) training days per week. The change in COD performance induced by the interventions was not always measured by the same test, and the COD test used in each study was shown in Table 2. Specifically, the *T*-test was the most performed (87.4%), where the player had to travel a total of 40 m and while maneuvering, performed 2 COD at 90° and 2 COD at 180° in a T-shaped circuit with the aim of moving in all directions in the least time possible, moving forward, sideways, and backward (a situation similar to that encountered in a real basketball game) (49). The other tests used were also maneuverability tests (59), in which different types of displacements were performed over 25 m or more and with several CODs

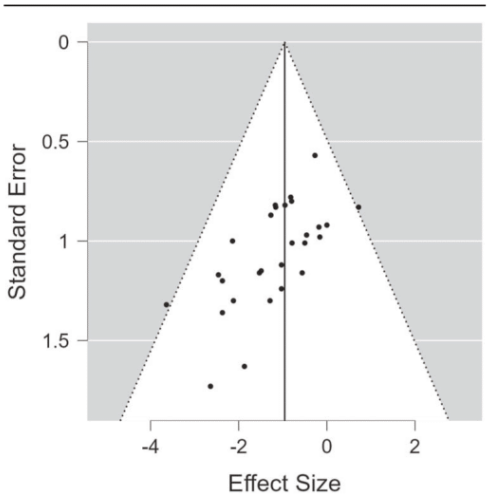

Figure 3. Funnel plot of all studies included.

Table 2

Intervention characteristics of the studies included in the systematic review with meta-analysis.*

Reference	Type of training	Force orientation	Main variables description	Period, duration, frequency	COD test assessed	% Change pre-post
Alp (1)	PT	Mix	Multidirectional jumps, hops and bounds with body weight	In-season, 8 wk, 3 d·wk^{-1}	*T*-test	EG: 1.2 CG: 2.6
Arazi et al. (3); EG1	Aquatic PT	Mix	*3 × 8–25 reps of each exercise:* AJ, SJ, speed and skipping drill	In-season, 8 wk, 3 d·wk^{-1}	*T*-test Illinois test	EG (T-t): 18.7 CG (T-t): 0.6 EG (It): 6.3 CG (It): 0.4
Arazi et al. (3); EG2	Land PT	Mix	*3 × 8–25 reps of each exercise:* AJ, SJ, speed and skipping drill	In-season, 8 wk, 3 d·wk^{-1}	*T*-test Illinois test	EG (T-t): 10.6 CG (T-t): 0.6 EG (It): 6.5 CG (It): 0.4
Arede et al. (4)	ST	Vertical	*2 blocks × 5 sets × 5 reps of:* parallel back squat	In-season, 10 wk, 2 d·wk^{-1}	V-cut	EG: 4.5 CG: 2.2
Asadi et al. (6)	PT	Mix	*3 × 20 reps of each exercise:* DJ (0.45 m BH), SJ (0.45 m BH), and DBJ (0.45 m BH)	Preseason, 6 wk, 2 d·wk^{-1}	*T*-test Illinois test	EG (T-t): 9.7 CG (T-t): −0.4 EG (It): 7.6 CG (It): 0.2
Asadi A. (5)	PT	Mix	*3 × 15 reps of each exercise:* DJ (0.45 m BH), SJ, and BJ	In-season, 6 wk, 2 d·wk^{-1}	*T*-test Illinois test	EG (T-t): 9.4 CG (T-t): −3.3 EG (It): 7.6 CG (It): 0.4
Asadi et al. (9)	PT	Vertical	*3 × 8–25 reps of each exercise:* AJ, SL-TJ, CMJ, and SL-CMJ	Preseason, 8 wk, 3 d·wk^{-1}	*T*-test Illinois test	EG (T-t): 9.3 CG (T-t): −0.2 EG (It): 6.2 CG (It): 0.3
Aztarain-Cardiel et al. (10); G1	PT	Vertical	*2 × 3–6 reps of:* CMJ, VH, and continuous (CMJ, VH)—3′ rest	In-season, 6 wk, 2 d·wk^{-1}	V-cut	EG: 7.5 CG: 1.2
Aztarain-Cardiel et al. (10); G1	PT	Horizontal	*2 × 3–6 reps of:* BJ, BH, and continuous (BJ, BH)—3′ rest	In-season, 6 wk, 2 d·wk^{-1}	V-cut	EG: 4.8 CG: 1.2
Aztarain-Cardiel et al. (10); G1	PT	Mix	*1 × 3–6 reps of:* CMJ, BJ, VH, BH, and continuous (CMJ, BJ, VH, BH)—3′ rest	In-season, 6 wk, 2 d·wk^{-1}	V-cut	EG: 5.9 CG: 1.2
Brini et al. (15)	MRSAT	Horizontal	*3 × 8 reps × 30 m* (6 × 5 m 90° COD), 20″–4′ rest	In-season, 12 wk, 2 d·wk^{-1}	*T*-test	EG: 3.5 CG: 1.7
Brini et al. (16); G1	PT	Vertical	*3 × 8–12 reps of:* DJ (0.5 m BH), 40″–3′ rest	In-season, 8 wk, 2 d·wk^{-1}	*T*-test	EG: 1.0 CG: 0.3
Brini et al. (16); G2	MRSAT	Horizontal	*3 × 8–10 reps × 30 m* (6 × 5 m 90° COD), 20″–4′ rest	In-season, 8 wk, 2 d·wk^{-1}	*T*-test	EG: 2.1 CG: 0.3
Brini et al. (16); G3	Combined PT and MRSAT	Mix	*3 × 8–10 reps of:* DJ (0.5 m BH) + *30 m* (6 × 5 m 90° COD), 20″–4′ rest	In-season, 8 wk, 2 d·wk^{-1}	*T*-test	EG: 2.6 CG: 0.3
Cherni et al. (19)	PT	Vertical	*4-7 × 6 reps of each exercise:* CMJ, HJ (0.4 m hurdle), and DJ (0.4 m BH)	In-season, 6 wk, 2 d·wk^{-1}	*T*-test	EG: 4.1 CG: −1.9
Cherni et al. (20)	PT	Vertical	*4-7 × 6 reps of each exercise:* CMJ, HJ (0.4 m hurdle), and DJ (0.4 m BH), 2′ rest	In-season, 8 wk, 2 d·wk^{-1}	*T*-test	EG: 4.1 CG: −1.9
Hoffman et al. (41)	ST	Vertical	*3 × 5–8 reps of each exercise:* PC, squat, CR, core, and others	In-season, 20 wk, 2 d·wk^{-1}	*T*-test	EG: 3.0 CG: 2.9
Maggioni et al. (48)	MRSAT	Horizontal	*3 × 6 reps × 40 m* (2 × 20 m 180° COD), 20″–3′ rest	In-season, 8 wk, 3 d·wk^{-1}	*T*-test Lane test	EG (T-t): 5.3 CG (T-t): 2.1 EG (Lt): 2.2 CG (Lt): 0.7
Nuhmani (62)	Combined ST and PT	Mix	FIFA 11+	In-season, 12 wk, 3 d·wk^{-1}	*T*-test	EG: 4.0 CG: 3.0

Table 2
Intervention characteristics of the studies included in the systematic review with meta-analysis.* *(Continued)*

Reference	Type of training	Force orientation	Main variables description	Period, duration, frequency	COD test assessed	% Change pre-post
Poomsalood et al. (71)	PT	Mix	*3–5 × 6–12 reps of each exercise:* SH, BH, VH, DH, and others	Pre-season, 4 wk, 2 d·wk^{-1}	*T*-test	EG: 11.0 CG: −0.8
Usgu et al. (85)	Combined ST and PT	Mix	*2-4 × 6–15 reps of each exercise:* SJ, side lunge, core, and others	In-season, 20 wk, 2 d·wk^{-1}	*T*-test Lane test	EG (T-t): 3.9 CG (T-t): 1.0 EG (Lt): 1.6 CG (Lt): 2.2

*COD = change of direction; PT = plyometric training; ST = strength training; MRSAT = multidirectional repeated sprint ability training; EG = experimental group; CG = control group; T-t = *T*-test; It = Illinois test; Lt = Lane test; PC = power clean; CR = calf raise; DJ = depth jump; SJ = squat jump; BJ = broad jump; DBJ = depth broad jump; BH = box height; AJ = ankle jump; SH = side hop; BH = broad hop; VH = vertical hop; DH = diagonal hop; SL = single leg; TJ = tuck jump; CMJ = countermovement jump; HJ = hurdle jump; m = meter; COD = change of direction; d·wk^{-1} = days·wk^{-1}.

between 45° and 180°. It is worth noting that none of the studies included an COD assessment in isolation.

Meta-analysis Results

A total of 28 intergroup comparisons involving 558 athletes (18% female) were included in the meta-analysis (Figure 4). In general, there were significant changes in COD actions ($p < 0.001$; ES, −1.12). The observed heterogeneity between all included studies (I^2, 67%; $p < 0.01$) and between the 3 intervention groups (I^2, 31.3%; $p < 0.23$) was high and moderate, respectively. Individually, all included interventions had a positive effect on COD performance, with a pre-post percentage change ranging from 1.2 to 18.7% (Table 2). Regarding ES analysis, interventions ranged from no ES to very large ES (Figure 4). The studies with the highest percentage change and ES were from the MT group. Thus, MT had the highest overall ES (ES = −1.41 [95% CI −1.99, −0.83], $Z = 4.80$ [$p < 0.01$]) across 15 intergroup comparisons (1,3,5,6,10,16,62,71,85) involving 301 athletes (16% female; Figure 4C), although the heterogeneity level was high (I^2, 77%; $p < 0.001$). When 2 outlier comparisons in MT were excluded (16,85), the ES result remained very similar (ES = −1.38 [95% CI −1.85, −0.91], $Z = 5.78$ [$p < 0.01$]), with a lower heterogeneity level (I^2, 58%; $p = 0.004$). As for the other force-orientations, VT showed significant changes with a large ES (ES = −1.05 [95% CI −1.39, −0.72], $Z = 6.14$ [$p < 0.01$]) and a low heterogeneity level (I^2, 0%; $p = 0.85$; Figure 4B) through 8 intergroup comparisons (4,9,10,16,19,20,41) and 163 players (32% female). Finally, HT did not have any significant effect on COD performance (ES = −0.59 [95% CI −1.35, 0.38], $Z = 1.51$ [$p = 0.13$]) across 5 intergroup comparisons (10,15,16,48) involving 94 athletes (0% female; Figure 4A).

Moderator Variables Effect

The effects of the moderator variables were displayed in Table 3. For all force-orientations trained, the analysis showed a larger ES on COD performance for training interventions shorter than 7 weeks (ES = −0.25 to −1.13) compared with those of longer than 7 weeks (ES = −0.07 to −0.18). The ES was also larger in high-frequency training (3 d·wk^{-1}) than in low-frequency training (2 d·wk^{-1}) for VT and MT; however, the ES for HT was not significant. Regarding the resistance training type, PT was the type that shown a higher ES (ES = −1.24 [95% CI −1.65, −0.83]) on COD performance. But analyzing the force-orientations, mixed (ES = −1.34 [95% CI −2.44, −0.25]) and vertical (ES = −1.10 [95% CI −1.48, −0.72]) PT exhibited the greatest changes, whereas the horizontal PT showed no significant changes. Combined MT (ES = −1.34 [95% CI −2.44, −0.25]) and strength VT training (ES = −0.89 [95% CI −1.60, −0.18]) also showed large ES. In addition, this moderator analysis of COD tests determined that *T*-test (ES = −1.24 [95% CI −1.73, −0.75]) and Illinois test (ES = −1.68 [95% CI −2.24, −1.13]) are the most sensitive tests for detecting changes in COD performance.

Discussion

The main objective of this meta-analysis was to investigate the effect of different training interventions on the performance of COD in adult basketball players of both genders. Specifically, the impact of force orientation (vertical, horizontal, or mixed) during training on COD performance was studied, with the aim of informing coaches' decisions regarding athlete training programs. It was hypothesized that combined vertical and horizontal training would be the most effective intervention, consistent with the specificity principle (35,66,75) and with the highly complex and multidirectional nature of COD actions (30,53). The analysis revealed that combined vertically and horizontally oriented training was indeed the most effective intervention for improving COD performance. These findings suggest that coaches should prioritize incorporating both vertical and horizontal tasks into their athletes' training programs when looking to optimize COD development.

Based on the results of this meta-analysis, the HT showed the lowest improvement in COD actions, with horizontal jumping interventions (36–72 contacts per session) (10) and COD training at 90° (15,16) and 180° (48) (total volume of 240 m·per session). Given the complexity of the COD and the high horizontal force requirements observed in these actions in previous research (11,53), these findings were unexpected. But this could be justified because, although the horizontal force demands in COD actions are high, gravity always acts in all sporting actions and the vertical force demands could be greater (75). However, previous research has found a relationship between the mechanical variables of the horizontal force-velocity profile (F-Vp) and COD performance in soccer ($r \leq -0.54$; $p \leq 0.03$) (76) and volleyball players ($r \leq -0.42$; $p < 0.01$) (70). Within the horizontal force variables, maximal strength ($r \leq -0.42$; $p \leq 0.02$) and power ($r \leq -0.58$; $p < 0.01$), and the ability to apply horizontal force effectively with a more forward orientation to the ground ($r \leq -0.54$; $p < 0.05$), correlated most strongly with COD performance.

To improve force generation in these variables of the horizontal F-Vp, Morin et al. (58) observed that soccer players

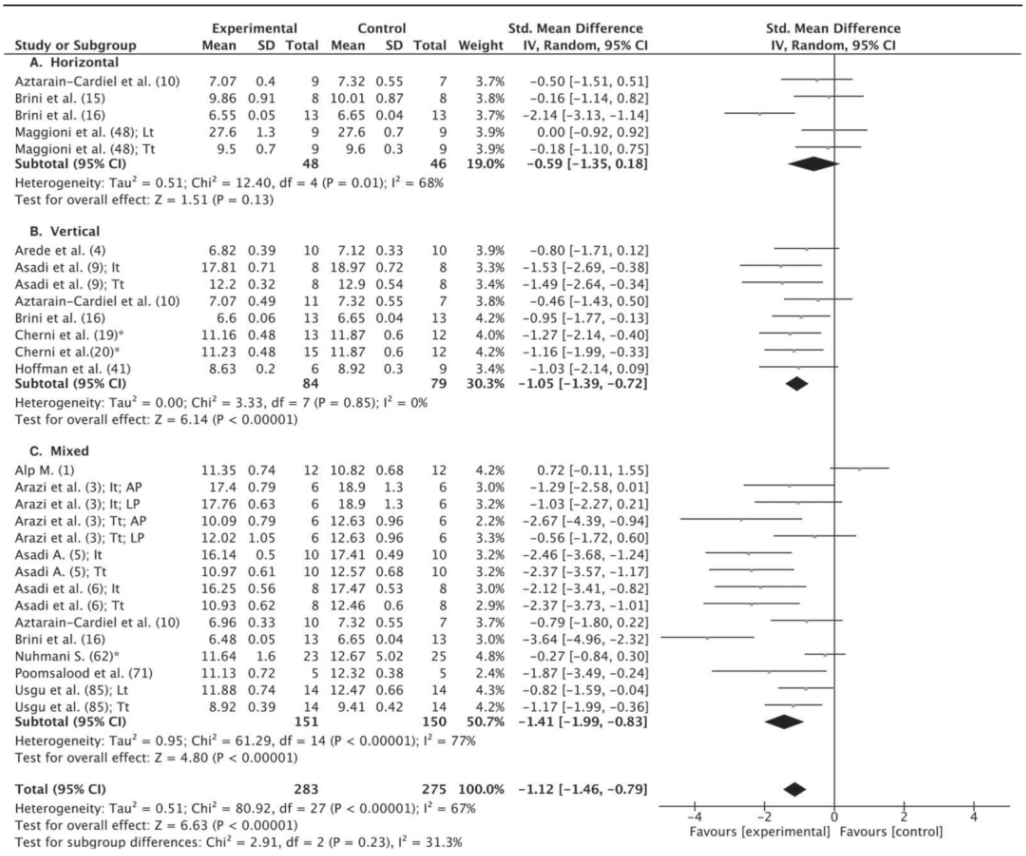

Figure 4. Forest plot comparing the effect of (A) horizontal orientation training, (B) vertical orientation training, and (C) mixed training and total effect on COD test. *Female sample. COD = change of direction.

improved their horizontal peak force production and mechanical effectiveness with heavy sled drag training. Specifically, the optimal load for maximizing power during sled-resisted sprint ranged between 69 and 96% of body mass depending on friction conditions (24). Lahti et al. (45) determined that an individualized training approach with resisted or assisted sprints is necessary based on the initial force production needs of each athlete to optimize mechanics and increase horizontal force production in sprint and COD actions (12). Therefore, it is recommended to work across the entire horizontal force spectrum, from the application of maximum forces with the sled at low speeds to the production of force at supramaximal speeds, according to the individual mechanical and force needs of each athlete (39). It is insufficient in most cases to work exclusively at the sprint speed itself to improve COD.

Regarding the horizontal interventions included in this study (10,15,16,48), all of them focused on the acceleration phase as part of the COD (21), but none of them proposed specific horizontal deceleration work that plays a key role in these actions (37,54). Previous research (33,46) recommended more horizontal work on eccentric actions and deceleration exercises to improve this COD phase. Moreover, none of the included studies had proposed individualized training or used high loads to resist movement. Therefore, it could be assumed that the stimulus applied with the training was not sufficient to generate adaptations in the performance of the athletes, which could explain the small effect found in this HT group. Furthermore, because of the limited number of studies and the different COD tests used, it would be difficult to draw clear conclusions about the effect of this training method on COD performance. Regarding the tests used, the *T*-test was the one that showed the greatest pre-post intervention changes in this group (16) and in comparison with other tests (48).

Although COD is a multidirectional skill, vertical force is typically greater than horizontal force for each athlete during COD (75). Previous research has also shown that there is a high correlation between the variables of the vertical F-Vp and COD actions in basketball players (13), with the most demanding CODs (≥90° cut) being more related to the vertical F-Vp variables ($r \geq 0.52$; $p \leq 0.05$). This meta-analysis supported these previous findings because vertically oriented training produced greater improvements in COD performance compared with horizontally oriented training. In addition, those interventions that used COD tests with angulations of 45° (i.e., V-cut) achieved lower improvements (4,10) than others that used tests with angulations ≥90° (i.e., *T*-test or Illinois test).

In this group, PT is a well-studied training method for improving COD performance (8) because it has been shown to generate great changes in basketball players' COD performance (74). The study of Asadi et al. (9) with vertical PT was found to be particularly effective in improving players' performance. The results of this meta-analysis show how vertical PT (9,10,16,19,20) is more effective than strength training (4,41) when both trainings are performed separately, possibly because PT is performed at higher speeds and vertical jumping actions show peaks of muscle activation similar to those in COD actions (64). PT improves intermuscular and intramuscular coordination, which promotes improvements in neural drive of agonist muscles, facilitates faster

Table 3

Influence of moderator variables according to the force-orientation trained on change of direction performance and sensitivity analysis of the COD test used.*†

Moderator variables	Outcome or subgroup	Studies	Effect estimate (standardized mean difference [95% CI])
Number of weeks according to force-orientation		28	−0.13 [−0.15, −0.11]
	HT < 7 wk	1	−0.25 [−0.73, −0.23]
	HT > 7 wk	4	−0.10 [−0.14, −0.06]
	VT < 7 wk	2	−0.52 [−0.84, −0.19]
	VT > 7 wk	6	−0.07 [−0.11, −0.03]
	MT < 7 wk	6	−1.13 [−1.35, −0.92]
	MT > 7 wk	9	−0.18 [−0.21, −0.14]
Frequency (training·per week) according to force-orientation		28	−0.13 [−0.15, −0.11]
	HT 2 $d \cdot wk^{-1}$	3	−0.10 [−0.14, −0.07]
	HT 3 $d \cdot wk^{-1}$	2	−0.08 [−0.52, 0.36]
	VT 2 $d \cdot wk^{-1}$	6	−0.07 [−0.11, −0.03]
	VT 3 $d \cdot wk^{-1}$	2	−0.83 [−1.20, −0.46]
	MT 2 $d \cdot wk^{-1}$	9	−0.20 [−0.23, −0.17]
	MT 3 $d \cdot wk^{-1}$	6	−0.54 [−0.93, −0.15]
Resistance training type according to force-orientation		28	−1.12 [−1.46, −0.79]
	HT plyometric	1	−0.50 [−1.51, 0.51]
	HT COD	4	−0.61 [−1.57, 0.36]
	VT plyometric	6	−1.10 [−1.48, −0.72]
	VT strength	2	−0.89 [−1.60, −0.18]
	MT plyometric	11	−1.45 [−2.18, −0.73]
	MT combined	4	−1.34 [−2.44, −0.25]
COD test		28	−1.13 [−1.47, −0.80]
	T test	17	−1.24 [−1.73, −0.75]
	Illinois test	5	−1.68 [−2.24, −1.13]
	V-cut	4	−0.64 [−1.13, −0.16]
	Lane test	2	−0.45 [−1.25, 0.35]

*COD, change of direction; HT, horizontal orientation training; VT, vertical orientation training; MT, mixed orientation training; CI, confidence interval.
†Negative effect size favors experimental group; positive effect size favors control group.

switch between muscle actions, which aids in a more efficient SSC (74). These adaptations allow the athlete to reduce reaction times to the ground, increase muscle force production, improvement of RFD, and movement efficiency, which positively affects the speed of the COD. Regarding this training method, previous meta-analyses have recommended that PT should be performed 2–3 times a week for a minimum of 6–8 weeks, with a total of 800–1,200 jumps in that period (8). It is also important to have a rest of at least 60–120 seconds between sets and 48–72 hours between training sessions to maximize the improvement in COD performance (8). It is worth noting that young players who want to improve their COD ability should be introduced to this type of training in their middle peak height velocity maturation stage (approximately 13–15.9 years old) because this is when the development of SSC capabilities start accelerating (7). Furthermore, although unilateral training may be more specific to COD actions (89), previous studies found that bilateral training was more effective than unilateral training for improving COD actions at 50° cut-off (2). This might be explained by the fact that, even though COD actions are generally unilateral, athletes often use an asymmetric bilateral strategy during large COD angles. Therefore, the combined use of both training modalities is recommended (57).

However, it is important to note that all the studies included in this group (4,9,10,16,19,20,41) recruited young adult basketball players without any previous experience in strength training. Although these vertically oriented training methods have demonstrated effectiveness, their efficacy appears to diminish in experienced athletes with higher levels of strength who aim to enhance sport-specific physical qualities (44,90).

Based on previous literature, it has been suggested that combining different directions of motion is the most optimal training approach to improve performance in complex actions such as COD (10,47) because of the fact that in these actions 3-dimensional forces act to move the athlete in the desired horizontal or lateral direction and oppose gravity. Furthermore, mixed training has been shown to be more effective than either vertical or horizontal training alone in improving COD performance in basketball (10,16) and football (73) players. The meta-analysis findings support these ideas because the interventions that combined vertical and horizontal force-orientations showed the greatest improvements in COD performance. However, the high heterogeneity observed in the MT results (I^2 = 77%) suggests that more studies are needed to obtain conclusive evidence.

In addition, some studies included in the review not only combined different training force orientations but also different training methods. Usgu et al. (85) analyzed the effects of combined strength and plyometric training, and Brini et al. (16) combined PT with multidirectional repeated sprint ability training. This combination of training methods showed in both cases a large training effect. These results are consistent with previous research, where Hammami et al. (36) indicated that combined strength and plyometric training has a greater effect on COD performance than isolated PT. Moreover, a previous meta-analysis studying the efficacy of different training sequences (50) concluded that combined strength and plyometric training is more effective in improving peak strength, power, and speed in the lower limbs than traditional strength training alone. The advantage of this type of combined training is that athletes may improve multiple determinants of COD performance

simultaneously (63) by performing a greater variety of specific stimuli to prepare them to meet the demands of COD in real-game situations. However, to maximizes the benefits of this training sequence, it is important to carefully quantify the load of each type of stimulus to achieve the desired adaptations. In this regard, previous research suggests that moderate training frequency ($\leq$2) is optimal (25). Moreover, it is recommended to perform a low volume of high-load exercise in a specific range of motion relevant to COD (i.e., $\geq$85% repetition maximum in half squat) combined with low-load exercises in which specific COD actions are performed (63). Also, previous studies (80,86) recommended long rest intervals (>3 minutes) between strength and plyometric exercises to enhance COD performance.

These results indicate that training force-orientation is a critical variable in determining training adaptations for COD. Although all training orientations analyzed in this study included a similar training volume and showed positive effects on COD performance, the MT group demonstrated the greatest improvements. Therefore, when other training variables are properly controlled and managed, mixed vertically and horizontally oriented training is proposed as the most optimal training method because it provides a greater variety of multidirectional stimuli that better prepare the athlete for real-game situations. Moreover, it is important to consider the training surface as another critical variable for improving COD performance because Arazi et al. (3) explained how aquatic PT produced significantly greater improvements in COD performance than land PT. In this regard, the buoyancy effect of water allowed for lower loads, faster SSC, and decreased damping phase, which facilitated greater neural adaptations and improved motor unit recruitment (51,81). The athletes were able to reduce contact times with the ground during COD, which is a determinant of performance in these actions (13,88).

Moderator analysis highlighted the variables that potentially have the most influence on the final result of the training, so coaches and physical trainers should consider when designing training programs. Although different training durations and frequencies showed significant improvements in every force-orientation, surprisingly it was a short (<7 weeks) and high-frequency (3 $d \cdot wk^{-1}$) program that produced the largest ES in all force-orientations. This contrasts with previous research that supports the need for long training programs for greater improvements (56,57). These findings could be explained becuase neuromuscular adaptations may be gained in short periods (32,42) and these adaptations lead to direct improvements in the most determinant variables of COD performance (i.e., speed, power, or RFD) (11,13). Once these neuromuscular improvements have been obtained, if the stimulus is unchanged, the adaptations on COD performance could be limited. Furthermore, the moderator analysis results indicate that a high training frequency leads to higher COD performance. This is in accordance with previous research findings (8) and may be explained because COD actions are technically complex (18,28,29,38), so that high-frequency training may contribute to improve the motor pattern.

Another notable result from the moderator analysis, according to resistance training type, was the finding that a multidirectional plyometric training was more effective than either orientations performed in isolation or another training type. These findings reinforce the large body of scientific evidence already available about the efficacy of plyometric training on COD performance (8,63,68,74), but it is worth highlighting the relevance of providing multidirectional stimuli during training according to the current results. However, combined training also showed a large ES on the effect on COD performance. In this sense, our results are consistent with previous studies (36,50) that showed that combined training is a really good choice to improve COD performance because it offers a wide variety of stimuli specific to these actions.

Finally, moderator analysis showed that the Illinois and *T*-test were the most sensitive for detecting changes in COD performance. The Lane test, which is a test with basketball-specific movements and path, was the least sensitive to detect changes in COD performance. Nevertheless, all the tests used to assess the COD performance were maneuverability tests (59) in which different types of displacements, distances covered, number, and angles of cuts were executed. This type of test is influenced by a multitude of factors (38,69), so it would not be the most advisable for analyzing the effect of the intervention on COD actions. Because more than 70% of the performance in these tests is directly influenced by linear speed (59), in future interventions, it would be recommended to use tests with a single COD, short distances and to analyze the effect of training on the COD deficit to isolate the COD action as much as possible (33,60,61).

Although this meta-analysis presents interesting findings, it is important to acknowledge its potential limitations. First, although all studies were classified as moderate-high quality according to the Cochrane Collaboration Guidelines Assessment, 5 of them showed a risk of bias by not taking into account other variables that may affect the final outcome of the intervention, such as differences in baseline performance between groups or not matching workloads and not using valid measurement instruments in the assessment. Second, even though an assessment of the potential effects of moderator variables was undertaken to show their effect on final COD performance, some subgroups did not have a representative number of studies. Thus, caution should be exercised in drawing conclusions. Third, it is worth noting that most of the sample consisted of basketball players with a limited experience in strength training. Therefore, caution should be exercised when generalizing the conclusions to highly trained basketball players. Finally, although the use of a specific sport and adult age group was intended to avoid possible maturation effects, the results of several groups showed high heterogeneity, as has been observed in previous meta-analyses. This could be attributed to the inclusion of both genders and different levels of sport, but it might be mainly because of the wide variety of COD tests used to assess the effects of training. Therefore, future intervention studies with a well-standardized methodology would be necessary to provide a more accurate understanding of this issue.

Additionally, it was noted that horizontally oriented training was less represented in the literature compared with vertically oriented training, despite its potential benefits. Future studies should consider horizontally oriented resisted and assisted interventions to further investigate its effectiveness. Furthermore, the inclusion of women in research on COD performance is still limited, with only 18% of studies in this review including female participants (19,20,62). Future studies should consider including more female athletes to gain insights into how training interventions affect their performance. It is also recommended that future interventions take a more individualized approach, adapting training proposals to the unique needs of each athlete based on previously evaluated variables. Finally, there is no gold standard assessment to evaluate COD performance, so not all researchers use the same test and results may not be comparable (3,5,9). In this regard, seeing as differing angles of COD are proposed to be unique physical capabilities (30), it is recommended

standardizing the assessment of COD with a battery of several COD tests with a single cut-off and various angles to create a "COD angle profile" for each athlete (34). This would allow a more accurate analysis of the training effect on the performance of different COD angles.

Practical Applications

This research suggests that regardless of the training methodology, the orientation of the force is a key factor when improving performance in multidirectional actions like COD. It is recommended to use mixed vertical and horizontally oriented training to prepare athletes for real-game situations. Additionally, a training program with a duration of 6 weeks and 3 sessions per week is recommended because it might be sufficient to optimize the COD performance of basketball players. Plyometric training is the best way to improve the COD performance of your athletes, but if you combine it with other training modalities such as strength, speed, or COD technique, and with different force-orientations, you could get more specific adaptations to the real game for the athletes. Finally, a training program should focus on the most demanding area of the force-velocity curve, depending on the context of each player. This individualized approach could help athletes achieve optimal results in COD performance.

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STUDY 9

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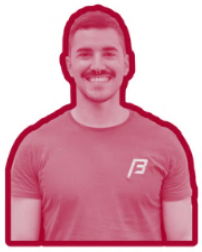
Effect of individualised strength and plyometric training on the physical performance of basketball players



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Effect of individualised strength and plyometric training on the physical performance of basketball players

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ABSTRACT

The aims of this study were to examine the effects of eight weeks of individualised force-velocity imbalance (F-Vimb) training on physical performance in basketball players and to analyse the differences in physical performance between two periods of time (four to eight weeks) with this training. Thirty male players (age, 22.8 ± 5.68 years; height, 1.87 ± 0.07 m; body mass, 86.3 ± 11.1 kg) were divided into an intervention group (INT, $n = 15$), who performed an individualised training based on individual F-Vimb; and a control group (CON, $n = 15$), who underwent a non-individualised training programme; both groups performed two days/week of intervention and the same pre-season basketball training. At baseline, at four weeks, and at eight weeks of intervention, an assessment was performed including countermovement-jumps, unilateral drop jumps, triple hop test, force-velocity profile, sprint and change of direction (COD). At four weeks, the INT showed improvements in sprint and vertical jumping actions (≥3.76%, ES ≥0.44, $p \leq 0.02$). At eight weeks, the INT continued to improve vertical jumping actions ($p < 0.05$) and showed improvements in horizontal jumping (6.80%, ES = 0.45, $p < 0.01$) and COD (≥2.99%, ES ≥0.96, $p < 0.01$). A significant reduction in F-Vimb was observed for INT (ES = 0.77, $p = 0.01$). In contrast, none of these changes were observed in CON. Thus, an individualised F-Vimb training intervention improved physical performance after eight weeks, with changes in sprint and vertical jump after first four weeks. Basketball coaches should optimise the force-velocity profile and improve the performance in sport-related actions as jumping and changing direction.

Highlights

- An individualised F-Vimb training programme improved sport-specific actions after eight weeks in basketball athletes.
- Improvements were specific to the orientation worked on, with vertical jumping and sprint actions being the most sensitive to change after just four weeks of individualised F-Vimb intervention.
- In complex actions such as COD, it would be recommended to optimise the F-V profile, emphasising a vertical force-orientation for at least 8 weeks.

KEYWORDS
Athletic performance; acceleration; muscle strength; agility; force-velocity profile; team sport

Introduction

High-intensity ballistic actions such as jumps, sprint and change of direction (COD) are critical to achieve the best result in a match of complex and dynamic team sports such as basketball (Abdelkrim et al., 2010; García et al., 2020). Within these high-intensity actions, the most frequent actions during games in elite basketball players for all playing positions are the directional changes (Salazar et al., 2020). In a match, 15.1% of the directional changes occur at high intensity ($<-3.5\ m{\cdot}s^{-2}$) (Svilar et al., 2018). COD is defined as the ability to decelerate and accelerate in a different direction in a planned manner (Nimphius et al., 2018). Although, during real games, COD occur mainly in reaction to external stimuli (e.g. movement of the ball or an opponent), the planned COD movements represent the mechanical and physiological basis for understanding the real situation. Both for offensive and defensive purposes, these high-speed movements are essential given the short duration of decisive actions in the game. Thus, to gain a physical advantage over the opponent in basketball, it becomes necessary to improve the COD (Brini et al., 2020). Therefore, the improvement of such physical attributes should be a priority in training programmes for basketball players.

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Previous studies have found that maximal strength and lower limb rate of force development (RFD) are factors that strongly influence COD performance (Barrera-Domínguez et al., 2020; Young et al., 2002). To improve the performance of this action, it has been recommended to implement specific programmes based on the individual force demands of each athlete (Barrera-Domínguez et al., 2020; Jiménez-Reyes et al., 2019) with similar movement patterns and force applications to COD (Falch et al., 2019). In this context, plyometric training is the modality most studied (Falch et al., 2019). Plyometric training showed COD improvements with effect sizes (ES) ranging from small (ES = 0.26) to large (ES = 2.8), depending on the type of COD test and the sample used (Asadi et al., 2016). In particular, when the sample is specifically composed of basketball players, plyometric training has also shown large improvements in the performance of COD (ES = 1.65) (Ramirez-Campillo et al., 2021). However, previous studies found that training with alternate heavy and light exercises set by set was more effective in improving peak strength, power and speed than other modalities such as strength training (Marshall et al., 2021) or plyometric training in elite level football players (Hammami et al., 2019). The main limitation of previous intervention research (Asadi et al., 2016; Falch et al., 2019) is that it has a "one-size-fits-all" approach to develop specific strength training programmes focusing on improving COD, without considering the individual needs in terms of physical capabilities, or individual responses to training over the course of the programme (Jiménez-Reyes et al., 2019).

Individualised training according to the strength demands of each athlete based on vertical force-velocity (F-V) profile (Samozino et al., 2012) could induce significant improvements in vertical jump actions compared to a training programme without individualisation (Jiménez-Reyes et al., 2016, 2019). This F-V profile allows coaches to characterise the mechanical capabilities of the musculoskeletal system to produce force, power and velocity with a simple linear model that could calculate the maximal theoretical force (F0), maximal theoretical velocity (V0) and maximal power (Pmax = F0·V0/4) (Jaric, 2015). It has also been theoretically proposed (Samozino et al., 2012) and experimentally supported (Samozino et al., 2014) that there is an optimal F-V profile for each athlete and, this optimal F-V profile is the one that maximises the ballistic performance (e.g. vertical or inclined jumping) and represents the optimal balance between force and velocity qualities for these movements (Samozino et al., 2014, 2012). Due to the optimal F-V profile for each athlete, it is possible to calculate the individual F-V Imbalance (F-Vimb) of each subject with respect to their individual F-V profile. Moreover, this F-Vimb has significant indirect associations with COD performance actions (Barrera-Domínguez et al., 2020) and allows training optimisation (Jiménez-Reyes et al., 2016). To our knowledge, there is no current evidence demonstrating the positive impact of individualised F-Vimb training on the direct improvement of COD.

Based on previous literature, our main objective was to examine the effects of an individualised F-Vimb combined strength and plyometric training programme on physical performance of basketball players. A secondary objective was proposed to analyse the differences in physical performance between two periods of time (four to eight weeks) with the same training. Individualised F-Vimb training has already shown great improvements in jumping actions (Jiménez-Reyes et al., 2016, 2019), so it was hypothesised that this training will also offer significant improvements in COD. Furthermore, and as a second hypothesis, although training with a duration of eight weeks is the most studied in the scientific literature and produces great improvements, it was hypothesised that four weeks are sufficient to significantly improve physical performance in our assessed vertical variables, such as countermovement jump (CMJ) or unilateral drop jump (DJu).

Materials and methods

Participants

Thirty male basketball players from the same club competing at the national level were randomly assigned into two groups, one intervention group (INT, $n = 15$; age, 22.9 ± 6.52 years; height, 1.88 ± 0.08 m; body mass, 90.3 ± 23.0 kg) who underwent an individualised F-Vimb intervention following the protocol of Jiménez-Reyes et al. (2016, 2019); and other control group (CON, $n = 15$; age, 22.7 ± 4.93 years; height, 1.84 ± 0.05 m; body mass, 82.2 ± 6.00 kg), who carried out a non-individualised training programme that was not specifically based on F-Vimb. Both groups carried out the same pre-season technical-tactical basketball training during the research. All players had at least six years prior experience playing at the federated level and one year of strength training directly prior to the intervention; they did regular training three days or more per week during the competitive period and did not present any injury six months prior to or during the investigation; and all of them completed 100% of the intervention programmed. The research was developed during the pre-season and ended just before the start of the competitive period. It was approved by the

Andalusian Ethics Committee for Biomedical Research (reference number: FBD_UHU2020). The experimental protocol was conducted according to the latest version of the Declaration of Helsinki. All players were informed about the objectives of the present study and gave their written consent to participate in it.

Study design and procedure

A randomised controlled trial design was used with a longitudinal follow-up of eight weeks, where all athletes performed at least three basketball training sessions and two strength training sessions per week, as recommended in previous research that aimed to improve performance in COD (Falch et al., 2019). The intervention design included a pre-assessment (T_1) just one week before the start of the intervention; an intra-intervention evaluation (T_2), week 4 (in the middle of the intervention) in which the training sessions were readjusted based on the new F-Vimb; and a final evaluation (T_3) just at the end of the intervention.

A week before the beginning of the research, all the players did two days to familiarise with the tests. For T_1, T_2, and T_3, the proposed evaluation was grouped into two different sessions, always before the sports training itself (7–8 pm) and with 48 h of difference between each session. In the first session, horizontal force-oriented tests were included: (i) sprint, COD and triple hop test. In the next session, the vertical force-oriented tests were evaluated: (ii) F-V profile, CMJ and DJu. All speed tests were carried out on the hardwood court where they trained and played the matches. Players were instructed to attend the assessment well hydrated and rested without any vigorous training in the preceding 24 h and without consuming caffeine or food in the previous 3 h, including alcohol for at least 24 h prior. Beforehand, the players performed a standardised activation that included 5 min of low-intensity movement with the ball, 5 min of hip mobility and core activation, 5 min doing landing, multi-directional bounds and acceleration–deceleration drills, and finally, 5 min of approaching the tests themselves, increasing the intensity with each repetition. All players performed a total of three attempts of each test with a 2-min rest between attempts. The mean of all attempts for each test was used for further analysis.

Training intervention

The assessments were used to classify the INT athletes according to the result obtained in the F-V profile. Players were classified as well-balanced F-V profile if they had less than 10% imbalance from the optimal profile (Well-balance subgroup INT, $n = 2$; CON, $n = 3$), low deficit when they had between 10% and 40% (Low-force deficit subgroup INT, $n = 5$ and CON, $n = 4$; Low-velocity deficit subgroup INT, $n = 2$ and CON, $n = 1$), and high deficit when they exceeded a 40% imbalance (High-force deficit subgroup INT, $n = 6$ and CON, $n = 7$) (Jiménez-Reyes et al., 2016). With this classification, INT players were separated into different subgroups according to the type and magnitude of the observed F-Vimb (Jiménez-Reyes et al., 2016, 2019). Table 1 details the intervention performed on each subgroup, with the same workload applied to each of them. On the other hand, CON athletes performed the same training to the well-balanced subgroup as shown in Table 1, the same for all subjects, without individualisation.

The training included bilateral and unilateral exercises on a vertical force-orientation with high and low loads (as detailed in Table 1), varying the velocity zones in the different areas of the F-V profile according to the individual needs of each player. The intervention was organised following the recommendations of the scientific literature (Jiménez-Reyes et al., 2016, 2019). Eighteen sets per week were performed, divided into six different exercises (three sets/exercise) separated in two days/week, with at least 72 h difference between each session (Asadi et al., 2016). During the intervention, players were verbally instructed to perform each repetition at their maximum velocity for strength exercises (Weakley et al., 2020). In this way, both the intensity and the intra-sets volume were monitored with a linear velocity transducer (Vitruve™, Madrid, Spain) (Pérez-Castilla et al., 2019), since it has shown to be the most effective control method (Benavides-Ubric et al., 2020; Dorrell et al., 2020; Sánchez-Medina et al., 2017; Zhang et al., 2022). Regarding the intra-set volume of the plyometric exercises, a low volume was sought (i.e. 40–60 jumps per session) (Asadi et al., 2016), to maintain the highest possible intensity at all times and cause minimal fatigue. A 120-second rest period was performed inter-sets to optimise intra-session recovery.

Physical fitness test

Vertical Test Assessments: Countermovement Jump, unilateral Drop Jump and Vertical Force-Velocity Profile. Vertical tests were evaluated using a Chronojump contact platform (Chronojump Boscosystem®, Barcelona, Spain) (De Blas et al., 2012). Each subject performed a DJu, a CMJ with their body weight, plus 5 CMJs with trap bar and additional loads ranging from 20 to 60 kg in a random order. CMJ tests with and without extra load were

Table 1. Individualized training programmes based on the F-V for each imbalance threshold. Adapted from Jimenez-Reyes et al. (2016, 2019).

Subgroup F-V profile (% Imbalance)	Session	Exercise	Training load	Execution speed/Reps
High force deficit (>40% of optimal thresholds)	1	Back squat	80%–90% RM	0.68–0.51 $m \cdot s^{-1}$ (~10% VL)
		Deadlift trap bar	70%–80% RM	0.71–0.58 $m \cdot s^{-1}$ (~10% VL)
		SL CMJ	10% BW	4 reps
	2	Deadlift barbell	85%–95% RM	0.52–0.39 $m \cdot s^{-1}$ (~10% VL)
		Clean pull	80% RM	>1.11 $m \cdot s^{-1}$ (~5% VL)
		CMJ trap bar	80% BW	3 reps
Low force deficit (between 10% and 40% of optimal thresholds)	1	Back squat	80%–90% RM	0.68–0.51 $m \cdot s^{-1}$ (~10% VL)
		CMJ trap bar	80% BW	3 reps
		SL CMJ	10% BW	4 reps
	2	Deadlift barbell	85%–95% RM	0.52–0.39 $m \cdot s^{-1}$ (~10% VL)
		Clean pull	80% RM	>1.11 $m \cdot s^{-1}$ (~5% VL)
		SL SJ	BW	4 reps
Well-balanced (between −10% and 10% of optimal thresholds)	1	Back squat	80%–90% RM	0.68–0.51 $m \cdot s^{-1}$ (~10% VL)
		Depth jump	BW (30 cm)	5 reps
		SL CMJ	10% BW	4 reps
	2	Deadlift trap bar	70-80% RM	0.71–0.58 $m \cdot s^{-1}$ (~10% VL)
		Clean pull jump	65% RM	5 reps
		Abalakov jump	BW	5 reps
Low velocity deficit (between −10% and −40% of optimal thresholds)	1	Depth jump	BW (30 cm)	3 reps
		SL SJ	BW	3 reps
		Band assisted CMJ	<BW	5 reps
	2	Clean pull jump	65% RM	3 reps
		SJ	BW	3 reps
		Abalakov jump	BW	5 reps
High velocity déficit (>40% of optimal thresholds)	1	Band assisted CMJ	<BW	5 reps
		Box jump	BW (30 cm)	3 reps
		SL CMJ	BW	3 reps
	2	Abalakov jump	BW	5 reps
		CMJ	BW	3 reps
		Clean pull jump	50% RM	3 reps

Abbreviations: RM, Repetition Maximum; BW, Body Weight; m/s, metres/seconds; CMJ, Countermovement Jump; SL, Single Leg; SJ, Squat Jump; VL, Velocity Loss.

performed bilaterally and DJu were unilateral. The DJu was performed from an initial height of 30cm (Tong et al., 2022), each subject dropped down until they came into contact with the platform with only one leg, in order to jump as high as possible and finally landing with the same leg. Each DJu and CMJ attempt was considered valid if during the entire test both hands were placed on the hips for DJu and CMJ without extra load or on the trap bar with elbows extended for loaded CMJ, the knees were not bent during the jump flight time and whether the landing was made at the same point as the takeoff. For the loaded CMJ to be valid, it had to reach at least 10 cm in height (García-Ramos et al., 2018).

An excel spreadsheet downloaded from jbmorin.net (JUMPFVPprofile (1).xlsx) was used to apply the Samozino et al. method and obtain the F0, V0, and Pmax (Samozino et al., 2012). Additionally, the spreadsheet also showed the individual optimal theoretical F-V profile for each subject and the F-Vimb of each individual with respect to the this F-V profile (Samozino et al., 2014). In addition, the values of the reactive strength index (RSI) were calculated through the flight time/contact time ratio for each leg extracted from the DJu.

Horizontal Test Assessment: Triple Hop Test. Initially, the participants stand with one leg behind the starting line. Once they performed the three consecutive maximum jumps forward with the same limb, the researcher measured with a tape the total distance jumped from the start to the point where the heel hit the ground at the completion of the third jump (Bolgla & Keskula, 1997). Arm swinging was allowed. Attempts were considered unsuccessful if the participant did not complete the test as instructed, lost balance during any part of the test, or was unable to stick the landing on the final jump for at least two seconds (Bolgla & Keskula, 1997).

Speed Test Assessments: Linear and change of direction speed. The times in the speed tests were measured with Chronojump single-beam photocells (Chronojump Boscosystem®, Barcelona, Spain). The photocells were placed 2 m apart from each other and at a height of 1.10 m (approximately the height of the players' hips). Each player was placed 0.5 m behind the first gate, in a two-point split stand. Then, each player accelerated at maximum speed to the second gate. The speed tests were: (1) sprint test, which the photocells were placed 10 m away in a straight line; and (2) COD test, which each player ran 5 m to pivot point marked on the floor and then changed of direction at 45° (COD45°), 90° (COD90°) and 180° (COD180°) to go to the second gate in the shortest possible time. The

COD tests were performed on both sides and laterality was defined by the leg on which the subjects leaned when performing the COD mechanics (Cuthbert et al., 2019).

Statistical analysis

Data were expressed as mean and standard deviation. The normality of the data was tested and confirmed using the Shapiro–Wilk test ($p > 0.05$). Homoscedasticity was determined with the Levene test. The relative and absolute reliability of the tests was evaluated by the intraclass correlation coefficient (ICC) and the coefficient of variation (CV) for all assessments. An ICC $\geq$0.8 was considered strong and a CV <5% was established as an intra-day reliability criterion. Training effects were evaluated using a 2 (groups: INT and CON) × 3 (time: T_1, T_2, and T_3) repeated measures ANOVA model, and the ES were determined using the partial eta-square. ES was considered trivial (<0.003), small (0.01), moderate (0.06), large (>0.14) (Lenhard & Lenhard, 2016). Additionally, the Bonferroni post-hoc for multiple comparisons was performed in order to identify those time periods where significant changes occurred, and the ES were determined using the Cohen's *d*. ES was considered trivial (<0.10), small (0.40), moderate (0.70), large (>0.80) (Lenhard & Lenhard, 2016). The alpha level was set to 0.05. Statistical analysis was performed with SPSS version 25 for Windows. (SPSS, Inc., Chicago, IL, USA).

Results

Table 2 shows baseline values in the sample with their ICC and CV relative and absolute reliability measurements. There were no significant differences between groups for any variables at baseline except for RSI R and RSI L ($p \leq 0.01$).

The F-Vimb was removed from tables to show it with more details in Figure 1. Players showed statistical differences between groups, both at four weeks of intervention (T2) ($p = 0.031$) and at the end of the intervention period (T3) ($p = 0.002$). In addition, INT showed significant changes ($p < 0.05$) in F-Vimb for all players at eight weeks (Figure 1(A)). The individual progression in the F-Vimb for CON (Figure 1(B)) and INT (Figure 1(C)) showed how only INT athletes improved their F-Vimb, all of them were nearer to equilibrium in F-V profile after eight weeks.

Table 3 shows comparative analysis inter- and intra-groups on analysed performance variables. INT showed significant group × time changes ($p < 0.01$) in F-Vimb. In addition, group × time interaction showed significant improvements in both bilateral (21.2%, ES = 0.57, $p <$ 0.01) and unilateral ($\geq$24.8%, ES $\geq$0.47, $p < 0.01$) peak vertical jump height in the INT. This interaction also was observed, although with a lower magnitude of change, in one-legged horizontal jump ($\geq$4.63%, ES $\geq$0.13, $p \leq 0.02$). Finally, velocity variables evaluated, both sprint and COD, with exception of the 90° angle, showed a group x time interaction effect, with the INT showing the greatest improvements (ES $\geq$0.10; $p \leq$ 0.05). A post-hoc Bonferroni analysis revealed improvements for height variables in vertical jumps such as CMJ and DJu (ES $\leq$0.44; $p < 0.01$); and sprint (ES = 0.80; $p = 0.02$) with only four weeks of individualised training, although these variables continued improving until eight weeks of training. However, for the variables COD and triple hop test changes (ES $\geq$0.45; $p < 0.01$) were observed after eight weeks of individualised intervention.

Discussion

The present study analysed the effect of an individualised F-Vimb combined strength and plyometric training programme on physical performance of basketball players. In addition, we wanted to determine the differences in performance between two periods of time (four to eight weeks) performing the same training. The most notable findings of the present study were (1) that the individualised F-Vimb training was effective in improving physical performance in all variables studied for eight weeks; (2) significant improvements in the vertical jump and sprint variables occur earlier (at week 4) than in the COD variables; and (3) the improvements were specific to the force-orientation trained, since the proposed intervention emphasised the vertical orientation and the highest percentages of change were observed in this direction.

The present study confirmed the result of previous work (Jiménez-Reyes et al., 2016, 2019) that an optimised and individualised F-Vimb training programme is an effective strategy to reach an optimal F-V profile and improve jumping performance. The time to reach optimal F-V profile could range from 4 to 15 weeks (Jiménez-Reyes et al., 2019), and depends on the baseline F-Vimb of each player. Athletes with a higher F-Vimb will take longer to reach the optimal F-V profile. In our case, after eight weeks of intervention, all INT players reached optimal F-V profile except for four players with the higher baseline F-Vimb. Therefore, in addition to individualised training, it should be recommended to adapt the duration of the training to each player and not to use fixed durations. Furthermore, this training approach has been shown to be effective

Table 2. Baseline of the study variables and their respective reliability measures.

Variables	CON ($n = 15$)		INT ($n = 15$)		ICC	CV	p-Value	ES
	Mean	*SD*	Mean	*SD*				*Cohen's d*
V0	3.27	0.53	3.48	1.24	–	–	0.55	−0.22
F0	32.0	4.22	35.5	7.53	–	–	0.13	−0.57
PMax	26.0	3.44	28.0	12.0	–	–	0.54	−0.53
CMJ (cm)	33.7	4.83	30.7	3.03	0.99	1.83	0.06	0.74
DJu R (cm)	14.0	3.87	13.1	3.71	0.99	1.75	0.54	0.23
DJu L (cm)	14.3	3.20	13.7	2.60	0.99	2.15	0.56	0.21
RSI R	0.87	0.21	0.65	0.15	0.99	2.07	<0.01*	1.23
RSI L	0.90	0.26	0.68	0.13	0.99	1.94	<0.01*	1.05
THTu R (m)	5.20	0.62	5.15	0.80	0.99	1.98	0.86	0.06
THTu L (m)	5.03	0.54	4.97	0.56	0.99	1.68	0.77	0.11
Sprint (s)	1.82	0.08	1.86	0.11	0.95	1.69	0.19	−0.49
COD45 R (s)	1.95	0.08	1.99	0.07	0.93	1.76	0.10	−0.62
COD45 L (s)	1.91	0.09	1.95	0.13	0.96	1.73	0.29	−0.39
COD90 R (s)	2.28	0.10	2.34	0.23	0.96	1.85	0.41	−0.31
COD90 L (s)	2.30	0.16	2.33	0.17	0.98	1.77	0.69	−0.15
COD180 R (s)	2.79	0.09	2.80	0.11	0.95	1.86	0.74	−0.12
COD180 L (s)	2.78	0.10	2.83	0.09	0.96	1.62	0.16	−0.53

Abbreviations: V0, Theoretical Maximal Unloaded Velocity; F0, Theoretical Maximal Force; PMax, Maximal Power; CMJ, Countermovement Jump; DJu, unilateral Drop Jump; RSI, Reactive Strength Index; THT, Triple Hop Test; COD, Change of Direction; cm, Centimetres; s, Seconds; R, Right; L, Left; CON, Control Group; INT, Intervention Group; SD, Standard Deviation; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; ES, Effect Size. Significant inter-groups differences: *$p < 0.05$.

for vertical jump capacity, since it is possible to individualise the vertical strength needs for each athlete (Morin & Samozino, 2016). In this sense, previous studies with the same intervention developed between 8 and 12 weeks in soccer and rugby players (Jiménez-Reyes et al., 2019) reported improvements of 12.5% in the height of the vertical jump. Our results were similar also for the CMJ, the improvements observed were 8.14% after four weeks of intervention, and 21.2% after eight weeks. These considerable improvements would be even greater than those evidenced in previous studies (Jiménez-Reyes et al., 2016, 2019), which could be explained by the sample itself. In our case, the sample were basketball players and they showed lower baseline values compared to other basketball players (Morrison et al., 2022). In addition, basketball players would be the ones who obtain the most benefits from plyometric training based on the vertical orientation, when compared to other sports such as soccer or rugby, due to the nature of basketball and its specificity with plyometric training (Asadi et al., 2016). In general, we can say that an individualised F-Vimb training programme, with the aim of optimising and reducing the imbalance in this profile, offers great effects on many variables related to the relationship between strength and speed in the vertical axis, such as V0, F0, Pmax and vertical jump (Jiménez-Reyes et al., 2016, 2019). However, when analysing the effects of this vertical training on horizontal hopping (i.e. triple hop test), it was observed that the changes in performance were smaller and took longer to appear (≤6.80% after eight weeks). These results

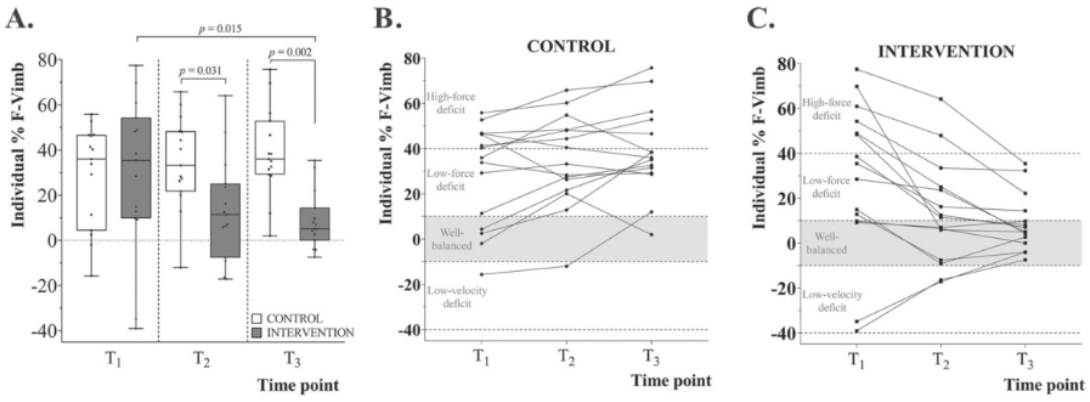

Figure 1. Comparative analysis of F-V imbalance changes throughout the three assessment periods showing: (A) mean values, deviation and significant differences intra- and inter-group; (B) individual changes in F-Vimb for Control Group; and (C) individual changes in F-Vimb for Intervention Group.

Table 3. Changes between pre- (T_1), intra- (T_2) and post- (T_3) intervention in the study variables for each group.

	CONTROL					INTERVENTION								
				% Change					% Change		Time		Group x Time	
Variables	T_1 Mean ± *SD*	T_2 Mean ± *SD*	T_3 Mean ± *SD*	T1-T2	T1-T3	T_1 Mean ± *SD*	T_2 Mean ± *SD*	T_3 Mean ± *SD*	T1-T2	T1-T3	*p*-Value	ES (η^2)	*p*-Value	ES (η^2)
CMJ (cm)	33.7 ± 4.83	32.7 ± 4.94	33.5 ± 5.18	−2.97	−0.59	30.7[a,b] ± 3.03	33.2[a,c] ± 3.83	37.2[b,c] ± 4.45	8.14	21.2	<0.01	0.56	<0.01	0.57
DJu R (cm)	14.0 ± 3.87	13.6 ± 3.28	13.1 ± 3.02	−2.86	−6.43	13.1[a,b] ± 3.71	14.9[a,c] ± 3.92	16.4[b,c] ± 4.83	13.7	25.2	<0.01	0.28	<0.01	0.53
DJu L (cm)	14.3 ± 3.20	14.3 ± 3.34	13.8 ± 3.16	−0.12	−3.50	13.7[a,b] ± 2.60	15.1[a,c] ± 3.03	17.1[b,c] ± 3.87	10.2	24.8	<0.01	0.31	<0.01	0.47
RSI R	0.87[a,b] ± 0.21	0.76[a] ± 0.19	0.76[b] ± 0.18	−12.6	−12.6	0.65[b] ± 0.15	0.71 ± 0.16	0.80[b] ± 0.15	9.23	23.1	0.09	0.08	<0.01	0.39
RSI L	0.90[b] ± 0.26	0.80 ± 0.23	0.77[b] ± 0.19	−11.1	−14.4	0.68[b] ± 0.13	0.75 ± 0.14	0.81[b] ± 0.12	10.3	19.1	0.66	0.01	<0.01	0.31
THT R (m)	5.20 ± 0.62	5.11 ± 0.72	5.05 ± 0.73	−1.73	−2.88	5.15[b] ± 0.80	5.32 ± 0.81	5.50[b] ± 0.86	3.30	6.80	0.31	0.04	<0.01	0.23
THT L (m)	5.03 ± 0.54	4.91 ± 0.46	4.89 ± 0.51	−2.39	−2.78	4.97 ± 0.56	5.12 ± 0.61	5.20 ± 0.54	3.02	4.63	0.86	0.01	0.02	0.13
V0	3.27 ± 0.52	3.59 ± 0.61	3.71 ± 0.87	9.79	13.5	3.48[a,b] ± 1.24	2.86[a] ± 0.54	2.85[b] ± 0.43	−17.8	−18.1	0.52	0.02	<0.01	0.24
F0	32.0 ± 4.22	31.5 ± 4.74	31.7 ± 5.11	−1.56	−0.94	35.5[b] ± 7.53	38.5 ± 5.23	41.2[b] ± 5.35	8.45	16.1	0.01	0.17	<0.01	0.20
PMax	26.0 ± 3.44	27.3 ± 3.53	28.8 ± 4.61	5.00	10.8	29.9 ± 9.88	27.9 ± 6.61	29.6 ± 7.01	−6.69	−1.00	0.09	0.08	0.06	0.10
Sprint (s)	1.82 ± 0.08	1.80 ± 0.06	1.82 ± 0.11	−1.10	0.09	1.86[a,b] ± 0.11	1.79[a] ± 0.08	1.75[b] ± 0.08	−3.76	−5.91	<0.01	0.22	<0.01	0.19
COD45 R (s)	1.95 ± 0.08	1.97 ± 0.15	1.93 ± 0.15	1.03	−1.03	1.99[b] ± 0.07	1.93[c] ± 0.10	1.84[b,c] ± 0.08	−3.02	−7.54	<0.01	0.27	<0.01	0.19
COD45 L (s)	1.91 ± 0.09	1.92 ± 0.15	1.88 ± 0.12	0.52	−1.57	1.95[b] ± 0.13	1.93 ± 0.14	1.84[b] ± 0.09	−1.03	−5.64	<0.01	0.18	0.13	0.07
COD90 R (s)	2.28 ± 0.10	2.38 ± 0.21	2.36 ± 0.12	4.39	3.51	2.34 ± 0.23	2.34 ± 0.16	2.27 ± 0.16	−0.01	−2.99	0.21	0.05	0.05	0.10
COD90 L (s)	2.30 ± 0.16	2.36 ± 0.23	2.33 ± 0.17	2.61	1.30	2.33 ± 0.17	2.34 ± 0.10	2.26 ± 0.14	0.43	−3.00	0.08	0.09	0.17	0.06
COD180 R (s)	2.79 ± 0.09	2.83 ± 0.17	2.85 ± 0.11	1.43	2.15	2.80[b] ± 0.11	2.77[c] ± 0.14	2.64[b,c] ± 0.17	−1.07	−5.71	0.03	0.11	<0.01	0.28
COD180 L (s)	2.78 ± 0.10	2.75 ± 0.14	2.81 ± 0.17	−1.08	1.08	2.83[b] ± 0.09	2.77 ± 0.11	2.68[b] ± 0.12	−2.12	−5.30	0.02	0.14	<0.01	0.26

Abbreviations: CMJ, Countermovement Jump; DJu, unilateral Drop Jump; RSI, Reactive Strength Index; THT, Triple Hop Test; V0, Theoretical Maximal Unloaded Velocity; F0, Theoretical Maximal Force; PMax, Maximal Power; COD, Change of Direction; cm, Centimetres; s, Seconds; R, Right; L, Left; SD, Standard Deviation; T_1, Pre-intervention assessment; T_2, Intra-intervention assessment; T_3, Post-intervention assessment; ES, Effect Size; η^2, partial eta square. Significant intra-groups differences: [a](between T_1-T_2; $p < 0.05$), [b](between T_1-T_3; $p < 0.05$), [c](between T_2-T_3; $p < 0.05$).

support the importance of taking force-orientation into account in order to improve performance in sporting actions (Loturco et al., 2018).

To our knowledge there is currently still no intervention in the scientific literature that develops this individualised programme of combined strength and plyometric training and that analyses its effect on sport-specific sprint and COD actions. Our results suggest that, although at the end of the intervention both sprint and COD achieve similar improvements, sprinting achieves these improvements earlier than COD. This could be because the specificity of training enables greater neurological/coordination improvements, as the vertical force-orientation has greater influence on sprint speed (Loturco et al., 2018). Regarding COD speed, it was observed that jumping actions show peaks of muscle activation very similar to COD actions (Falch et al., 2020), and previous research (Barrera-Domínguez et al., 2020) shown a high relationship between F-Vimb and COD. The data from the present study confirmed these previous findings, as shown by how this individualised F-Vimb training approach induced improvements in COD. Being in our case, slightly higher than those observed in a recent meta-analysis (Falch et al., 2019) that did not include individualised training interventions. In addition, it was determined that the observed changes in COD may not be proportional to those observed in vertical jumps, as COD showed significant changes after 8 weeks of intervention, but not after 4 weeks of training, as for the jump variables. This interaction could be found between the improvement in the RSI and the COD, as both variables offered significant changes after eight weeks of intervention, and being not observed at four weeks of intervention. Therefore, the COD could be more determined by the RSI than by the jump height as observed in previous studies (Barrera-Domínguez et al., 2020), since RFD would be a determinant for better performance in these actions (Baena-Raya et al., 2020).

A novel aspect presented in this study was the inclusion of an intra-intervention assessment with the aim of offering coaches and trainers with the improvement of the players in both periods. In this way, they will be able to choose how long the training should be programmed as a minimum in order to achieve improvements in the performance. Currently, there are studies that report that training two days a week during a four-week training period would be effective in improving performance in COD in junior athletes of team sports (Keller et al., 2020), and their results are variable depending on the type of training used. The results of the present study indicate that the COD is complex, since they combine different abilities such as acceleration, deceleration and re-acceleration, at the same time that all the force-orientations interact (Dos'Santos et al., 2018). This may mean that longer periods of time, at least eight weeks, are needed to achieve performance improvements, compared to vertical jump and sprint actions that showed significant improvements in just four weeks of training. These results are in line with those observed in previous studies in which the effects of combined training on COD performance were analysed and concluded that a minimum intervention period of between six and eight weeks is necessary for changes on the COD (Falch et al., 2019). Despite this, more research with different population samples is considered necessary, since the duration of training and its effect would be largely dependent on the sample used.

Despite the novelty of this study, it is not without limitations. First of all, the size of sample used could be considered a limitation as it was carried out with a sample of 30 basketball players. In addition, the proposed intervention emphasised the work on a vertical force-orientation. Throughout the study, the importance of the different force-orientations in COD performance is highlighted; therefore, it is recommended for future research to consider other sports and include different force-orientations in training when the objective is to improvement COD performance.

In conclusion, an individualised F-Vimb combined strength and plyometric training programme improved physical performance in jumping, sprint and COD variables for eight weeks, with changes in F-V profile, vertical jump and sprint after the first four weeks of intervention. In contrast, none of these changes were observed in the CON. Therefore, the authors would think that these vertical jump and sprint variables obtain faster changes than the COD variables and that the improvements were specific with respect to the force-orientation trained, since the proposed intervention emphasised the vertical orientation and the highest percentages of change were observed in this direction.

Perspective

Until this point, it would be recommended that strength and conditioning coaches use this individualised F-Vimb training if their main goal is to improve the vertical jump or sprint in only four weeks. But to achieve improvements in COD, it would be recommended to train based on the individual F-V profile and motor control demands of each athlete and combining different intensities to optimise the F-V profile, emphasising the different force-orientation as necessary to improve COD performance, for a period of at least eight weeks.

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STUDY 10

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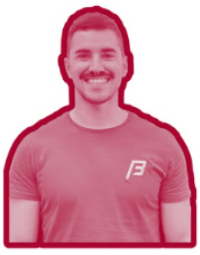
Effect of individualized training based on change of direction deficit upon speed performance in basketball players



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Effect of individualized training based on change of direction deficit upon speed performance in basketball players

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Abstract

Purpose: Linear and changes of direction (COD) speed are considered key performance determinants in basketball. The aim of this study was to analyzed the effect of an individualized COD deficit-based training programme on linear and multidirectional speed efficiency and performance in basketball players. Additionally, the differences in physical performance between two time periods (four and eight weeks) with this training were analyzed.

Methods: Thirty-six male basketball players (age, 21.4±3.23 years; height, 1.87±0.07 m; body mass, 83.6±7.83 kg) were divided into an intervention group (INT, n=18), who performed an individualized COD deficit-based training; and a control group (CON, n=18), who underwent a non-individualized multidirectional repeated sprint training programme. Both groups performed the intervention two days per week. Baseline, four-week, and eight-week assessments included 10-meters linear speed and COD (5+5 meters at 45º, 90º and 180º cut) tests.

Results: An improvement in all-directional movement efficiency was observed from four weeks in INT group (effect size (ES) ≥1.61, p <0.01), with no change in the CON group. At eight-weeks, significant improvements were observed in the INT players' mean speed performance (mean difference (MD) –0.09, ES =0.34, p <0.01), with COD180º showing the greatest changes (MD ≤–0.18, ES ≥0.44, p <0.01).

Conclusions: An individualized COD deficit-based training program improved speed performance after eight weeks, with changes in all-directional movement efficiency after first four weeks. Given basketball's unpredictable and multidirectional nature, strength and conditioning coaches should seek the optimal trade-off between the linear and multidirectional speed demands on their players.

Keywords: *Deceleration; Acceleration; Resisted sprint; Eccentric training; Agility.*

Introduction

High intensity actions such as sprints, accelerations, decelerations or changes of direction (COD) are key performance indicators in basketball given the speed and short duration of game actions in basketball[1]. Specifically, it has been observed that the most frequent action performed by basketball players during a game is the COD regardless of playing position or gender[2]. COD is defined as the ability to decelerate and accelerate in a pre-planned manner towards a given direction[3]. Although in real game situations CODs mainly occur in reaction to external stimuli (i.e. agility skill), it is not possible to replicate game-specific stimuli in an isolated context. Therefore, the movement mechanics of planned CODs are considered an adequate approximation for understanding the biomechanical and physiological basis of these actions in real game situations. Thus, it is recommended that strength and conditioning coaches develop individualized and effective training programmes tailored to each athlete's speed needs[4] to improve their ability to perform COD at maximum intensity in any direction in basketball players[5].

A key consideration for improving COD performance is the appropriate selection of assessment tests, which presents several challenges. Firstly, there are over 50 different tests to measure COD performance in basketball players, each with different features[6]. Secondly, these tests involve a wide variety of physical capacities (e.g., linear speed, anaerobic metabolic capacity or test-specific movement skills) depending on the distance covered, angles, and number of cuts[3]. As a result, the outcomes of these COD tests may be influenced by other abilities and may not effectively isolate the player's COD capacity[3]. Specifically, more than 70% of the time during these tests is spent sprinting linearly rather than performing the COD action itself[7], leading to strong correlations between linear speed (LS) and COD[8]. To overcome this limitation, previous studies[7] have developed the concept of change of direction deficit (CODD). The CODD seeks to isolate the COD action from the player's linear sprinting ability. It expresses in percentage terms as the amount of time an athlete has been specifically in the COD action during the entire test and indicates the athlete's efficiency in these actions[9]. Besides being the only way to isolate COD actions during speed tests, the CODD allows for the analysis of the individual relationship between LS and COD for each player[4]. This allows practitioners to classify basketball players according to their "multidirectional speed profile" based on whether they are more efficient in linear or COD actions.

To enhance performance in COD actions, previous scientific literature recommends developing specific training programmes based on the force demands according to the individual needs of each player[10,11], incorporating movement patterns similar to the COD action and considering the direction and timing of force application[12]. In this regard, COD are complex actions, where the force demands are directly dependent on the cutting angle[13]. These actions require rapid (up to 400 ms) and multidirectional force application[5]. Numerous training approaches have been proposed for COD performance improvement[12]. [1415]However, most previous studies aiming to improve COD performance in basketball players have adopted a "one-size-fits-all" approach[11], which does not account for individual physical abilities or responses to training. Current meta-analysis study[16] suggest that a "one-size-fits-all" approach using horizontal force orientation is not

effective for improving COD performance in basketball. Therefore, individualized training approaches are recommended to improve COD performance[4].

As basketball is a multidirectional sport, in which players must be able to execute both LS and COD up to 180° at maximum intensity[17]; it was recommended to improve the COD efficiency and performance that a trade-off between both LS and COD skills should be sought, based on the individual needs of each athlete[4]. In this sense, according to CODD threshold classification[4], multidirectional speed dominants (MSD) basketball players are faster in COD actions but not efficient in accelerations and high LS[18]. Thus, training should focus on the development of the maximum propulsive force in acceleration actions[19]; with emphasis on concentric actions, unilateral exercises focused on the first steps of acceleration and resisted sprints[20]. On the other hand, linear speed dominant (LSD) players are characterized as very fast in LS but not efficient in changing direction, for whom training programmes with an emphasis on deceleration tasks[21], eccentric training[22], and COD technique-oriented drills[23] are recommended. Finally, balanced players have been found to show the best "multidirectional speed profile" for a sport like basketball[4]. That is, these players show the best trade-off between their individual LS and COD abilities, so they should put the focus on maintaining-improving both skills simultaneously.

To the authors' knowledge, no previous intervention study in the scientific literature has included individualized horizontal strength training according to each basketball player's CODD to improve COD performance. Therefore, the main purpose of this study was to analyzed the effect of an individualized CODD-based training programme on linear and multidirectional speed efficiency and performance in male basketball players. Additionally, a secondary purpose was to analyze the differences in speed performance between two time points (four and eight weeks) with an individualized versus a general training program. It was hypothesized that the individualized training approach would yield the greatest gains in LS and COD actions specific to basketball compared to non-individualized approaches, but that at least 8 weeks of training would be required to achieve improvements in speed performance.

Methods

Subjects

Thirty-six male basketball players from two teams belonging to the same competitive level (i.e., Spanish N1 National League) and similarly ranked in the championship were randomly assigned into two groups. An intervention group (INT, n=18; age, 20.1±1.45years; height, 1.84±0.07m; weight, 79.8±8.91kg) who underwent individualized intervention based on CODD classification[4]; and other control group (CON, n=18; age, 22.7±4.93years; height, 1.84±0.05m; weight, 82.2±6.00kg), who undertook a non-individualized, unloaded, multidirectional repeated sprint training (MRST) programme. For inclusion, players had (i) to have at least 6 years of previous experience playing at federated level and 1 year of strength training directly prior to the

intervention; (ii) to perform basketball training 3 days a week over the season and (iii) to be injury free for at least 6 months prior to the intervention. Thirty-one players completed the intervention and five players were not included in the data analysis (INT, n=2; CON, n=3) due to missing one or more training sessions for medical reasons unrelated to the intervention. The research was conducted throughout the second part of the season and finished just prior to the completion of the season. The present research was approved by the Andalusian Ethics Committee for Biomedical Research (reference number: FBD_UHU2020). The experimental protocol was conducted according to the latest version of the Declaration of Helsinki.

Design

An 8-week follow-up cuasi-experimental repeated measures design was used, where all athletes performed three basketball sessions, and two strength and conditioning training per week. The intervention design included a pre-assessment (T_1) just one week before the start of the intervention; an intra-intervention evaluation (T_2), week 4 (in the middle of the intervention) in which the strength training sessions were readjusted according to the new CODD classification of each athlete; and a final evaluation (T_3) just at the end of the intervention.

Prior to the start of the research, all players were familiarized with the tests and exercises. For T_1, T_2, and T_3, the assessments were always carried out before the final technical-tactical basketball training of week (7pm - 8pm) on the indoor parquet court where players usually trained and played. The assessment included (i) 10 meters LS test and (ii) 505 modified COD test at 45º, 90º and 180º. Before each assessment, the players performed a standardized activation that included 5 minutes of low-intensity movement, 5 minutes of hip mobility and core activation, 5 minutes doing landing, multi-directional bounds and acceleration-deceleration drills, and finally, 5 minutes of approaching the tests themselves, increasing the intensity with each repetition. All players performed a total of 3 attempts of each test with a 2-minute rest between attempts. The mean of all attempts for each test was used for further analysis.

Testing procedures

Linear speed (LS) and change of direction (COD) test. The times in the speed tests were measured with Chronojump single-beam photocells (Chronojump Boscosystem®, Barcelona, Spain). The photocells were placed 2 meters apart from each other and at a height of 1.10 meters (approximately the height of the players' hips). Each athlete was placed 0.5 meters behind the first gate, in a two-point split stance. Then, each player accelerated at maximum speed to the second gate. The speed tests were: (i) LS test, which the photocells were placed 10 meters away in a straight line; and (ii) COD test, which each player ran 5 meters to pivot point marked on the floor and then changed of direction at 45º (COD45º), 90º (COD90º) and 180º (COD180º) to go to the second gate in the shortest possible time (Figure 1). The COD performance at 45°, 90° and 180° left and right directions was defined by the leg on which the subjects set on the court when

performing the COD. The mean speed variable was calculated as the average of the LS, COD45º, COD90º and COD180º values. The CODD for each angulation was obtained as follows[9]:

$$CODD\% = \frac{COD\ time - LS\ time}{LS\ time}\ x\ 100$$

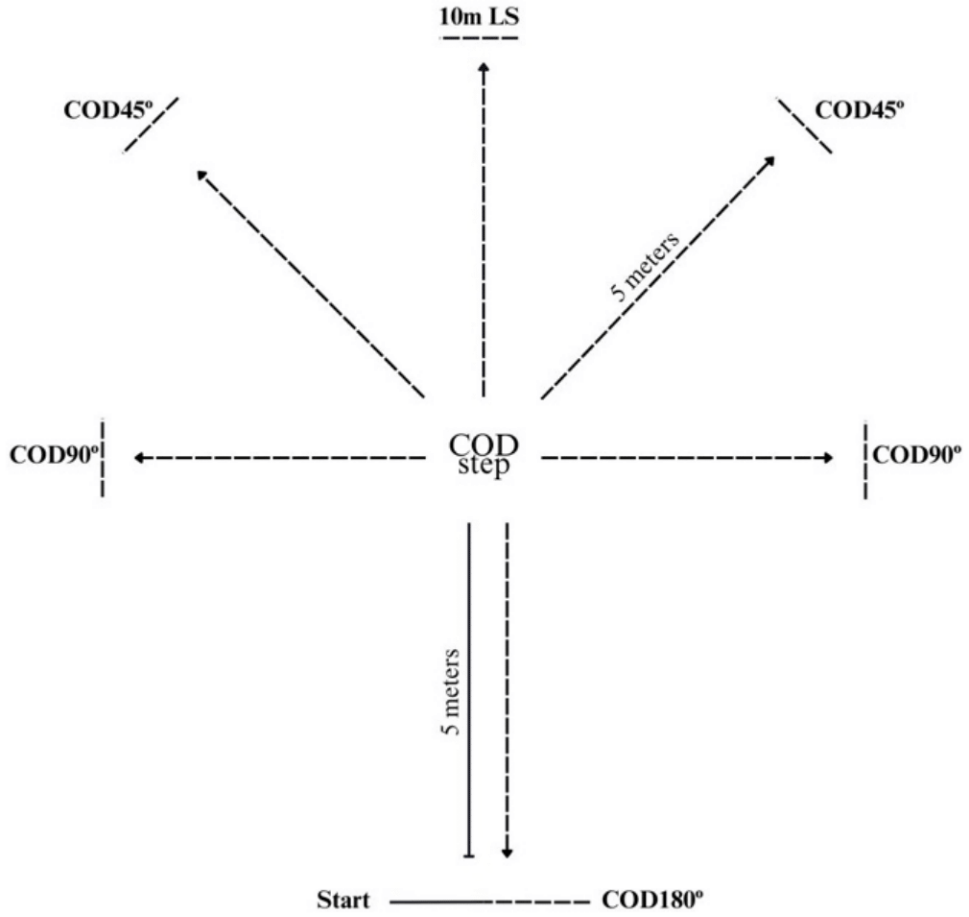

Figure 1. Schematic presentation of linear speed (10 meters) and change of direction (5+5 meters at 45º, 90º and 180º cut) tests.

Training protocol

The LS and COD assessments were conducted to classify the INT athletes according to their CODD in a 180º turn. INT players were classified as MSD (INT, n=11; CON, n=0) if they had less than a 43% CODD180º, balanced when they had between 43-49% (INT, n=2; CON, n=6) and LSD (INT, n=3; CON, n=9) when they exceeded 49% CODD180º[4]. INT training was individualized according to this classification, focusing on seeking the best trade-off between both linear and multidirectional speed. CON undertook a standardized MRST[24]. *Table 1* details the intervention performed on each INT subgroup and CON.

Table 1. Training programs for each INT subgroups and CON players.

Training groups	Session	Exercise	Training Volume	Training Load
MSD (INT)	1	Moderate Sled Training	3x 4x 10 metres	30% BM (~15% VL)
		Repeated Broad Bound	3x 2x 6 bounds	2 – 4 RPE (20 – 40% BM)
		HK Lateral Bound	3x 6 bounds	BM
	2	Heavy Sled Training	3x 5x 5 metres	60% BM (~40% VL)
		Repeated Lateral Bound	3x 2x 6 bounds	2 – 4 RPE (20 – 40% BM)
		HK Broad Bound	3x 6 bounds	BM
Balanced (INT)	1	Technical: 5m Acc to Dec	3x 4 reps EL	BM
		FW Forward Lunge	3x 2+6 reps EL	FW
		AEC Lateral Lunge	3x 6 reps EL	Bands AEC
	2	Heavy Sled Training	3x 5x 5 metres	60% BM (~40% VL)
		Repeated Lateral Bound	3x 2x 6 bounds	2 – 4 RPE (20 – 40% BM)
		HK Broad Bound	3x 6 bounds	BM
LSD (INT)	1	Technical: 5m Acc to Dec	3x 4 reps EL	BM
		FW Forward Lunge	3x 2+6 reps EL	FW
		AEC Lateral Lunge	3x 6 reps EL	Bands AEC
	2	Technical: COD180º to Dec	3x 2 reps EL	BM
		FW Lateral Lunge	3x 2+6 reps EL	FW
		AEC Forward Lunge	3x 6 reps EL	Bands AEC
CON	1 2	MRST (5 COD90º)	3x 8x 30 metres (6x 5 metres)	BM

Abbreviations: INT, Intervention Group; CON, Control Group; MSD, Multidirectional Speed Dominant, LSD, Linear Speed Dominant; HK, Half-Kneeling; Acc, Acceleration; Dec, Deceleration; FW, Flywheel; AEC, Accelerated Eccentric Loading; COD, Change of Direction; MRST, Multidirectional Repeated Sprint Training; EL, Each limb; BM, Body Mass; VL, Velocity Loss.

18 sets per week were performed, divided into 6 different exercises (3 sets/exercise) separated in 2 days/week[11], with at least 72h difference between each session[12,16]. Resistance sprint training was undertaken with the Exer-Genie system at moderate (30-40% body mass) and high (60-70% body mass) intensities with short distances (5-10 meters) to emphasize the acceleration phase[25]. For eccentric overload exercises a flywheel technology with low-to-medium inertia loads was used. Two preparatory reps were performed in each set prior to the six targeted reps to ensure effectiveness and, players were instructed to slow down the movement in the last third of the eccentric phase and exit the "hole" as quickly as possible to ensure a true eccentric overload[26]. Band-based plyometric exercises were performed in pairs (the same pairs throughout the intervention), one player executing the movement at maximum intensity and the other resisting it. Resisting players were instructed to withstand a load between two to four points on the rate of perceived exertion scale of the exercising player, to ensure low loads. Regarding the volume of the accelerated eccentric loading[27] and plyometric exercises[14], it was low (<60 contacts per session), to maintain the highest possible intensity at all times and cause minimal fatigue. To work and improve COD technique, exercises involving the action itself were performed with instructions such as (i) “slam on the brakes and drop the hips”; (ii) “cushion and push/punch the ground away”; and (iii) “face towards the direction of travel”[23]. A 120-second rest period was performed inter-sets to optimize intra-session recovery.

Statistical analysis

The data were presented as means and standard deviations. Normality of the data was assessed and confirmed with the Shapiro-Wilk test. Homogeneity of variances was evaluated using Levene's test. The intraclass correlation coefficient (ICC) and the coefficient of variation (CV) were used to assess both relative and absolute reliability of the tests. An ICC ≥0.8 was deemed acceptable[28], and a CV below 5% was set as the criterion for intra-day reliability[29]. Training effects were analyzed with a 2 (groups: INT and CON) x 3 (time points: T_1, T_2, and T_3) repeated measures ANOVA model adjusted by between-group differences at baseline, and effect sizes (ES) were calculated using partial eta-squared. ES were categorized as trivial (<0.01), small (0.01-0.05), moderate (0.06-0.13), and large (>0.14)[30]. The model was adjusted for baseline between-group differences (T_1). Furthermore, Bonferroni post-hoc adjustments were applied to identify the specific time periods with significant changes, and Cohen's d was used to determine the ES. ES thresholds were defined as trivial (<0.20), small (0.20-0.39), moderate (0.40-0.80), and large (>0.80)[30]. A *p*-value <0.05 was considered statistically significant. All statistical analyses were conducted using SPSS version 29 for Mac (SPSS, Inc., Chicago, IL, USA).

Results

Table 2 shows baseline values for the sample along with their ICC and CV relative and absolute reliability measurements. There were no significant differences between-groups for any variables at baseline, except for CODD180º (p <0.01). The test reliability, both in relative and absolute terms, was confirmed (ICC ≥0.85; CV ≤3.18).

Table 2. Baseline of the study variables and their respective reliability measures.

Variables	CON (n = 15)		INT (n = 16)		ICC	CV	*p* Value	ES
	Mean	SD	Mean	SD				*Cohen's d*
LS 10m (s)	1.81	0.08	1.89	0.12	0.91	2.28	0.09	0.62
COD45º R (s)	1.94	0.07	1.95	0.08	0.85	2.24	0.92	–0.03
COD45º L (s)	1.90	0.08	1.99	0.13	0.91	3.18	0.06	0.70
COD90º R (s)	2.30	0.10	2.28	0.11	0.95	1.32	0.89	–0.05
COD90º L (s)	2.29	0.16	2.32	0.13	0.94	1.51	0.71	0.13
COD180º R (s)	2.81	0.09	2.82	0.14	0.92	1.69	0.68	0.15
COD180º L (s)	2.80	0.10	2.83	0.15	0.91	2.40	0.40	0.31
Mean Speed (s)	2.21	0.07	2.24	0.10	–	–	0.28	0.40
CODD45º (%)	6.13	4.47	4.65	6.52	–	–	0.47	–0.26
CODD90º (%)	26.3	7.71	22.3	5.63	–	–	0.11	–0.59
CODD180º (%)	53.4	6.58	42.2	7.17	–	–	<0.01*	–1.62

*Abbreviations: LS, Linear Speed; COD, Change of Direction; cm, Centimeters; s, Seconds; R, Right; L, Left; CON, Control Group; INT, Intervention Group; SD, Standard Deviation; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; ES, Effect Size. Significant between-groups differences: * p <0.05.*

Changes in CODD throughout the intervention for each group are illustrated in *Figure 2*. Differences between groups were observed for CODD at 90° and 180°, both at T_2 (p <0.01) and T_3 (p <0.01). However, the CODD at 45° showed no difference between groups at any time during the investigation. In addition, the individual progression in the

CODD for CON and INT showed that only INT athletes improved their CODD at each cutting angulation throughout the intervention.

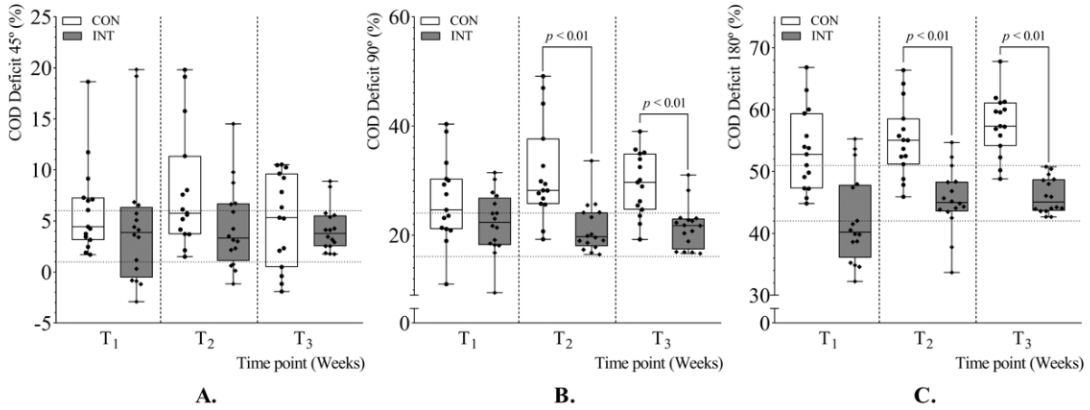

Figure 2. Comparative analysis of COD efficiency changes at different cutting angles in the control group (white box) and the intervention group (grey box) throughout the three assessments during the intervention. **A.** CODD45º; **B.** CODD90º; and **C.** CODD180º.

Table 3 shows the comparative analysis of between- and within-group changes in speed performance. Group*time interaction revealed significant improvements in mean speed performance (mean difference (MD) –0.09, ES =0.34, $p \leq 0.01$) in the INT group. The INT group showed improvements mainly in the force-oriented >90º COD (MD ≤–0.5, ES ≥0.23, $p \leq 0.03$). Velocity-oriented COD and LS did not present a group x time interaction effect. A post-hoc group*time Bonferroni analysis revealed that all improvements in speed performance occurred after 8 weeks. Significant enhancements in mean speed and COD performance (T_1-T_3) were observed in INT group (ES ≥0.74; $p < 0.05$), while no significant changes were found in CON group over the intervention. Furthermore, significant between-group differences were observed at T_3 for the mean speed (ES =1.64; $p < 0.01$) and COD variables (ES ≥1.03; $p < 0.05$).

Discussion

The present study analyzed the effect of an individualized, CODD-based horizontal strength training programme on efficiency and performance in linear and multidirectional speed actions in male basketball players across three time points (zero, four and eight weeks of intervention). The most notable findings of the present study were as follows: 1) CODD-based strength training tailored to the individual force needs of each athlete improved efficiency in linear and multidirectional speed actions in all basketball players regardless of initial CODD score or COD angles tested; 2) the greatest improvements in performance were observed in force-oriented speed actions (COD angle >90º); and 3) individualized CODD training was effective in improving speed performance, but a minimum time period of 8 week was necessary to find significant changes.

To the best authors' knowledge, this is the first intervention research with basketball players that has provided individualized horizontal force training based on the CODD. It is also one of the first intervention study to analyze the effect of training on the

Table 3. Changes between pre- (T_1), intra- (T_2) and post- (T_3) intervention in the study variables for each group.

Variables	CON					INT					Time		Group x Time	
	T_1	T_2	T_3	Mean dif.		T_1	T_2	T_3	Mean dif.					
	Mean ± SD	Mean ± SD	Mean ± SD	T1-T2	T1-T3	Mean ± SD	Mean ± SD	Mean ± SD	T1-T2	T1-T3	*p* Value	ES (η^2)	*p* Value	ES (η^2)
LS 10m (s)	1.81 ± 0.08	1.80 ± 0.06	1.81 ± 0.11	–0.01	0.00	1.89 ± 0.12	1.85 ± 0.09	1.81 ± 0.09	–0.04	–0.08	<0.01	0.49	0.60	0.04
COD45 R (s)	1.94 ± 0.07	1.97 ± 0.15	1.93 ± 0.15	0.03	–0.01	1.95 ± 0.08	1.94 ± 0.10	1.90 ± 0.10	–0.01	–0.05	0.88	0.01	0.79	0.02
COD45 L (s)	1.90 ± 0.08	1.92 ± 0.15	1.88 ± 0.12	0.02	–0.02	1.99 ± 0.13[b]	1.94 ± 0.10	1.89 ± 0.12[b]	–0.05	–0.10	0.02	0.26	0.72	0.02
COD90 R (s)	2.30 ± 0.10	2.38 ± 0.21	2.36 ± 0.12[*]	0.08	0.06	2.28 ± 0.11	2.28 ± 0.16	2.23 ± 0.16[*]	0.00	0.05	0.24	0.10	0.03	0.23
COD90 L (s)	2.29 ± 0.16	2.36 ± 0.23	2.33 ± 0.17	0.07	0.04	2.32 ± 0.13	2.31 ± 0.10	2.25 ± 0.11	–0.02	–0.07	0.06	0.19	0.09	0.16
COD180 R (s)	2.81 ± 0.09	2.83 ± 0.17	2.85 ± 0.11[*]	0.02	0.04	2.82 ± 0.14[b]	2.73 ± 0.19	2.64 ± 0.15[b*]	–0.09	–0.18	0.06	0.18	<0.01	0.53
COD180 L (s)	2.80 ± 0.10	2.75 ± 0.14	2.81 ± 0.17[*]	–0.05	0.01	2.83 ± 0.15[b]	2.73 ± 0.13[c]	2.62 ± 0.15[b,c*]	–0.10	–0.21	<0.01	0.37	<0.01	0.44
Mean Speed (s)	2.21 ± 0.07	2.23 ± 0.13	2.24 ± 0.11[*]	0.02	0.03	2.24 ± 0.10[b]	2.20 ± 0.09	2.15 ± 0.10[b*]	–0.04	–0.09	0.37	0.07	<0.01	0.34

Abbreviations: LS, Linear Speed; COD, Change of Direction; cm, Centimeters; s, Seconds; R, Right; L, Left; CON, Control Group; INT, Intervention Group; SD, Standard Deviation; T_1, Pre-intervention assessment; T_2, Intra-intervention assessment; T_3, Post-intervention assessment; ES, Effect Size; η^2, partial eta square. The model was adjusted by between-group differences T_1. [a] Significant within-group differences ($p < 0.05$) between T_1-T_2. [b] Significant within-group differences ($p < 0.05$) between T_1-T_3. [c] Significant within-group differences ($p < 0.05$) between T_2-T_3. [*] Significant between-group differences ($p < 0.05$) at the same assessment time.

multidirectional movement efficiency of athletes, measured by the CODD[31]. Previous studies that have examined CODD throughout a training intervention calculated this variable in absolute value and found no effect of sprint training on CODD in football players[32], and no effect of individualized training based on the dynamic strength index on CODD in basketball players[33]. Therefore, no training approaches have shown an enhancement in multidirectional speed efficiency to date. This may be explained since the training programmes were not specific and adapted to the speed needs of each athlete, thus not providing sufficient stimulus to produce adaptations in the multidirectional speed efficiency of the athletes[16]. Furthermore, the CODD was calculated as an absolute value[31] and not in percentage terms [9], which standardises the CODD measurement and allows athletes to be classified to programme more effective training[4]. The present study addressed these previous limitations by using the percentage-based CODD to individualize training and thus provide adequate training stimuli for each athlete. The results show significant between-groups differences in movement efficiency after both four and eight weeks of training, with INT players best trading off their individual linear and multidirectional speed demands. In other words, INT players were the most efficient players in all movement directions tested. These findings are in line with the initial hypothesis of the study and the proposals of previous studies[4], which recommend specific training for each player according to their individual speed needs. [2134]Because basketball is a complex team sport, with an unpredictable and multidirectional nature in which players must be prepared to perform movements at maximum intensity in any direction[17]. Strength and conditioning

basketball coaches must analyze the individual speed demands of each player to create fast, efficient and robust tri-dimensional players[5]. To this end, the current training approach has been shown to be effective in the development of multidirectional speed efficiency in basketball players by achieving a balance between LS and COD abilities.

Previous studies highlighted the importance of the specificity of training principle[35], as it found greater training effects in actions specific to the force orientation trained[36,37]. In this sense, although multiple force orientations interact in sports multidirectional movements, horizontal force is critical in the braking and acceleration COD phases[38]. Specifically, recent studies have shown moderate changes in COD180º performance in football players with non-individualized linear (2.30%, ES =0.44; p =0.55) or curvilinear sprint training (3. 07%, ES =0.93; p <0.01)[32], and with resisted sprint training with low (2.69%, ES =0.60; p =0.43) or high loads (3.77%, ES =0.80; p <0.01)[20]. However, horizontally oriented strength training programmes with basketball players have not shown a significant effect on the COD performance[16,36,37]. This could be justified because they were not adjusted to the individual needs of the players[16], so that "one-size-fits-all" training programs might not be an efficient training stimulus for a group of individuals with different CODD and, therefore, different training needs[4]. Interestingly, the present study results with an individualized CODD-based training approach showed a large performance improvement in linear and multidirectional speed actions of 4.02% in the mean speed (ES =1.23; p <0.01), and an improvement specifically in the COD180º of even 7.42% (ES =1.72; p <0.01). These results were greater than with any other horizontally oriented strength, plyometric or speed training used in the previous scientific literature with football[20,32] or basketball players[16,36,37]. Therefore, although individualized CODD-based training is not yet a common practice in the strength and conditioning field, it would be recommended to use it to achieve greater performance in a shorter period of time. This approach is a quick and easy way to assess and accurately determine the individual speed needs of each athlete in multiple specific angles relevant to their sport context, from which it becomes straightforward to design a training programme focused on improving the speed needs specific to each athlete.

There is current research that indicates that two days of training per week for 4 weeks might be a sufficient period of time to find improvements in COD performance in junior team sports players[39], although these results in terms of the intervention duration might be variable and depend on the type of training undertaken and other variables. In the current study, assessments were included at 4 and 8 weeks of training to analyze at what point it begins to exhibit significant improvements in COD performance. The results indicate that at least 8 weeks of intervention are necessary to observe significant effects of training on COD performance. These results are consistent with those observed in previous studies that examined the effects of plyometric training and concluded that a period of at least seven weeks[14], or a six-to-eight-week period of combined training[12], is necessary to produce improvements in COD performance. Both linear and multidirectional speed actions are complex, as they involve different abilities such as acceleration, deceleration and re-acceleration, at the same time that all the force-

orientations interact[13]; that may be the reason why long periods of time are needed for their development.

Although the current study presents interesting findings and a novel approach to literature, some limitations should be considered when interpreting the results. Firstly, the lack of training load control over specific basketball training sessions may have an effect on the findings. However, randomization should allow to distribute the confounding effects similarly between both groups. Secondly, the size and characteristics of the sample. The results of this study include only 31 amateur male basketball players, so caution should be exercised when extrapolating the results to samples from other sports or with different characteristics. As this is the first scientific study to involve an individualized CODD-based training intervention, it is suggested that future research should develop similar individualized CODD-based training approaches in samples of different genders, sports or competitive levels to gain a better understanding of the effect of this kind of training.

Practical applications

Due to the unpredictable and multidirectional nature of basketball, it is recommended that basketball coaches seek the optimal trade-off between the linear and multidirectional speed demands on their basketball players, to develop efficient athletes in any movement direction on the court. In this regard, the CODD is a powerful tool that provides extensive information to the strength and conditioning coach on the relationship between linear and COD speed for each athlete. This framework allows the basketball coach to take better decisions and design specific training programmes focused on the individual weaknesses and needs of each athlete. The current approach to individualized CODD-based training has been found to be effective in seeking the trade-off between linear and COD speed for each individual athlete, thus improving performance in speed actions regardless of movement direction.

Conclusions

An individualized CODD-based training programme is more efficient at improving speed performance at maximum intensity in basketball players than a MRST programme common to all athletes regardless of the individual needs of each one. The experimental results obtained in the current study support the theoretical principles about CODD that have been hypothesized in previous studies. This CODD approach could, therefore, be considered potentially useful for any strength and conditioning coach attempting to prescribe optimal training to improve both linear and multidirectional speed performance of their athletes, through a more efficient monitoring and understanding of the individual determinants of speed performance. Lastly, it is noteworthy that the improvement of the athlete's overall multidirectional speed profile was observed after 8 weeks of the current training programme.

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Declaration of interest statement

The authors declare no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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STUDY 11

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Effect of different individualised strength training approaches to improve physical performance in male basketball players

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Effect of different individualised strength training approaches to improve physical performance in male basketball players

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Abstract

Porpuse: Training individualisation is a key principle for maximising improvements in athletes' performance, but there are still few approaches to individualisation of training in basketball players. That is why we aimed to: (I) analyse the effects of two individualised training approaches, one based on force-velocity (F-V) profile and the other based on change of direction deficit (CODD), on performance in male basketball players; (II) compare the inter-individual differences in adaptations of these physical abilities and; (III) assess differences in physical performance between two time periods of training intervention.

Methods: Forty-five male basketball players (age, 22.3±4.18 years; height, 1.86±0.15 m; body mass, 86.3±7.85 kg) were divided into three groups: a vertical group (VG, n=15), who performed an individualised training based on F-V profile; a horizontal group (HG, n=15), who underwent individualised intervention based on CODD; and a control group (CG, n=15). Assessments included countermovement-jumps, unilateral drop jumps, F-V profile, sprints, and change of direction (COD) tests. Individualised strength training was administered twice weekly for 8 weeks.

Results: Both intervention groups demonstrated large significant group x time interactions in jump ($\eta_p^2 \geq 0.24$, $p < 0.01$) and speed ($\eta_p^2 = 0.23$, $p < 0.01$) variables, with no significant changes in the CG. Notably, the largest performance gains were achieved in the specific force orientation targeted by each intervention.

Conclusion: These findings suggest that addressing the individual needs of each athlete and the specificity of the physical ability are key considerations for effective training programming in basketball players.

Keywords: *Acceleration; Deceleration; Plyometric; Agility; Team Sports.*

Introduction

Basketball is a team sport of an unpredictable, multidirectional and intermittent nature characterised by a combination of high-intensity, short-duration actions with low to medium intensity movements[1]. However, high-intensity ballistic actions such as jumps, accelerations, decelerations and changes of direction (COD) are key performance indicators for basketball players and the ones that determine the decisive actions in real game situations[2]. In this regard, basketball players perform maximal-intensity multidirectional actions every 1 to 3 seconds during the game[1], with deceleration actions involving COD being executed most frequently due to sport-specific demands[3]. Notably, 15.1% of CODs in a game are executed at high intensities (<−3.5 m·s−2)[4]. Accelerations and linear speed (LS) are also considered key abilities, with basketball players performing over 105 sprints per game with short distances between 3.9 and 9.5 meters, which represent 2-6% of total game time[5]. Jumping is similarly essential, as it is a skill performed in most technical actions, both offensive (e.g., jump shots or layups) and defensive (e.g., blocks); during a competition, male players perform between 41 and 56 jumps[5]. Therefore, strength and conditioning basketball coaches must focus on developing accurate and effective training programs to create fast, efficient and robust basketball players to execute jumps, accelerations and decelerations at maximum intensity in all directions[6].

The performance of these high-intensity multidirectional ballistic actions is closely linked to the ability of each player to mobilise their own body mass, both as much as possible and within the shortest time possible[7]. Given the complexity and multidirectionality of these ballistic actions with high demands for fast force (<400ms)[6], many studies highlight lower-limb neuromuscular power and rate of force development as critical factors for effective performance[8,9]. Numerous training methodologies have been evaluated for their impact on ballistic performance[10], with plyometric training being the most extensively studied approach. This method has shown improvements in ballistic performance, with effect sizes (ES) from small (ES = 0.26) to large (ES = 2.8), depending on the test assessed or the sample characteristics used[11]. Specifically, plyometric training yields significant performance gains in basketball players due to the specificity to the sport itself[12]. However, a recent meta-analysis examining the effect of different training proposals on the performance of COD actions in adult basketball players[13] revealed that, to date, there was no intervention in basketball players that adheres one of the most important training principles: individualisation[14]. Furthermore, it was suggested that training without considering individual needs or responses to training is not efficient for improving ballistic performance in basketball players.

New paradigms that have been developing in recent years advocate the individualisation of training and specify that high intensity ballistic performance is largely influenced by each athlete's individual force and velocity needs, both with vertical[15] and horizontal force-orientations[16]. On the one hand, Samozino *et al.*[17] confirmed that each athlete has an optimal vertical force-velocity (F-V) profile that maximises ballistic movements by achieving an ideal balance of force and velocity in

vertical ballistic actions[7]. On the other hand, Barrera-Domínguez *et al.*[16] examined the effect of COD Deficit (CODD) on athletes' linear and multidirectional performance, determining optimal thresholds for different cutting angles at which athletes achieved their best performance across the whole linear and multidirectional speed profile. Athletes with higher performance in LS actions are often inefficient in COD, because they reach a high sprint momentum that is difficult to manage over the deceleration phase and the cutting action itself[18]. Conversely, athletes with higher performance in COD actions exhibited lower performance in LS due to being less efficient accelerating[16]. Given the multi-directional nature of basketball, it was advisable to seek a trade-off between LS and COD for each individual athlete, in order to create robust three-dimensional players adapted to sport's demands[16].

Existing literature reveals that both approaches attempt to improve sport performance by seeking the optimal balance between individual force and velocity needs in different sport specific movements, jumping through the F-V profile and multidirectional speed through the CODD. However, to the best of the authors' knowledge, there is no longitudinal study that analyses and compares the effects of both approaches on the performance of basketball players. Thus, the main purpose of this study was to analyse the effects of two individualised training approaches, one based F-V profile and the other based on change of direction deficit (CODD) on performance in male basketball players. Secondly, the study aimed to compare the inter-individual differences in adaptations of these physical abilities. Finally, it was aimed to assess differences in physical performance between two different time periods (four-eight weeks of training intervention). As both individualised training approaches seek to align a balance between the individual force and velocity demands of each athlete, it was initially hypothesised that both approaches would be effective and produce increases in athlete performance, but these effects would probably be specific to the force orientation trained.

Material and methods

Participants

Forty-five male basketball players from three teams belonging to the same competitive level (i.e., Spanish N1 National League) were classified into three groups: a vertical group (VG, n = 15; age, 22.9 ± 6.52 years; height, 1.88 ± 0.08 m; body mass, 90.3 ± 23.0 kg) who underwent an individualised F-V profile intervention following the protocol of Jiménez Reyes *et al.*[19,20]; a horizontal group (HG, n = 15; age, 21.1±1.45 years; height, 1.86 ± 0.07 m; weight, 85.8 ± 8.91 kg) who underwent individualised intervention based on CODD threshold[16]; and a control group (CG, n = 15; age, 22.7 ± 4.93 years; height, 1.84 ± 0.05 m; body mass, 82.2 ± 6.00 kg). All players had at least six years prior experience playing at the federated level and one year of strength training directly prior to the intervention; they did regular training four days per week during the competitive period and did not present any injury six months prior to or during the investigation; and all of them completed 100% of the intervention programmed. The research was developed throughout the second part of the season and finished just before the end of the

competitive period. All players were informed about the study's objectives and gave their written consent to participate in it. The experimental protocol adhered to the latest version of the Declaration of Helsinki and it was approved by the Andalusian Ethics Committee for Biomedical Research (reference number: FBD_UHU2020).

Study design and procedure

A quasi-experimental repeated measures, 8-week follow-up design was used, in which all groups performed four on-court basketball training sessions (90 minutes/session), and one game (40 minutes/game) per week. Moreover, both intervention groups undertook two strength and conditioning sessions (60 minutes/session) every week. The intervention design included three assessment points: a pre-assessment (T_1) conducted one week prior to the intervention; an intra-intervention evaluation (T_2), at week 4 (just in the middle of the intervention) in which the training sessions were readjusted based on the new assessment data; and a post-evaluation (T_3) just at the end of the intervention.

One week before the study began, players completed two familiarization sessions with the testing procedures. For T_1, T_2, and T_3 assessments, the evaluations were organised into two sessions, always before the sports training itself (7 pm - 8 pm) with 48-hour interval between sessions. In the first session, horizontal force-oriented tests were included: (i) LS and COD tests. In the second session, vertical force-oriented tests were evaluated: (ii) F-V profile, CMJ and DJu. All tests were carried out on the hardwood court where players regularly trained and played. Players were instructed to attend the assessment well-hydrated, adequately rested, and to avoid any intense physical activity during the preceding 24 hours. Additionally, they were asked to refrain from consuming caffeine, food (for the preceding 3 hours), and alcohol (for at least 24 hours prior to testing). Before each assessment, players completed a standardised warn-up consisting of 5 minutes of low-intensity ball handling, 5 minutes of hip mobility and core activation exercises, 5 minutes of landing, multidirectional bounding, and acceleration-deceleration drills, followed by 5 minutes of gradual intensity increases to prepare for the specific tests. Each player performed 3 attempts for each test, with a 2-minute rest interval between attempts. The average of all attempts for each test was used for further analysis.

Training intervention

Both intervention groups carried out their strength training twice weekly, 60 minutes before the on-court basketball session. The workload was equalised and adjusted following previous scientific recommendations[19,20] by performing 18 sets per week, divided into 6 different exercises (3 sets/exercise) and a 120-second rest period was performed inter-sets to optimise intra-session recovery (detailed in *Supplementary material 1a* and *Supplementary material 1b*). Throughout the intervention, players were verbally instructed and encouraged to perform each exercise at maximum intensity[21].

For VG, players were classified according to the F-V profile as: "well-balanced", if they had less than 10% imbalance from the optimal F-V profile (Well-balance subgroup VG, n = 2); "low deficit", when they had between 10-40% (Low-force deficit subgroup VG, n = 5; Low-velocity deficit subgroup VG, n = 2); and "high deficit", when they

exceeded a 40% imbalance (High-force deficit subgroup VG, n = 6)[20]. Training for VG was then individualized according to this classification, targeting specific velocity zones within the F-V profile to match each player's individual needs *(Supplementary material 1a)*.

On the other hand, HG athletes were classified according to the CODD180º. HG players players were labelled as: "multidirectional speed dominant" (MSD; HG, n=11), if they had less to 43% CODD180º; "balanced", when they had between 43-49% (HG, n=2); and "linear speed dominant" (LSD; HG, n=3) when they exceed 49% CODD180º[16]. As basketball is a multidirectional sport, in which players must be able to execute both LS and COD up to 180° at maximum intensity[22], the HG training program was individualised to create more efficient players in COD by seeking the trade-off between LS and COD according to the individual needs of each athlete. *Supplementary material 1b* details the intervention performed on each HG subgroups.

Physical fitness test

Vertical Test Assessments: Countermovement Jump, unilateral Drop Jump and Vertical Force-Velocity Profile. Vertical tests were evaluated using a Chronojump contact platform (Chronojump Boscosystem®, Barcelona, Spain)[23]. Each subject performed a DJu, a CMJ with body weight, plus 5 CMJs with trap bar and additional loads ranging from 20 to 60 kg in a random order. CMJ tests, with and without extra load, were performed bilaterally, while DJu were unilateral. The DJu was performed from an initial height of 30cm[24], each subject dropped down until came into contact with the platform with only one leg, in order to jump as high as possible and finally landing with the same leg. Each DJu and CMJ attempt was considered valid if both hands were placed on the hips for DJu and CMJ without extra load or on the trap bar with elbows extended for loaded CMJ, the knees were not bent during the jump flight time and whether the landing was made at the same point as the take-off. For the loaded CMJ to be valid, it had to reach at least 10 cm in height[25].

An Excel spreadsheet downloaded from jbmorin.net (JUMPFVPprofile(1).xlsx) was used to apply the Samozino *et al.* [7] method and obtain the F0, V0, and Pmax. Additionally, the spreadsheet also showed the individual optimal theoretical F-V profile for each subject and the F-V imbalance of each individual with respect to the F-V profile[17]. In addition, the values of the reactive strength index (RSI) were calculated through the flight time/contact time ratio for each leg extracted from the DJu.

Speed Test Assessments: Linear and change of direction speed. The times in the speed tests were measured with single-beam photocells (Chronojump Boscosystem®, Barcelona, Spain). The photocells were placed 2 meters apart from each other and at a height of 1.10 meters (approximately the height of the players' hips). Each player was placed 0.5 meters behind the first gate, in a two-point split stand. Then, each player accelerated at maximum speed to the second gate. The speed tests were: (1) LS test, which the photocells were placed 10 meters away in a straight line; and (2) COD test, which each player ran 5 meters to pivot point marked on the floor and then changed of

direction at 45º (COD45º), 90º (COD90º) and 180º (COD180º) to go to the second gate in the shortest possible time. The COD tests were performed on both sides, with laterality defined by the leg on which the subjects leaned when performing the COD mechanics[26]. Basketball players' mean speed performance was calculated as the average of the four speed tests assessed and the CODD for each angulation was obtained as follows[27]:

$$CODD\% = \frac{COD\ time - LS\ time}{LS\ time}\ x\ 100$$

Statistical analysis

Data were expressed as mean and standard deviation. The normality of the data was tested and confirmed using the Shapiro-Wilk test (p >0.05). Homoscedasticity was determined with the Levene test. The relative and absolute reliability of the tests was evaluated by the intraclass correlation coefficient (ICC) and the coefficient of variation (CV) for all assessments. An ICC ≥0.8 was considered strong and a CV <5% was established as an intra-day reliability criterion. Training effects were evaluated using a 3 (groups: CG, VG, and HG) x 3 (time: T_1, T_2, and T_3) repeated measures ANOVA model, and the effect size (ES) were determined using the partial eta-square (η_p^2). ES was considered trivial (<0.003), small (0.01), moderate (0.06), large (>0.14)[28]. The model was adjusted by inter-group differences T_1. Additionally, the Bonferroni post-hoc for multiple comparisons was performed to identify where significant changes occurred, and the ES were determined using the Cohen's d. ES was considered trivial (<0.10), small (0.10-0.39), moderate (0.40-0.79), large (>0.80)[28]. Finally, responders (Rs) and non-responders (NRs) to the interventions were determined through calculating 2CV[29]. Athletes were labelled as NRs if they did not get a post-intervention performance increase greater than 2CV, and this was established as follows: CMJ: 1.452 cm, DJu: 1.086 cm, RSI: 0.084 cm, LS: 0.068 s, COD45º: 0.082 s, COD90º: 0.060 s, and COD180º: 0.092 s, respectively. The alpha level was set to 0.05. Statistical analysis was performed with SPSS version 25 for Windows (SPSS, Inc., Chicago, IL, USA).

Results

Table 1 shows baseline performance, inter-group differences, and reliability metrics (ICC and CV values). There were no significant differences between groups at baseline for any variables, except for RSI (p ≤0.01), with differences mainly between VG and HG. Relative and absolute reliability measures were confirmed for all assessments (ICC ≥0.90; CV ≤4.94).

Table 2 shows comparative analysis inter- and intra- group changes in classification and performance variables. According to classification variables, the F-V profile imbalance showed large significant group x time interactions (η_p^2 =0.25, p <0.01), with VG players achieving the best F-V profile after 8 weeks of intervention. Concerning the classification variable used to individualise HG training, CODD180º, large group x time changes were observed (η_p^2 =0.17, p =0.08), being the HG the only group in which all players reached a balanced CODD180º and the one that showed the greatest significant

differences with CG (d =–1.88, p <0.01) and VG (d =–1.20, p <0.05) after 8 weeks of training.

Table 1. Baseline of the classification and performance variables, inter-groups differences and their respective reliability measures.

Variables	CG (n = 15)	VG (n = 15)	HG (n = 15)				
	Mean (SD)	Mean (SD)	Mean (SD)	ICC	CV	*p* Value	ES (η_p^2)
Classification							
F-V Profile	29.1 (34.4)	29.1 (21.6)	-	-	-	*0.99*	0.01
CODD180º	53.4 (6.58)	51.5 (8.46)	49.6 (6.96)	-	-	*0.39*	0.04
Performance							
CMJ (cm)	33.7 (4.83)	30.7 (3.02)	34.9 (5.72)	0.99	2.12	*0.07*	0.12
DJu (cm)	14.2 (3.32)	13.4 (2.88)	16.1 (3.02)	0.98	3.57	*0.06*	0.12
RSI	0.89 (0.22)	0.67 (0.12)*	0.97 (0.16)*	0.97	4.94	*<0.01*	0.37
LS 10m (s)	1.82 (0.08)	1.86 (0.11)	1.88 (0.13)	0.92	1.81	*0.23*	0.07
COD45º (s)	1.93 (0.07)	1.97 (0.09)	1.97 (0.09)	0.90	1.12	*0.34*	0.05
COD90º (s)	2.29 (0.12)	2.33 (0.19)	2.30 (0.12)	0.98	1.33	*0.74*	0.01
COD180º (s)	2.78 (0.08)	2.81 (0.09)	2.81 (0.14)	0.94	1.65	*0.68*	0.02
Mean Speed (s)	2.20 (0.07)	2.24 (0.10)	2.24 (0.10)	0.93	1.48	*0.45*	0.04

*Abbreviations: F-V, Force-Velocity; CODD, Change of Direction Deficit; CMJ, Countermovement Jump; DJu, unilateral Drop Jump; cm, Centimeters; RSI, Reactive Strength Index; LS, Linear Speed; COD, Change of Direction; s, Seconds; CG, Control Group; VG, Vertical Group; HG, Horizontal Group; SD, Standard Deviation; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; ES, Effect Size; η_p^2, partial eta square. Significant inter-groups differences: ‡ (between CON-VER; p <0.05), † (between CON-HOR; p <0.05), * (between VER-HOR; p <0.05).*

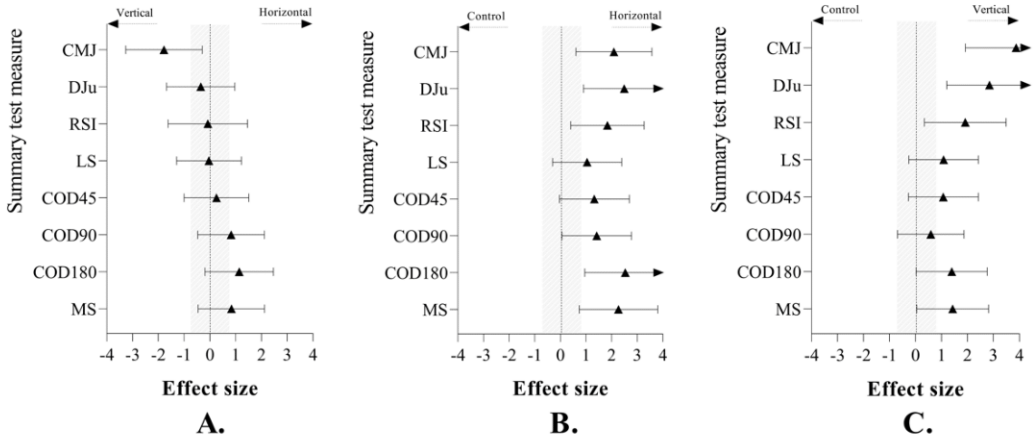

Figure 1. Standardised differences (Cohen's d, CI95%) for Countermovement Jump (CMJ), unilateral Drop Jump (DJu), Reactive Strength Index (RSI), 10-meter Linear Sprint (LS), Change of Direction 45º (COD45º), 90º (COD90º), 180º (COD180º), and Mean Speed (MS) time according to **A.** Vertical Group (VG) vs Horizontal Group (HG); **B.** Control Group (CG) vs HG; **C.** CG vs VG.

On the other hand, these observed changes in the classification variables used to individualise training resulted in different magnitudes of changes in athletes' performance variables. In this regard, both the jump ($\eta_p^2 \geq 0.24$, p <0.01) and speed (η_p^2 =0.23, p <0.01) variables showed large significant group x time interactions. A post-hoc Bonferroni analysis revealed that, although both training approaches improved vertical jump and

showed significant differences with CG, the VG achieved the largest improvements at both 4 weeks (≥7.29%, d ≥1.47, p <0.01) and 8 weeks (≥17.0%, d ≥3.70, p <0.01) of training. Both individualised interventions groups also showed improvements in speed performance, though HG achieved the greatest improvements (≥5.49%, d ≥2.04, p <0.01) after 8 weeks of training.

Table 2. Changes in vertical jumping, sprinting and change of direction performance between pre- (T_1), intra- (T_2) and post- (T_3) intervention for each group.

		T_1	T_2	T_3	% Change		Time	Group x Time
Test	Group	Mean (SD)	Mean (SD)	Mean (SD)	T1-T2	T1-T3	p (ES)	p (ES)
Classification variables								
F-V profile	CG	29.1 (34.4)	33.9 (26.1)‡	36.0 (25.3)‡	14.2	19.2	*<0.01* (0.31)	*<0.01* (0.25)
	VG	29.1 (21.6)[a,b]	13.5 (22.9)[a]‡	10.0 (15.7)[b]‡	–53.6	–65.6		
	HG	-	-	-	-	-		
CODD 180º	CG	53.4 (6.58)	55.1 (5.91)	55.9 (6.91)†	2.88	2.72	*<0.01* (0.29)	*<0.01* (0.17)
	VG	51.5 (8.46)	54.5 (6.22)	51.8 (7.86)*	5.11	–1.09		
	HG	49.6 (6.96)[b]	47.3 (9.18)	44.5 (6.99)[b]†*	–9.57	–13.9		
Performance variables								
CMJ (cm)	CG	33.7 (4.83)	32.7 (4.93)‡†	33.5 (5.18)‡†	–3.37	–0.88	*0.09* (0.06)	*<0.01* (0.51)
	VG	30.7 (3.02)[a,b]	33.2 (3.83)[a,c]‡	37.2 (4.45)[b,c]‡*	7.29	17.0		
	HG	34.9 (5.72)[a,b]	36.9 (7.04)[a]†	38.5 (7.17)[b]†*	5.62	9.34		
DJu (cm)	CG	14.2 (3.32)	14.0 (3.08)‡	13.4 (2.93)‡†	–1.61	–5.23	*0.56* (0.02)	*<0.01* (0.38)
	VG	13.4 (2.88)[a,b]	15.0 (3.29)[a,c]‡	16.8 (4.22)[b,c]‡	10.3	18.9		
	HG	16.1 (3.02)[b]	17.3 (3.89)[c]	19.0 (3.97)[b,c]†	6.51	14.6		
RSI	CG	0.89 (0.22)	0.78 (0.20)†	0.77 (0.18)‡†	-16.2	-16.1	*0.03* (0.09)	*<0.01* (0.24)
	VG	0.67 (0.12)	0.73 (0.14)	0.80 (0.14)‡	6.51	15.4		
	HG	0.97 (0.16)	1.02 (0.14)†	1.02 (0.22)†	3.95	2.89		
LS 10m (s)	CG	1.82 (0.08)	1.80 (0.06)	1.82 (0.11)	–1.05	–0.29	*<0.01* (0.29)	*0.07* (0.10)
	VG	1.86 (0.11)[b]	1.82 (0.09)	1.79 (0.08)[b]	–2.25	–4.13		
	HG	1.88 (0.13)[b]	1.84 (0.09)	1.80 (0.09)[b]	–2.16	–4.58		
COD 45º (s)	CG	1.93 (0.07)	1.94 (0.14)	1.91 (0.12)†	0.57	–1.39	*0.04* (0.07)	*0.05* (0.11)
	VG	1.97 (0.09)[b]	1.94 (0.09)[c]	1.87 (0.08)[b,c]	–1.69	–5.61		
	HG	1.97 (0.09)[b]	1.92 (0.08)[c]	1.84 (0.07)[b,c]†	–2.18	–6.37		
COD 90º (s)	CG	2.29 (0.12)	2.37 (0.20)	2.35 (0.14)†	3.03	2.20	*<0.01* (0.17)	*0.03* (0.12)
	VG	2.33 (0.19)	2.34 (0.12)	2.32 (0.13)	0.37	–0.54		
	HG	2.30 (0.12)	2.29 (0.13)	2.24 (0.13)†	–0.97	–3.43		
COD 180º (s)	CG	2.78 (0.08)	2.79 (0.14)	2.82 (0.12)†	0.08	1.33	*<0.01* (0.13)	*<0.01* (0.26)
	VG	2.81 (0.09)	2.79 (0.09)	2.72 (0.09)	–0.85	–3.40		
	HG	2.81 (0.14)[b]	2.72 (0.16)[c]	2.63 (0.15)[b,c]†	–3.88	–7.47		
Mean speed (s)	CG	2.20 (0.07)	2.23 (0.13)	2.22 (0.11)‡†	0.77	0.69	*0.03* (0.08)	*<0.01* (0.23)
	VG	2.24 (0.10)[b]	2.22 (0.08)	2.17 (0.08)[b]‡	–1.00	–3.27		
	HG	2.24 (0.10)[b]	2.20 (0.09)[c]	2.13 (0.09)[b,c]†	–2.30	–5.49		

*Abbreviations: F-V, Force-Velocity; CODD, Change of Direction Deficit; CMJ, Countermovement Jump; DJu, unilateral Drop Jump; cm, Centimeters; RSI, Reactive Strength Index; LS, Linear Speed; COD, Change of Direction; s, Seconds; CG, Control Group; VG, Vertical Group; HG, Horizontal Group; SD, Standard Deviation; T_1, Pre-intervention assessment; T_2, Intra-intervention assessment; T_3, Post-intervention assessment; ES, Effect Size (η_p^2, partial eta square). The model was adjusted by inter-group differences T_1. Significant inter-groups differences: ‡ (between CON-VER; p <0.05), † (between CON-HOR; p <0.05), * (between VER-HOR; p <0.05). Significant intra-groups differences: a (between T_1-T_2; p <0.05), b (between T_1-T_3; p <0.05), c (between T_2-T_3; p <0.05).*

The results of the inter-group analysis for post-assessment changes in performance variables are illustrated in *Figure 1*. Standardised differences for jump and speed outcomes showed significantly better results in the VG (d ≥1.43, p <0.01) and HG (d ≥1.42, p <0.01) compared to the CG at post-test. Likewise, large significant differences were found between HG and VG only in CMJ (d = –1.78, p <0.01).

Finally, *Table 3* shows the percentage of NRs to each individualised training interventions. The CG, with non-individualised training, proved to be inefficient in producing changes in most athletes, with up to 87% of NRs. Each individualised training group only obtained 22% of NRs. The COD90º variable showed the highest number of NRs, regardless of the training group.

Table 3. Individual patterns of response on the performance variables by control, vertical, and horizontal groups.

Tests	Individual response															NRs
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	(%)
CONTROL																**64%**
CMJ	↓	↑	↔	↓	↔	↔	↓	↓	↑	↓	↓	↓	↓	↑	↔	80%
DJu	↔	↑	↑	↑	↑	↑	↑	↑	↑	↑	↔	↔	↔	↔	↔	40%
RSI	↔	↑	↑	↔	↑	↑	↑	↑	↑	↑	↑	↔	↔	↑	↔	33%
LS 10m	↑	↑	↑	↑	↑	↑	↓	↔	↓	↓	↓	↔	↑	↓	↓	53%
COD 45º	↓	↑	↑	↓	↑	↑	↓	↓	↔	↓	↔	↔	↑	↔	↓	67%
COD 90º	↓	↓	↑	↓	↓	↔	↓	↓	↓	↓	↓	↔	↑	↔	↓	87%
COD 180º	↓	↔	↔	↓	↓	↔	↓	↓	↓	↓	↓	↔	↑	↑	↓	87%
VERTICAL																**22%**
CMJ	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	00%
DJu	↑	↔	↔	↑	↔	↑	↑	↔	↑	↑	↔	↔	↑	↑	↔	47%
RSI	↑	↔	↔	↔	↑	↑	↑	↑	↑	↔	↑	↑	↑	↑	↑	26%
LS 10m	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↔	↑	07%
COD 45º	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↔	↑	07%
COD 90º	↓	↑	↔	↑	↑	↔	↑	↑	↑	↑	↓	↑	↓	↓	↔	47%
COD 180º	↑	↑	↔	↔	↑	↑	↔	↑	↑	↑	↑	↑	↑	↑	↑	20%
HORIZONTAL																**22%**
CMJ	↑	↔	↔	↑	↑	↑	↑	↓	↓	↑	↔	↑	↑	↑	↑	33%
DJu	↑	↔	↔	↔	↑	↑	↑	↑	↑	↑	↑	↑	↑	↔	↑	27%
RSI	↑	↔	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	07%
LS 10m	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↔	↑	↑	07%
COD 45º	↔	↑	↑	↑	↑	↑	↔	↑	↔	↑	↔	↑	↑	↑	↑	27%
COD 90º	↑	↔	↔	↑	↑	↑	↓	↓	↑	↑	↓	↓	↑	↔	↑	47%
COD 180º	↑	↔	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	07%

Abbreviations: CMJ, Countermovement Jump; DJu, unilateral Drop Jump; RSI, Reactive Strength Index; LS, Linear Speed; m, meters; COD, Change of Direction; NRs, non-resporders. ↑denote responders (white boxes); ↔ denote non-responders (light grey boxes), and ↓indicate adverse responses (dark grey boxes). The percentage of participants demonstrate non-responders including both non- and adverse responses.

Discussion

The current study aimed (I) to analyse the effects of two individualised training approaches, one based on force-velocity (F-V) profile and the other based on CODD, on the ability of male basketball players to jump, accelerate and change direction; (II) to compare the inter-individual differences in adaptations of these physical abilities and; (III) to assess differences in physical performance between two different time periods (four-eight weeks of training intervention). The most notable findings of this study were: (A) each of the individualised training programs was effective in improving the variable on which the training was based. That is, the VG and HG were more efficient in the F-V profile and CODD180º, respectively. Additionally, (B) both individualised training approaches led to performance improvements across all measured outcomes after 8 weeks. (C) These improvements were of greater magnitude in actions specific to the force-orientation training focus; greater gains were observed in vertical variables among

players who underwent F-V profile-based training, and in horizontal variables for those trained based on CODD180º. Furthermore, (D) significant changes in vertical jump performance occurred earlier (at week 4) than those observed in linear and multidirectional speed. Finally, (E) it is worth noting that specific basketball training without individualisation was insufficient for enhancing physical performance, as over 60% of athletes in this group were classified as NRs. Thus, it is recommended that strength and conditioning coaches implement individualsed training stimuli, tailoring programs to optimize each player's responsiveness to specific training variables.

According to the principle of specificity and transfer of training[30], previous research[31,32] highlights the importance of training specific force orientation to the ability to be improved. However, recent meta-analysis studies[33] suggest no substantial difference between force-oriented training in enhancing vertical performance, implying that both orientations appear to be effective for the development of vertical actions, such as vertical jumps. Furthermore, horizontally oriented resistance or plyometric training may be superior at enhancing horizontal performance, such as horizontal jumps, sprint acceleration capacity and change of direction speed[33,34]. Conversely, other meta-analysis studies found that vertically oriented training was more effective for improving performance in horizontal speed and COD actions in basketball players[13]. It is evident that there is still much controversy about how the force orientation of training influences performance in a multidirectional sport such as basketball. This lack of agreement may stem from variations in training protocols, including differences in volume, intensity, and individual player needs[13]. In line with this, studies that have considered additional factors influencing training adaptations suggest that vertically or horizontally force-oriented training will improve performance within tasks aligned to the same force orientation in basketball[35] and football players[36]. The current study's findings confirmed this previous evidence, underscoring the importance of force orientation in training. Specifically, our results demonstrated that each training group achieved the greatest improvements in tasks specific to the trained force orientation, suggesting that training specificity likely facilitates greater neuromuscular coordination and adaptations[37].

To date, scientific literature has not previously addressed on the training individualisation of basketball players. Accordingly, previous meta-analysis studies[13] criticise the lack of intervention studies that individualise training programs to enhance basketball players' performance. Non-individualised training protocols may provide insufficient training stimuli to generate adaptations in players' performance[13]. Supporting this, a recent study examining the effects of combined, non-individualized vertical and horizontal strength training in basketball players[38], reported no significant improvements in vertical jump performance (≤4.28%, $g \leq 0.68$; $p \geq 0.06$), and COD actions (≤1.84%, $g \leq 0.49$; $p \geq 0.65$) following 8 weeks of training. In contrast, our study observed greater improvements in jump (≥5.62%) and speed (≥1.00%) performance in both force orientation groups with only four weeks of individualised training. Both force orientation groups demonstrated further significant performance gains following eight weeks of intervention ($\eta_p^2 \geq 0.25$, $p < 0.01$). Given that both studies involved basketball players, the large differences in training outcomes suggests that individualized training, tailored to

each player's needs, yields superior adaptation effects. Additionally, other authors who analysed the effect of individualised strength training based on the dynamic strength index[39] or the F-V profile[40] on basketball players reported notable performance improvements in basketball players. These findings align with the present study, which indicates that individualising training to target specific force orientations leads to better outcomes than generalized basketball training. Moreover, our analysis of NRs revealed that both individualised training protocols resulted in a higher proportion of athletes responding positively to the training (78% Rs), compared to the non-individualized, basketball-specific group (36% Rs). This evidence suggests that individualised training approaches not only achieve faster and more substantial performance improvements but also result in fewer NRs.

It is well-documented that a short-term intervention (4 to 8 weeks) involving strength or ballistic training programs can significantly enhance physical performance in male team sport players[39,41]. Regardless of the force orientation trained, male youth team sports players demonstrate improvements in jumping and COD performance within four weeks of training[41]. Similarly, Plesa *et al.*[39] reported significant gains in jump and COD performance among highly trained basketball players after just five weeks of individualised training based on the dynamic strength index. Thus, these findings suggest that measurable performance improvements can occur within the first month of training. The results of the present study partially align with these findings. Significant improvements were observed in vertical jump actions (≥7.29%, $d \geq 1.47$, $p < 0.01$) after four weeks of individualised training. However, linear and COD performance did not show significant changes at this time point, although a tendency towards improvement was evident (≥1.00%, $d \geq 0.23$, $p \geq 0.32$). So, the timing of performance improvements depends on the specific skill being targeted. In this sense, performance improvements in jumping actions occurred earlier than in speed and COD actions. This discrepancy may be attributed to the complexity of COD movements, which integrate multiple abilities — such as acceleration, deceleration, and re-acceleration— while involving interactions across various force orientations[42]. Consequently, longer training durations, such as eight weeks, may be required to elicit significant improvements in COD performance[40], compared to vertical jump that responded significantly to just four weeks of training. These findings are consistent with a recent meta-analysis on combined training effects on COD speed, which concluded that a minimum intervention period of six to eight weeks is necessary to achieve significant improvements in performance[10].

Despite the novelty of this study, several limitations should be considered when interpreting the results. First, the absence of training load quantification during specific basketball training sessions may have influence the findings. Nevertheless, the randomization process likely ensured that any confounding effects were evenly distributed across the groups. Second, F-V profile assessment could not be carried out with the HG to avoid disturbing their intervention. Nonetheless, this variable was only used to individualise the VG training, so it did not affect the results. Third, the study duration was limited to 8 weeks (16 sessions), which may restrict the generalisability of the findings to adaptations that occur over a full basketball season. Basketball is a sport

where athletes aim to achieve peak performance weekly, and this dynamic could not be evaluated within the scope of the present research. Finally, while this study implemented individualised training protocols based on two key variables relevant to basketball performance, future research should focus on analysing the effect of different ways of individualising training; which seems to offer the greater improvements in performance.

Conclusions

The findings highlight the significant potential of programming training based on the individual needs of each player. The 'one-size-fits-all' approach appears insufficient to elicit meaningful adaptations in most athletes. Both individualised training approaches — based on the F-V profile and the CODD180º— proved to be efficient strategies for improving basketball players' performance. Furthermore, the assessment of these variables is both accessible and time-efficient in a basketball team setting, facilitating the practical implementation of such individualised training programs within the physical preparation systems used throughout the basketball season. Strength and conditioning basketball coaches strongly encouraged to consider the specific force orientation targeted in their training designs to optimise player performance. The integration of force vector-specific training may be critical, as the greatest improvements were achieved in the physical capacities directly aligned with the targeted force vector during the intervention. This underlines the need for specificity in strength training protocols. In summary, addressing the individual needs of each athlete and ensuring specificity in the development of targeted abilities are key considerations for effective training program design for basketball players.

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Supplementary Material

Supplementary material 1a. Vertical individualised training programs based on the F-V for each imbalance threshold. Adapted from Jimenez-Reyes et al. (Jiménez-Reyes et al., 2016, 2019).

Individualised vertical training (% F-Vimbalance)	**Session**	**Exercise**	**Training load**	**Execution speed**
High force deficit (>40% of optimal thresholds)	1	Back squat	80-90% RM	0.68 – 0.51 m·s^{-1} (~10% VL)
		Deadlift trap bar	70-80% RM	0.71 – 0.58 m·s^{-1} (~10% VL)
		SL CMJ	10% BW	
	2	Deadlift barbell	85-95% RM	0.52 – 0.39 m·s^{-1} (~10% VL)
		Clean pull	80% RM	> 1.11 m·s^{-1} (~5% VL)
		CMJ trap bar	80% BW	
Low force deficit (between 10% and 40% of optimal thresholds)	1	Back squat	80-90% RM	0.68 – 0.51 m·s^{-1} (~10% VL)
		CMJ trap bar	80% BW	
		SL CMJ	10% BW	
	2	Deadlift barbell	85-95% RM	0.52 – 0.39 m·s^{-1} (~10% VL)
		Clean pull	80% RM	> 1.11 m·s^{-1} (~5% VL)
		SL SJ	BW	
Well-balanced (between -10% and 10% of optimal thresholds)	1	Back squat	80-90% RM	0.68 – 0.51 m·s^{-1} (~10% VL)
		Depth jump	BW (30 cm)	
		SL CMJ	10% BW	
	2	Deadlift trap bar	70-80% RM	0.71 – 0.58 m·s^{-1} (~10% VL)
		Clean pull jump	65% RM	
		Abalakov jump	BW	
Low velocity deficit (between -10% and -40% of optimal thresholds)	1	Depth jump	BW (30 cm)	
		SL SJ	BW	
		Band assisted CMJ	<BW	
	2	Clean pull jump	65% RM	
		SJ	BW	
		Abalakov jump	BW	
High velocity déficit (>40% of optimal thresholds)	1	Band assisted CMJ	<BW	
		Box jump	BW (30 cm)	
		SL CMJ	BW	
	2	Abalakov jump	BW	
		CMJ	BW	
		Clean pull jump	50% RM	

Abbreviations: RM, Repetition Maximum; BW, Body Weight; m/s, meters/seconds; CMJ, Countermovement Jump; SL, Single Leg; SJ, Squat Jump; VL, Velocity Loss.

Additional information:

1. For optimal control of velocity area, intensity and intra-sets volume of training, the execution speed of the strength exercises was monitored with a linear velocity transducer (Vitruve^{TM}, Madrid, Spain) (Pérez-Castilla et al., 2019), since it has shown to be the most effective control method (Zhang et al., 2022).
2. Regarding the intra-set volume of the plyometric exercises, a low volume was sought (<60 jumps per session), to maintain the highest possible intensity at all times and cause minimal fatigue (Asadi et al., 2016).

Supplementary material 1b. Horizontal individualised training programs according to the CODD180º thresholds. Based on Barrera-Domínguez et al. (Barrera-Domínguez et al., 2024).

Individualised horizontal training (% CODD180º)	Session	Exercise	Training Volume	Training Load
Multidirectional Speed Dominant (CODD180º <43%)	1	Moderate Sled Training	3x 4x 10 metres	30% BM (~15% VL)
		Repeated Broad Bound	3x 2x 6 bounds	20 – 40% BM
		HK Lateral Bound	3x 6 bounds	BM
	2	Heavy Sled Training	3x 5x 5 metres	60% BM (~40% VL)
		Repeated Lateral Bound	3x 2x 6 bounds	20 – 40% BM
		HK Broad Bound	3x 6 bounds	BM
Balanced (CODD180º between 43% and 49%)	1	Technical: 5m Acc to Dec	3x 4 reps EL	BM
		FW Forward Lunge	3x 2+6 reps EL	FW
		AEC Lateral Lunge	3x 6 reps EL	Bands AEC
	2	Heavy Sled Training	3x 5x 5 metres	60% BM (~40% VL)
		Repeated Lateral Bound	3x 2x 6 bounds	20 – 40% BM
		HK Broad Bound	3x 6 bounds	BM
Linear Speed Dominant (CODD180º >49%)	1	Technical: 5m Acc to Dec	3x 4 reps EL	BM
		FW Forward Lunge	3x 2+6 reps EL	FW
		AEC Lateral Lunge	3x 6 reps EL	Bands AEC
	2	Technical: COD180º to Dec	3x 2 reps EL	BM
		FK Lateral Lunge	3x 2+6 reps EL	FW
		AEC Forward Lunge	3x 6 reps EL	Bands AEC

Abbreviations: CODD, Change of Direction Deficit; HK, Half-Kneeling; Acc, Acceleration; Dec, Deceleration; FW, Flywheel; AEC, Accelerated Eccentric Loading; COD, Change of Direction; EL, Each limb; BM, Body Mass; VL, Velocity Loss.

Additional information:

1. Resistance sprint training was undertaken with the Exer-Genie system (Ghigiarelli et al., 2023) at moderate (30-40% body mass) and high (60-70% body mass) intensities with short distances (5-10 metres) to emphasise the acceleration phase (Zabaloy et al., 2023).
2. In exercises with flywheel, two preparatory reps were performed in each set prior to the six targeted reps to ensure effectiveness; and players were instructed to slow down the movement in the last third of the eccentric phase and exit the "hole" as quickly as possible to ensure a true eccentric overload (Martínez-Hernández, 2023).
3. Regarding the volume of the accelerated eccentric loading (Handford et al., 2022) and plyometric exercises (Asadi et al., 2016), it was low (<60 contacts per session), to maintain the highest possible intensity at all times and cause minimal fatigue.
4. To work and improve COD technique, exercises involving the action itself were performed (Dos'Santos et al., 2019) with instructions such as (i) "slam on the brakes and drop the hips"; (ii) "cushion and push/punch the ground away"; and (iii) "face towards the direction of travel" (Dos'santos et al., 2021).

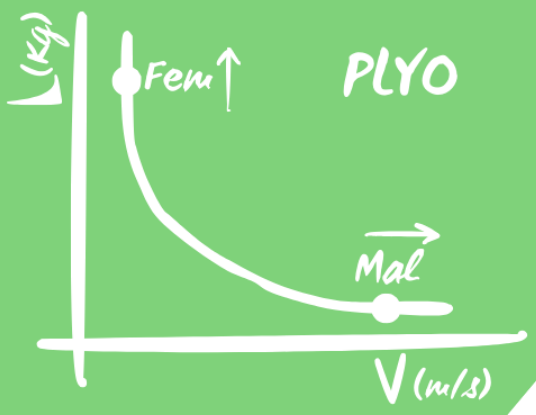
CHAPTER 1

Decisive factors for a greater performance in changes of direction

↑↑ RFD ECC

↓ Ratio ISO/CON

↓ Ratio ECC/CON

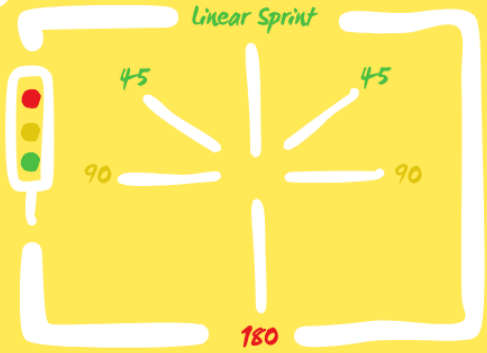


CHAPTER 2

New tools and standardization to assess change of direction

COD angle profile

Modified 505 test



CODD Thresholds

New tool

ASSTRAPP

SPORT METRICS

CHAPTER 3

New approach to individualized change of direction training

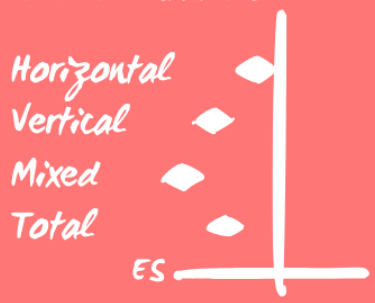
Mixed

F-V Profile

& CODD-based

individualised training

Force orientation



Linear Speed Dominant — Balanced — Multidirectional Speed Dominant

COD Technique — Braking — Plyometry — Conccentric Force

Eccentric Force — Deccelerations — Resistant Sprint

GENERAL RESULTS

Table 11 showed a relationship of the doctoral thesis' original hypothesis with the main results found in each study included. This information is detailed in the corresponding section of each study. Additionally, on the previous page, an infographic was included to graphically summarise the findings found in each chapter of this doctoral thesis.

Table 11. Relationship between the doctoral thesis hypothesis and the main results of each study.

Study	Hypothesis	Results/Conclusions
Chapter 1. Decisive factors for a greater performance in changes of direction.		
1	1A 1B 1C 1E	Fat mass percentage showed a significantly large effect on 45° COD performance in male basketball players. The functional movement variables assessed showed no relationship with COD performance at different cutting angles in male athletes. The reactive strength index was the force-related variable most strongly associated with COD performance, regardless of cutting angle. Vertical force-velocity profile showed a strong relationship with force-oriented COD actions. Age was found to influence body composition, functional movement and COD performance in basketball players.
2	1D	Most inter-limb asymmetries assessed in different tests had no impact on athletic performance. However, asymmetry in the anterior reach of the YBT that showed a significant moderate correlation with the reactive strength index.
3	1B 1C 1F 1G	Dynamic balance demonstrated a strong significant relationship with COD performance, but only in the female gender. Athletes with the highest performance in all jumping tasks were the fastest in all speed tests. Faster male basketball players in linear speed were less efficient in COD actions, as they exhibited large CODD. Jumping tests with a predominantly horizontal direction and a short SSC primarily explained speed performance in male players. Vertical jumps with a long SSC explained to a greater extent the performance in speed actions of female players.
4	1C	Force demands in COD actions were directly influenced by cutting angle. Concentric strength showed the strongest relationship with 45° COD, whereas isometric and eccentric strength were critical for 90° cuts. All muscle actions demonstrated a significant relationship with 180° COD performance. The rate of eccentric force development was the only variable associated with performance across all cutting angles. Despite the importance of eccentric strength in COD actions, a smaller difference between the athlete's eccentric and concentric strength was related to a higher COD performance.
5	1B 1C 1G 1H	The assessed functional movement variables showed no relationship with COD performance at different cutting angles in female athletes. All jumping-related variables had a moderate to very strong significant effect on COD performance in female basketball players. Performance variables influencing COD, measured through execution time and CODD, differed.

Table 11. (continued)

Study	Hypothesis	Results/Conclusions
Chapter 2. New tools and standardization to assess change of direction.		
6	2A 2B	CODD is a valid variable for evaluating the efficiency of athletes in COD actions. CODD enables the classification of athletes based on their individual multidirectional speed needs. The classification of the athlete using CODD depends on the specific cutting angle assessed.
7	2C	Asstrapp is a valid and reliable tool for measuring execution time in COD tests.
Chapter 3. New approach to individualised change of direction training.		
8	3A 3B	Although there are a wide variety of training approaches —such as plyometric, strength, speed or combined training— for improving COD performance, the meta-analysis revealed that a combination of plyometric training and strength exercises, incorporating both vertical and horizontal force orientations within the training program, was the most effective for improving COD performance in basketball players. This training methodology with a duration of six weeks, and three training sessions per week seems to be the minimum recommended stimulus.
9	3C 3F	An individualised training program based on the vertical force-velocity profile was effective in enhancing physical performance in basketball players. Significant improvements in jumping performance were observed earlier (after four weeks of training) compared to multidirectional speed actions.
10	3D 3F	CODD-based strength training tailored to the individual strength needs of each athlete improved efficiency in linear and multidirectional speed actions in all basketball players, regardless of initial CODD threshold or COD angles tested. The greatest improvements in performance were observed in force-oriented COD actions (COD angle >90°). A minimum time period of 8 weeks was required to achieve significant changes in COD performance.
11	3C 3D 3E 3F 3G	Each individualised training program, both force-velocity profile-based and CODD-based, were effective in improving the target variable on which the training was based. Both individualised training approaches resulted in performance enhancements across all measured outcomes after 8 weeks. The improvements were more pronounced and specific to the trained force orientation; greater gains were observed in vertical variables among players who underwent training based on the vertical force-velocity profile, while horizontal variables showed greater improvements in those who followed CODD-based training. Significant changes in vertical jump performance occurred earlier (in week 4) than those observed in linear and multidirectional speed. Basketball-specific training without individualisation was an insufficient stimulus for improving physical performance, as more than 60% of athletes in this group showed no adaptations after training.

GENERAL DISCUSSION

This doctoral thesis aimed to advance scientific knowledge in the field of performance improvement for linear and multidirectional movements involving COD in basketball players. To achieve this, three major chapters with specific objectives were proposed, each addressing key aspects COD performance improvement: (1) analysing the determinants of COD performance to identify the critical factors influencing this specific skill; (2) implementing a standardised assessment framework to enable training programming and validating a novel AI-based tool that will be practical, accessible and useful for sports professionals; and (3) applying precise and effective training programs, tailored to the individual needs of each player.

DISCUSSION CHAPTER 1

Previous research on the main determinants of COD performance (Hewit et al., 2013; Pereira et al., 2018) has identified COD as a complex multidirectional skill influenced by technique, anthropometric characteristics, functional mobility, and different physical abilities such as linear speed, as well as lower limb strength and power ***(Figure 2B)***. The present doctoral thesis aimed to analyse the effect of multiple variables on COD performance based on cutting angle and gender in basketball players.

In this regard, very interesting findings emerged, which were detailed below: (1) Anthropometric characteristics showed little relationship with COD performance in basketball players regardless of cutting angle or gender. The only variable with a significantly large effect on 45° COD performance in male basketball players was fat mass percentage (Barrera-Domínguez et al., 2020). (2) Functional movement variables (i.e., WB-DF, SEBT and YBT) showed no relationship with COD performance at different cutting angles in male athletes (Barrera-Domínguez et al., 2020). However, for female athletes, dynamic balance was found to be a key determinant across all cutting angles, and a significantly large relationship was identified between ankle mobility and

45° COD performance (Barrera-Domínguez, Almagro, et al., 2024). (3) Linear speed was associated with COD performance across all cutting angles in the female gender ***(Study 5)***, and was particularly relevant at 180º cutting angles in the male gender (Barrera-Domínguez et al., 2020). (4) Strength variables —regardless of the muscle action type, force manifestation or force orientation— showed the strongest relationship with COD performance in both genders. Among muscle actions, eccentric strength showed the greatest relationship with COD performance at all cutting angles, specifically the rate of eccentric force development (Barrera-Domínguez et al., 2024). However, faster basketball players changing direction showed a lower eccentric/concentric force ratio. That is, having high levels of concentric strength in relation to the athlete's own eccentric strength is also decisive for optimal performance in these actions. Furthermore, while strength variables were related to COD performance in both genders, key differences emerged in muscle contraction speed and force orientation. Strength variables with a long SSC and a vertical force orientation were the most important predictors of COD performance in female athletes. Conversely, in male athletes, strength with a short SSC and a horizontal force orientation was the primary determinant of COD performance (Barrera-Domínguez, Almagro, et al., 2024).

However, the methodology used to assess COD performance should be carefully considered, as all these relationships disappeared when CODD was used as the reference method for assessing COD actions ***(Study 5)***. Thus, (5) CODD could be considered a measure of athletes' efficiency in these actions, but it is recommended to evaluate performance through execution time in simple COD tests with a single cut at different angles ***(Study 5)***. Finally, (6) while age category and gender showed significant differences in the performance of different physical capacities (Barrera-Domínguez, Almagro, et al., 2024; Barrera-Domínguez et al., 2020), inter-limb asymmetries did not appear to affect performance in basketball and handball players (Barrera-Domínguez et al., 2021). This finding supports the notion that asymmetries are largely independent of athletic performance (Afonso, Peña, et al., 2022), whereas gender (Freitas, Alcaraz, et al., 2021; Mancha-Triguero et al., 2021) and age (Calleja-González et al., 2018) directly influence the athletes' physical performance.

Anthropometric characteristics

Basketball is an intermittent team sport in which players exhibit specific anthropometric and physical characteristics to suit the needs of the sport itself. The impact of these specific anthropometric traits on performance is of particular interest to strength and conditioning coaches aiming to maximise player performance. In this sense, anthropometric variables such as body height or leg length may influence COD performance, as shorter athletes would require less time to lower their centre of mass during the deceleration phase (Brughelli et al., 2008; Sheppard & Young, 2006). However, the studies developed in this doctoral thesis found no relationship between the body height and COD performance, regardless of cutting angle or gender. This discrepancy may be attributed of different COD tests protocols or sample characteristics across studies.

In general, COD performance relies on rapid accelerations and decelerations of BM; therefore, a lower body fat percentage combined with high relative strength would benefit COD performance (Peterson et al., 2006). This may explain the observed influence of fat mass on 45° COD performance, where players with a higher fat percentage required more time to complete the COD (Barrera-Domínguez et al., 2020). Consistent with the present findings, previous studies conducted in elite basketball players (Chaouachi et al., 2009; Spiteri et al., 2015) have reported similar association using the T-Test. Furthermore, several studies have evidenced a weak (Meylan et al., 2009) to moderate-high (Chaouachi et al., 2009; Peterson et al., 2006) relationship between BM and the T-Test performance in elite basketball players. However, our results found no relationship between BM and BMI (body mass index) with COD performance in basketball players. This underscores the importance of body composition over more general characteristics such as BM, BMI or height (Barrera-Domínguez et al., 2020). From a logical perspective, it seems reasonable that an athlete with a lower fat mass percentage would perform better in COD, particularly at wider cutting angles that require higher speeds. Lower BM levels combined with an increase in maximal strength would enhance the athlete's relative strength, thereby improving their ability to accelerate and decelerate during COD actions (Bourgeois et al., 2017).

Functional movement

Regarding functional movements and their relationship with COD performance in basketball players, a limitation in ankle dorsiflexion suggests a potential movement impairment that may alter mechanics during multidirectional tasks and COD (Gonzalo-Skok et al., 2015). Indeed, a study by Gonzalo-Skok et al. (2015) involving 15 elite male basketball players found that ankle mobility asymmetry, as assessed by the WB-DF test, was associated with decreased performance in sport tasks, including COD. Conversely, the finding of this doctoral thesis indicates that neither restricted ankle mobility, nor inter-limb asymmetry in the WB-DF test seem to affect COD performance in male players (Barrera-Domínguez et al., 2020, 2021). Among the different studies included in this chapter, a relationship between ankle mobility and COD performance was only observed at 45º cutting angle in female players (Barrera-Domínguez, Almagro, et al., 2024). Therefore, these findings suggest that closer monitoring of ankle mobility in female athletes may be beneficial.

On the other hand, while previous studies have reported a significant relationship between dynamic balance and COD performance in male basketball athletes (Gonzalo-Skok et al., 2015) and other team sports (Lockie et al., 2016), the findings derived from this doctoral thesis did not identify any relationship between dynamic balance tests — neither SEBT nor YBT— and COD performance in male basketball players (Barrera-Domínguez et al., 2020), except for the YBT in COD actions at 90º. When analysing each reach direction separately, only lateral reach in the SEBT showed a strong correlation with all COD angles analysed (Barrera-Domínguez et al., 2020). This may be explained by the significant involvement of the frontal plane in COD actions (Falch, Rædergård, & van den Tillaar, 2020b). Furthermore, when analysing the female athletes, our studies

found large significant relationships between dynamic balance and COD actions, with these relationships being stronger as the cutting angle became sharper (Barrera-Domínguez, Almagro, et al., 2024). These gender differences could be attributed to significant structural and biomechanical differences in the lower limbs between male and female athletes, such as wider hips and greater joint instability in female athletes (Sizer & James, 2014). Based on these findings, it can be confirmed that unilateral actions like COD demand high levels of dynamic stability, and highlight the need for adequate mobility patterns and functional stability in female basketball players to optimize multidirectional performance. Finally, although inter-limb asymmetries in functional mobility tests have been linked to both injury risk (Plisky et al., 2006) and COD performance (Gonzalo-Skok et al., 2015) in basketball players, none of our studies identified a relationship between inter-limb asymmetry and COD performance (Barrera-Domínguez et al., 2020, 2021).

Linear speed

Numerous previous studies have identified strong relationships between linear speed and COD, confirming that linear speed is a key determinant factor for COD performance in basketball players (Barrera-Domínguez et al., 2020; Chaouachi et al., 2009; Michael et al., 2021). This is primarily due to how COD actions are often assessed in sport. Many sport professionals assess COD actions through execution time in manoeuvrability tests (Nimphius et al., 2018), which involve multiple COD at different cutting angles, simulating sport-specific movements. However, due to these manoeuvrability tests involving a broad spectrum of physical qualities (e.g., linear speed, anaerobic capacity, and movement specificity within the test), the result may be masked by another skill and fail to reflect the athlete's specific COD capacity. Specifically, 74.8% of the variance in manoeuvrability tests has been attributed to linear speed (Delextrat et al., 2017). This may be because the majority of these commonly used tests include over 70% of total distance as linear sprinting, failing to isolate the COD action itself (Nimphius et al., 2016). For this reason, while moderate to high correlations indicate that linear speed contributes to COD performance in basketball players of both genders (Michael et al., 2021), current scientific literature recommends considering linear speed as a distinct physical ability, independent of COD actions (Barrera-Domínguez, Jones, et al., 2024; Nimphius et al., 2016; Young et al., 2015).

The findings of the studies developed in this doctoral thesis align with the most recent literature (Barrera-Domínguez, Almagro, et al., 2024; Barrera-Domínguez et al., 2020). Although strong correlations were observed between linear speed tests and COD performance at different cutting angles in both male players ($r \geq 0.537$, $p < 0.001$) (Barrera-Domínguez et al., 2020) and female players ($r \geq 0.686$, $p < 0.001$) ***(Study 5)***, this relationship between both abilities disappeared when isolating the time exclusively dedicated to the cutting action in COD tests using the CODD as the assessment method ***(Study 5)***. Additionally, the strength variables explaining linear and multidirectional speed performance differed in female basketball players (Barrera-Domínguez, Almagro, et al., 2024). In this regard, a multiple regression analysis revealed that a short SSC (i.e.,

assessed through a drop jump) was the primarily determinant of linear speed performance, accounting for 68% of the variance. Conversely, long SSC (i.e., assessed through a counter-movement jump) was the strength variable explaining up to 63% of the performance in multidirectional speed actions with COD in female athletes (Barrera-Domínguez, Almagro, et al., 2024). These findings, together with previous literature (Nimphius et al., 2016; Young et al., 2015), would confirm the need to consider the linear speed and COD skill as two completely independent skills.

Finally, it is worth highlighting the findings of Baena-Raya, Rodríguez-Pérez, et al. (2021), how demonstrated in a recent case study that COD performance is less dependent on linear speed actions and more influenced by an athletes' ability to apply horizontal force during the acceleration phase of linear sprinting —a phase of linear acceleration that also occurs in multidirectional actions—. That is, the fastest athletes in multidirectional actions were not necessarily the fastest in linear actions; rather, those who achieved a higher horizontal force ratio during the linear acceleration phase demonstrated superior COD performance in basketball players of both genders (Baena-Raya, Jiménez-Reyes, et al., 2021; Baena-Raya, Rodríguez-Pérez, et al., 2021). The first study included in this chapter corroborates these previous findings, as it observed a significant relationship ($r \geq –0.514$, $p < 0.05$) between horizontal force application during sprinting and COD performance (Barrera-Domínguez et al., 2020). Therefore, based on the results detailed in this section, it could be stated that, while COD actions involve linear accelerations both before and after the cutting action itself, linear speed does not demonstrate a direct relationship with COD ability per se.

Muscle capacity of the lower limbs

Among all the determinant factors related to COD performance throughout the doctoral thesis, lower limb muscular capacity is undoubtedly the one that shows the greatest effect on COD performance. To the best of the author's knowledge, there are no previous scientific studies analysing the relationship between different muscle actions (i.e., concentric, eccentric and isometric) and COD performance based on the cutting angle. Given that force demands during COD actions are directly dependent on the cutting angle (Dos'Santos, Comfort, et al., 2018), this analysis was considered essential to compare between different cutting angles. Specifically, one of the studies included in this chapter aimed to analyse this aspect, reinforcing the assertion of the existing scientific literature that strength is an indispensable component for COD success (Barrera-Domínguez et al., 2020; Young et al., 2002). Furthermore, it shed light on the relationship between different muscle actions and specific force-independent capacities, according to each cutting angle (Barrera-Domínguez et al., 2024). In this regard, for wide cutting angles of 45°, concentric muscle action showed the greatest influence on COD performance (Barrera-Domínguez et al., 2024). This may be explained by the high velocities achieved at these cutting angles, where the ability to produce force rapidly in a concentric manner becomes crucial (Bourgeois et al., 2017). Achieving optimal 45° COD performance primarily requires focusing on maintaining velocity (Hader et al., 2015), with very short ground contact times (i.e., less than 150 milliseconds) and minimal

braking forces (McBurnie & Dos'Santos, 2022). Thus, it makes sense that concentric strength is highly relevant for COD at 45°. However, when performing COD at sharper cutting angles, the strength requirements undergo significant changes, and other muscular actions become increasingly influential in COD performance. In this regard, Barrera-Domínguez et al. (2024) demonstrated a strong relationship between isometric strength and COD performance at moderate angles, up to 90°. Previous research has indicated that the mechanical characteristics of cuts from 90° onwards lead to longer ground contact times during the COD step, ranging from 250 to 500 milliseconds (McBurnie & Dos'Santos, 2022). This may justify the need for the lower limbs to sustain reaction forces isometrically for a longer duration in the final step of the cut, while the rest of the body reorganises and redirects towards a new movement trajectory (Dos'Santos, & Jones, 2021a).

These ground contact times and the demands for braking and reacceleration forces continue to increase as the cutting angle closes to 180° (Bourgeois et al., 2017). The results found in this doctoral thesis are in line with previous literature and show that the sharpest angles of 180° are the most demanding in strength, and show a strong relationship with all muscle actions (Barrera-Domínguez et al., 2024). Furthermore, it is worth noting that, among all muscle actions and force-independent qualities, the rate of eccentric force development peak showed the strongest relationship with COD performance, and was the only variable that exerted a significant impact across all cutting angles. This could be explained by the fact that COD are executed at maximal intensities and velocities with high external load demands, as demonstrated by recent studies that have recorded values of knee joint angular velocities ranging between 469 and 493°/s during the deceleration phase prior to the cut (Nedergaard et al., 2014). These high knee joint angular velocities underscore the paramount importance of rapid eccentric force production capacity and pre-activation of the knee extensors to facilitate large rate of eccentric force development peaks in the first 40 milliseconds of the stance phase (Barrera-Domínguez et al., 2024).

Although eccentric muscle action plays a crucial role in COD performance (Jones et al., 2017, 2022; Smajla et al., 2022), primarily due to substantial peaks in eccentric force during braking actions, which can reach 168% greater force compared to the propulsive phase (Harper et al., 2022); it is recommended to consider the interaction between different muscle actions. COD involves ballistic high-intensity actions that engage all muscle actions at high velocities. Therefore, the interaction between different muscle actions was analysed, yielding very interesting findings. Surprisingly, the fastest players in COD exhibited higher concentric strength relative to their own eccentric and isometric strength, which was reflected in lower eccentric/concentric and isometric/concentric force ratios (Barrera-Domínguez et al., 2024). This trend was evident at both sharper (i.e., 180°) and shear (i.e., 45°) cuts, underscoring the importance of possessing high levels of concentric strength relative to other muscle actions to achieve superior performance across multiple COD angles. While the ability to quickly apply eccentric strength during maximal deceleration in COD is critical (Harper et al., 2022), players who exhibit rapid eccentric force production with minimal disparities between

eccentric and concentric strength stand out in all multidirectional sport actions, regardless of cutting angle. These findings explain how cutting angles moderate the relationship between different muscle actions and COD performance, highlighting the multifaceted nature of COD. These findings suggest an analysis of force ratios for a more comprehensive assessment.

When analysing different independent force qualities, it is essential to understand that the relationship between these qualities and COD performance is not generic. In other words, generalisations should be avoided, as this relationship will depend, on the one hand, on the cutting angle; and, on the other hand, on the characteristics and gender of the sample. Specifically, Barrera-Domínguez, Almagro, et al. (2024) found that, in a sample of female basketball players, all independent force qualities and their different orientations showed significant differences between performance levels in both linear speed tests and COD, aligning with previous research (Spiteri et al., 2013, 2015). However, a more detailed analysis revealed that unilateral countermovement jumping, which involves vertical forces through a long SSC (>250 ms) (Turner & Jeffreys, 2010), was the most influential variable on multidirectional speed performance in female athletes (Barrera-Domínguez, Almagro, et al., 2024). While previous studies emphasised the importance of developing all force components for female basketball players (Spiteri et al., 2014, 2015), the current findings suggest that, to improve COD performance in women, maximum strength exercises with vertical force orientations should be the main focus. However, this might contradict previous research (Falch, Rædergård, & van den Tillaar, 2020a) suggesting that exercises involving a short SSC are more specific to COD. The discrepancy may be due to the fact that a longer SSC is more relevant to COD actions in athletes with lower relative strength, as observed in the female sample compared to the male sample in this thesis study (Barrera-Domínguez, Almagro, et al., 2024). In this context, it was suggested that there might be a strength threshold above which athletes benefit more from short SSC exercises (Falch et al., 2021), but below this threshold, the focus should be on maximum strength and long SSC exercises. Therefore, exercises involving long SSC with a vertical force orientation have previously proven to be more effective in enhancing both linear and multidirectional speed performance in less experienced and weaker athletes (Barrera-Domínguez, Almagro, et al., 2024; Zweifel, 2017).

Conversely, Barrera-Domínguez, Almagro, et al. (2024) also analysed this relationship in male basketball players, finding significant differences between performance in all speed tests, both linear and multidirectional, and horizontal force variables with a short SSC (<250 ms) (Turner & Jeffreys, 2010). Specifically, the unilateral triple hop test had the greatest impact on speed performance, regardless of the cutting angle. This could be because the linear speed and COD tests analysed involved high force demands with a horizontal orientation (Baena-Raya et al., 2020; McBurnie & Dos'Santos, 2022; Robles-Ruiz et al., 2021). In this regard, previous interventions with male basketball players have shown that horizontal plyometric training leads to greater improvements in COD performance compared to vertical training (Aztarain-Cardiel et al., 2022; Gonzalo-Skok et al., 2019). Furthermore, male players exhibit a rate of force

development 1.5 times higher than females (Laffaye et al., 2014), suggesting that males benefit more from short SSC stimuli (Barrera-Domínguez, Almagro, et al., 2024). Finally, it is worth highlighting the importance of optimising the force-velocity profile in male basketball players (Barrera-Domínguez et al., 2020). A balanced force-velocity profile maximises individual neuromuscular capacities and the power applied relative to the BM of each athlete during the vertical jump (Samozino et al., 2012). One of the studies included in this chapter (Barrera-Domínguez et al., 2020), found a strong significant relationship ($r \geq 0.589$, $p < 0.001$) between imbalance in the force-velocity profile with force-oriented COD actions (i.e., >90° of cut angle). These results indicate that male basketball players with a balanced profile achieved better performance in multidirectional actions with sharp cuts. Additionally, the strongest relationship ($r \geq 0.711$, $p < 0.001$) was found between the F_0 variable extracted from the profile (i.e., the theoretical maximum force that the athlete is able to manifest) and the force-oriented COD actions (Barrera-Domínguez et al., 2020). Once again, these findings highlight the key role of lower-limb strength in COD actions, particularly in angles greater than 90°.

DISCUSSION CHAPTER 2

Nowadays, the assessment of COD actions presents several challenges in sport practice that should be addressed to advance scientific and practical knowledge. First, there are over 50 different tests for measuring COD performance in basketball players, each with different characteristics (Sugiyama et al., 2021). Additionally, these tests involve a wide range of physical capacities (e.g., linear speed, anaerobic metabolic capacity or test-specific movement skills) depending on the types of movements involved, the distance covered, the angles and the number of cuts (Nimphius et al., 2018). Consequently, the results of these COD tests may be influenced by other capacities and fail to effectively isolate the player's COD ability. Moreover, the tools currently used to assess these speed actions present numerous limitations, such as cost, lack of portability and other factors, which make them inaccessible and impractical to use in the day-to-day practice of sport professionals. For these reasons, the present doctoral thesis aimed to (1) standardise the evaluation of multidirectional speed with COD tests at different angles to create a COD angle profile specific to each basketball player; (2) create a classification system based on CODD to better understand the individual multidirectional needs of each player; and (3) develop and validate a novel AI-based tool to assess speed actions in an accessible and practical way for all professionals.

COD assessment: standardisation and classification of athletes

To develop a proper assessment of COD, it is crucial to firstly clarify what aspects of athletes' performance in this skill need to be analysed and to understand that COD, manoeuvrability and agility tests, are completely different from each other and do not measure the same skill (Jones & Dos'Santos, 2023). When selecting a test to assess COD speed, it is important to establish a clear protocol and select the appropriate and specific movement pattern for basketball players. However, there is currently no 'gold standard'

protocol for assessing COD speed in basketball players (Sugiyama et al., 2021). Additionally, the unpredictable nature of basketball and the wide variety of on-court movements performed across a broad spectrum of angles and approach distances to the cut (Gonzalo-Skok & Bishop, 2023), make the standardisation of assessing COD ability even more challenging. Nevertheless, there is a general consensus that, to effectively assess COD speed, the test protocol should be of short duration (i.e., less than 5 seconds or a distance of 10 metres), and include a single cut (Beato et al., 2024; Nimphius et al., 2018; Ryan et al., 2023; Westheim et al., 2023). Furthermore, due to the significant dependence of cutting angle on COD performance (Dos'Santos, Comfort, et al., 2018), the multidirectional requirements associated with basketball, and the requirement for athletes to be equally proficient cutting to both sides across a wide spectrum of angles; it is highly recommended to assess athletes for this ability across multiple COD tests with a single COD at various angles ***(Figure 1, Study 6)***. This approach allows for the creation of a COD angle profile individual for each basketball player (Gonzalo-Skok & Bishop, 2023).

On the other hand, it is recommended that strength and conditioning coaches select a COD assessment test that allows them to (1) compare the evaluated athlete with others of similar level and characteristics (i.e., cross-sectional inter-athlete comparison); (2) monitor an athlete's progress over time (i.e., longitudinal intra-athlete comparison); and (3) classify the athlete and prescribe an individualised training program based on their individual speed needs to enhance performance in the assessed skill (Weakley et al., 2023). In this regard, assessing COD performance using exclusively execution time, as traditionally done, may obscure other physical qualities required for the test and falls short of providing information to individualise training programs for athletes (Nimphius et al., 2016). To illustrate with a practical example: if an athlete improves their linear speed (through the execution time in linear test), without a real improvement in COD performance, the time spent in the COD test might also decrease (which would erroneously indicate a better COD performance). Therefore, execution time in COD tests should not be considered a sensitive measure for detecting changes in COD performance. Beyond simply measuring execution times, it is recommended to provide additional information about what happens during the COD test (i.e., analysis of kinetic variables related to acceleration-deceleration, assessment of the COD strategy employed, and movement quality analysis). Additionally, the use of CODD would be highly recommended to determine the player's COD efficiency and identify weaknesses in their performance to address them effectively (Barrera-Domínguez, Jones, et al., 2024; Nimphius et al., 2018; Ryan et al., 2023; Westheim et al., 2023). For diagnostic purposes, this approach is crucial, as the COD skill involves distinct sub-phases that include initial acceleration, deceleration, turning and re-acceleration (depending on the angle), and each of these sub-phases presents unique physiological and biomechanical demands (Dos'Santos, Comfort, et al., 2018; Dos'Santos, McBurnie, et al., 2019; Harper et al., 2022; Westheim et al., 2023).

Specifically, the CODD expresses the amount of time an athlete spends on the cutting action itself in a COD test and indicates the athlete's COD efficiency (Freitas,

Pereira, et al., 2021; Nimphius et al., 2016). A low CODD suggests high efficiency in COD relative to linear speed, and vice versa, a higher CODD indicates superior acceleration ability and linear speed, but reflects inefficient COD technique or deficiencies in specific muscular force qualities, resulting in poorer COD performance (Freitas et al., 2019; Loturco et al., 2022; Pereira et al., 2018). This CODD metric allows coaches and researchers to determine the athlete's COD effectiveness and identify weaknesses to target in training. Previous studies showed that faster and more powerful linear speed athletes tend to exhibit higher CODD values (Freitas, Alcaraz, et al., 2021; Loturco et al., 2022; Pereira et al., 2018). This may be related to the challenges of managing higher speeds prior to executing a COD, such as the higher sprint impulse and the subsequent braking forces (Freitas, Alcaraz, et al., 2021; Freitas et al., 2019). Therefore, it was recommended that athletes with high CODD should focus on training COD technique and the ability to handle higher braking forces. Conversely, athletes with low CODD should prioritise acceleration and high speed, while continuing to maintain the COD technique and the muscular force qualities required (Freitas, Alcaraz, et al., 2021; Harper et al., 2022; McBurnie, Harper, et al., 2021). This information can be very useful for optimising training programs. However, to the author's knowledge, there are no existing studies that provide cut-off points to classify CODD as "high" or "low," which would enable better categorisation and individualised training for basketball players based on this variable. Furthermore, previous research (Freitas, Alcaraz, et al., 2021) has indicated that male athletes exhibited higher CODD values than female athletes, highlighting the need to identify different CODD thresholds according to gender.

In this regard, one of the most innovative and practical studies within this doctoral thesis (Barrera-Domínguez, Jones, et al., 2024) aimed to establish this classification and determine the cut-off points for each cutting angle based on gender. The findings revealed that CODD thresholds are angle-specific, with players exhibiting a CODD within the ranges of 3–8%, 17–25% and 43–51% for cutting angles of 45°, 90° and 180°, respectively, demonstrating a balanced CODD with no significant differences between genders ***(Table 3, Study 6)***. This balance represents the optimal relationship between linear speed and COD. Conversely, players falling below this range in any of the specified angles would be classified as multidirectional speed dominant players (i.e., they have a high COD ability, but have a low linear speed performance). On the other hand, athletes exceeding this CODD threshold for each cutting angle would be classified as linear speed dominant players (i.e., they have high linear speed performance, but are inefficient in COD actions). These findings have the potential to enable strength and conditioning coaches to effectively identify their athletes' strengths and weaknesses in COD actions based on specific cutting angles. Subsequently, coaches can design individualised training programs tailored to each athlete's CODD angle profile. Another noteworthy finding in this research (Barrera-Domínguez, Jones, et al., 2024) was the strong relationship between CODD scores and COD execution time for each cutting angle. This corroborates the conclusions of previous studies (Freitas, Pereira, et al., 2021; Gonzalo-Skok & Bishop, 2023; Nimphius et al., 2016), and supports the validity of CODD as a measure of athletes' efficiency in COD actions. This variable accurately reflects the physical quality

to be measured —COD in isolation— while being sensitive to change and mitigating the influence of other physical attributes that might otherwise affect test results. Therefore, CODD has been shown to provide valuable insights into the relationship between each athlete's linear speed and COD, allowing for the identification of individual strengths and weaknesses of each athlete in these skills. Moreover, the CODD thresholds identified enable the classification of basketball players, the sharing and comparison of standardised data across different samples, improved performance monitoring and management of each player and, most importantly, the design of training programs targeting each athlete's specific weaknesses and needs.

Validation of a novel AI-based tool

A wide range of technological tools, such as electronic time gates (ETG), radar, laser devices, photo-finish camera, and resistance-monitored instruments, have been used in the scientific literature to assess COD performance. Among these, ETG are the time-based reference tool considered the gold standard in the scientific literature (Altmann et al., 2018). However, this technology presents several limitations such as its high cost, which may hinder accessibility for coaches and institutions with budget constraints; and its lack of portability, making it difficult to use in the daily practice of basketball coaches. As an alternative to these expensive traditional tools, a variety of mobile applications have emerged. Taking advantage of advanced technology and high-speed cameras integrated into modern smartphones, these applications offer a means to assess COD performance in a more cost-effective way. However, these applications often do not provide real-time feedback, requiring coaches to manually assess their athletes afterwards, leading to time-consuming assessments that do not facilitate live decision making in sports training. Nevertheless, advancements in technology, AI and computer vision offer the potential to overcome this limitation by enabling smartphones to autonomously identify measurement targets, analyse them and provide test results in real time. Due to the novelty of this technology, validation and reliability studies involving AI in speed testing remain limited. Therefore, this doctoral thesis aimed to develop and validate an AI-based measurement tool for assessing speed in COD tests (Barrera-Domínguez et al., 2025).

From a reliability perspective, the findings of the study (Barrera-Domínguez et al., 2025) demonstrated that Asstrapp exhibits excellent relative within-session reliability (APP1, ICC ≥0.911; APP2, ICC ≥0.905) when measuring execution time in both the traditional and modified COD 505 tests. Additionally, the ICC was used to compare agreement between ETGs and Asstrapp, revealing an almost perfect inter-device reliability (ICC ≥0.987). These ICC values were higher than those reported for other manually evaluated apps (ICC =0.671–0.840) (Balsalobre-Fernández, Bishop, et al., 2019) and were comparable to the ICC values found in recent studies analysing the reliability of other apps with automated time assessment in speed tests (Krishnan et al., 2023; Marco-Contreras et al., 2024). Additionally, the absolute reliability values assessed through the CV showed that the results of all the measurement tools were very acceptable and stable, with the CV being very similar across devices in the different COD tests. The

CV found were in line with previous evidence analysing the reliability of a manual application assessing the modified 505 test (CV =3.2%) (Balsalobre-Fernández, Bishop, et al., 2019) and traditional 505 (CV =6.3%) (Chen et al., 2021). However, previous studies analysing reliability in an application that assesses time automatically do not provide CV values (Marco-Contreras et al., 2024). Therefore, Asstrapp practitioners and users can trust that the results provided by the app to measure the execution time of COD tests are reliable.

On the other hand, our previous research (Barrera-Domínguez et al., 2025) revealed a very high concurrent validity of Asstrapp compared to ETG, showing an almost perfect inter-device association ($r \geq 0.970$; $r^2 \geq 0.942$) and the slope coefficient was very close to the identity line (slope ≥0.960) for all COD tests evaluated. These findings were in line with those found in previous studies that aimed to analyse the validity of both manual (r =0.964; 95% CI =0.95-1.00) (Balsalobre-Fernández, Bishop, et al., 2019) and automatic (r^2 =0.958, p <0.001) (Marco-Contreras et al., 2024) mobile applications for assessing COD performance. Additionally, almost perfect inter-smartphone validity using Asstrapp was observed, showing an even stronger association ($r \geq 0.980$; $r^2 \geq 0.960$). This agreement in the results obtained inter-device and inter-smartphone was also supported by the Bland-Altman plots ***(Figure 3, Study 7)***. In other words, the measured values between both devices and smartphones were very consistent in the two COD tests evaluated, confirming the validity of Asstrapp.

Finally, although all previous analyses denote a very high validity of Asstrapp to measure execution time in COD tests, it is recommended to be cautious with the measurement instrument used according to the COD test evaluated. Since significant, but small and stable, differences were observed in traditional 505 COD test execution time between ETG and Asstrapp (Barrera-Domínguez et al., 2025). This finding can be explained by several reasons. Firstly, the sampling frequency between devices was different. This could explain the inter-device difference observed in the traditional 505 COD test, as it is a test with a flying start and higher speeds. Furthermore, it should be noted that the ETG system used in the validation is single beam. Although the ETG were adjusted as recommended by previous scientific literature (Haugen et al., 2015), it could be that this system was not appropriate for use in tests with a short distance (≤10 metres) and with a flying start (García-López et al., 2012; Haugen et al., 2015). This timing system can be activated by cutting the single beam through either of the athlete's limbs while running and shows absolute time differences ranging from +0.03 to +0.05 seconds compared to a dual-beam ETG (Haugen et al., 2014). Barrera-Domínguez et al. (2025) showed similar differences between ETG and Asstrapp (+0.049 vs. APP1; +0.044 vs. APP2). Asstrapp's AI was programmed so that only the subject's hip activates the system when crossing the start or finish test line, thus avoiding any measurement errors and providing very similar results between smartphones. This method of activating the Asstrapp timing system is likely to be more similar to the dual-beam ETG system. These reasons above could explain the small differences observed between Asstrapp and single beam ETG in the traditional 505 COD test, so the result provided by the Asstrapp AI might be the one that best fits the reality.

These findings prove that Asstrapp is a valid and reliable tool for measuring the execution time of COD tests. Moreover, Asstrapp is an affordable and accessible sports assessment tool for all coaches, an easy and quick tool to use, it is more portable than traditional laboratory instruments and has the advantage of providing immediate feedback. For all these reasons, this application can be recommended to any sports professional to assess, quantify and train COD.

DISCUSSION CHAPTER 3

Although, as highlighted throughout this doctoral thesis, COD actions are crucial for basketball players' performance, intervention studies analysing the effect of different training programs on these actions in basketball players remain scarce in the scientific literature. Surprisingly, there are no intervention proposals that individualise training based on each player's needs to enhance COD performance. For these reasons, the present doctoral thesis aimed, on the one hand, to describe and determine the magnitude of the effect of different training methodologies -according to the force orientation- on COD performance in basketball players. On the other hand, it aimed to examine the impact of different individualised training programs on physical performance in basketball players, one with a predominantly vertical force orientation based on the force-velocity profile, and another with a predominantly horizontal force orientation based on the CODD, on physical performance in basketball players.

In response to these initial aims, four scientific studies were conducted. Among them, a systematic review with meta-analysis and three intervention studies, which yielded the following interesting findings. Firstly, (1) the literature review identified a wide variety of training approaches, including plyometric, strength, speed or combined training, aimed at improving COD performance. These interventions were assessed using different COD tests, such as the T-test, Illinois test, V-cut and Lane test. Following these findings, (2) the meta-analysis study revealed that combining both vertical and horizontal force orientation within a training program was the most effective strategy for improving COD performance in basketball players. Additionally, the potential moderating effects of different interventions variables on COD performance were examined, showing that (3) plyometric training, followed by combined plyometric and strength training, had the greatest effect. These training methodologies, with a duration of at least six weeks and three training sessions per week, appear to be the minimum recommended duration and frequency. Finally, it was determined that the T-test and Illinois test were the most sensitive for detecting changes in COD performance following the intervention period.

However, after reviewing the current literature, no individualised training programs for basketball players were found. Therefore, this doctoral thesis proposed different individualised training methods for basketball players demonstrating that (4) each individualised training program was effective in improving the specific variable on which the training was based (i.e., vertical force-velocity profile and CODD). Furthermore, (5) these improvements were of greater magnitude than those reported in previous literature, particularly in the specific actions related to the force-orientation training approach. That

is, greater gains were observed in vertical variables among players who underwent training based on the force-velocity profile, whereas players trained based on CODD showed greater improvements in horizontal variables. Although (6) both individualised training approaches led to performance improvements across all outcomes measured after eight weeks, significant improvements in vertical jump performance were observed earlier (after four weeks) compared to linear and multidirectional speed (after eight weeks). Finally, (7) it is noteworthy that non-individualised basketball-specific training was insufficient to enhance physical performance, as more than 60% of athletes in this group were classified as non-responders to the training stimuli. Therefore, it is strongly recommended that conditioning coaches implement individualised training stimuli, tailoring programs to optimise each player's responsiveness to specific training variables.

Force orientation effect

Due to the complexity and high horizontal force demands required in COD actions (Baena-Raya et al., 2020; McBurnie & Dos'Santos, 2022), it was initially hypothesised that training interventions focused on improving horizontal force application would be effective in improving these actions. However, horizontal training interventions did not yield significant improvements in COD performance (Barrera-Domínguez, Martínez-García, et al., 2024). This could be explained by several reasons. Firstly, while horizontal force demands in COD actions are high, gravity is always present in all sporting actions, and vertical force demands may be even higher (Randell et al., 2010). Secondly, none of the studies focusing on horizontal force in basketball players have proposed an individualised training, nor have they even used high loads to resist the movement. Therefore, it could be assumed that the training stimulus applied was insufficient to induce adaptations in athletes' performance. In this regard, Morin et al. (2017) observed that to improve maximal horizontal force production and mechanical efficiency in acceleration actions, heavy sled training was required. Specifically, the optimal load for maximising power during resisted sled sprinting ranged from 69 to 96% of BM, depending on friction conditions (Cross et al., 2017). Additionally, Lahti et al. (2020) determined that an individualised training approach, using resisted or assisted sprints based on each athlete's initial force production needs, was necessary to optimise mechanics and increase horizontal force production in sprint and COD actions (Baena-Raya, Rodríguez-Pérez, et al., 2021). Therefore, it was recommended to train across the entire spectrum of horizontal force application, from maximal force at low velocities using sled to force generation at supramaximal velocities, depending on each athlete's individual mechanical and strength needs (Hicks et al., 2020). In most cases, training exclusively at sprint speed or using unloaded plyometric exercises is insufficient to improve COD performance.

Training with a vertical force orientation has demonstrated a greater effect on COD performance in basketball players. Furthermore, our meta-analysis results (Barrera-Domínguez, Martínez-García, et al., 2024) showed that vertical plyometric training was more effective than strength training when performed independently, probably due to the higher velocity of plyometric exercises and that vertical jumping actions display muscle

activation peaks similar to those observed in COD actions (Falch, Rædergård, & Van den Tillaar, 2020c). Additionally, plyometric training improves inter- and intra-muscular coordination, promoting improvements in neural drive of agonist muscles and facilitating a faster switch between muscle actions, which contributes to a more efficient SSC (Ramirez-Campillo et al., 2021). These adaptations enable athletes to reduce ground contact times, increase muscle force production, improve the rate of force development and movement efficiency, all of which positively influence COD speed. However, it is important to note that all studies included in the meta-analysis recruited young adult basketball players with no previous strength training experience (Barrera-Domínguez, Martínez-García, et al., 2024). In relation to this, although vertical plyometric training has demonstrated its efficacy, its impact appears to diminish in experienced athletes with higher strength levels who aim to develop sport-specific physical qualities (Keller et al., 2020; Zweifel, 2017). Therefore, it was recommended that the individual characteristics and needs of athletes be considered prior to the implementation of any training program to enhance COD performance.

Based on previous literature, it has been suggested that combining different movement directions may be the most optimal training approach for improving performance in complex actions such as COD (Aztarain-Cardiel et al., 2022; Loturco et al., 2018). This may be due to COD actions involve three-dimensional forces that propel the athlete in the desired horizontal or lateral direction, while counteracting gravity. In this line, training that integrates multiple force orientations has been more effective than isolated vertical or horizontal training in improving COD performance in basketball (Aztarain-Cardiel et al., 2022; Brini et al., 2022) and football (Ramírez-Campillo et al., 2015) players. Our meta-analysis findings (Barrera-Domínguez, Martínez-García, et al., 2024) support these notions, as interventions combining vertical and horizontal force orientations showed the greatest improvements in COD performance. Therefore, although recent meta-analyses (Huang et al., 2024) refute the specificity and orientation theory of training, the findings of this thesis suggest that force orientation is critical in determining training adaptations for optimising COD performance.

Finally, some studies included in the review not only combined different force orientations but also integrated multiple training methods. For instance, Usgu et al. (2020) examined the effects of combined strength and plyometric training, and Brini et al. (2022) incorporated plyometric training with repeated multidirectional sprint training. In both cases, this combination of training methods led to a greater improvement in COD performance. These findings align with previous research, in which Hammami, Gaamouri, Shephard, et al. (2019) reported that combined strength and plyometric training had a greater effect on COD performance than isolated plyometric training. This was further supported by a previous meta-analysis on the effectiveness of different training sequences (Marshall et al., 2021), which concluded that combined strength and plyometric training was more effective in improving maximal strength, power and lower-limb speed than traditional strength training in isolation. The advantage of this combined training approach may be because athletes can simultaneously improve multiple key determinants of COD performance (Falch et al., 2019) by engaging in a wider variety of

sport-specific stimuli, better preparing them to meet the demands of COD in real-game situations.

Impact of novel approaches to individualise training

Given the lack of individualised training programs for basketball players, it was deemed necessary to examine the effect of various individualised training interventions based on each athlete's strength and speed needs requirements to optimise performance in the most efficient way possible. Firstly, it was analysed the effect of the training approach of Jiménez-Reyes et al. (2016), which aims to maximise individual neuromuscular capacities and power in vertical jumps (Samozino et al., 2012). However, to date, the impact of this training approach on COD performance in basketball players has not been analysed. Additionally, as no previous individualised training program based on athletes' multidirectional speed existed, this doctoral thesis presents a novel individualised training approach based on the CODD. By using our previously developed classification system (Barrera-Domínguez, Jones, et al., 2024), this method enables the prescription of specific training stimuli according to each athlete's needs. The details of both training intervention are available their respective studies and in ***Supplementary Material 1 (Study 11)***.

The results of the individualised training program based on the vertical force-velocity profile in basketball players confirmed the previous findings in football and rugby players (Jiménez-Reyes et al., 2016, 2019). These studies showed that this training approach was an effective strategy for achieving an optimal profile and improving jump performance, as it allowed to propose stimuli adapted to the vertical force needs of each athlete (Morin & Samozino, 2016). Previous research using the same intervention over 8 to 12 weeks in football and rugby players (Jiménez-Reyes et al., 2019) reported improvements of 12.5% in vertical jump peak height. Barrera-Domínguez et al. (2023) found similar results for the CMJ, with improvements of 8.14% after four weeks of intervention and 21.2% after eight weeks. These substantial improvements exceeded those reported in previous studies (Jiménez-Reyes et al., 2016, 2019), which may be attributed to the characteristics of the sample. Specifically, our basketball players exhibited lower baseline values compared to those reported in other basketball cohorts (Morrison et al., 2022). Furthermore, basketball players obtain greater benefits from plyometric training compared to others in football or rugby, due to the nature of basketball and its specificity to plyometric exercises (Asadi et al., 2016). These performance improvements were also observed in both linear (5.91%) and multidirectional (>3.00%) speed actions after eight weeks of training (Barrera-Domínguez et al., 2023). However, the improvement in linear speed performance occurred earlier than those in COD. This might be attributed to the specificity of the training, which facilitated significant neurological and coordinative adaptations in linear speed (Loturco et al., 2018). Regarding CODs, it was observed that jumps exhibit muscle activation peaks highly similar to COD actions (Falch, Rædergård, & Van den Tillaar, 2020c), and previous research (Barrera-Domínguez et al., 2020) showed a high relationship between the vertical force-velocity profile and COD performance. The findings of Barrera-

Domínguez et al. (2023) confirmed these previous observations, as this individualised training approach, based on the vertical force-velocity profile, induced improvements in COD performance, and being slightly higher than those reported in a recent meta-analysis (Falch et al., 2019) without individualised training interventions.

Regarding the individualised training approach based on CODD, to the author's knowledge, this doctoral thesis includes the first intervention in basketball players that has provided individualised training specifically tailored to CODD. It is also one of the first interventions to examine the effect of training on multidirectional movement efficiency in basketball players, assessed through CODD (Nimphius et al., 2016). Previous studies examining CODD throughout a training intervention calculated this variable in absolute terms and found no effect of sprint training on CODD even in football players (Solleiro-Duran et al., 2025). Similarly, no effect of an individualised training based on the dynamic strength index on CODD was found in basketball players (Pleša et al., 2024). Therefore, to date no training approach has demonstrated improvements in multidirectional speed efficiency in basketball. This may be attributed to the fact that previous training programs were neither specific nor adapted to the speed requirements of each athlete, failing to provide sufficient stimulus to induce adaptations in the athletes' multidirectional speed efficiency (Barrera-Domínguez, Martínez-García, et al., 2024). Furthermore, CODD is often calculated as an absolute value (Nimphius et al., 2016) rather than in percentage terms (Freitas, Pereira, et al., 2021), which standardises CODD measurement and facilitates athlete classification for more effective training programming (Barrera-Domínguez, Jones, et al., 2024). ***Study 10*** addressed these previous limitations by using percentage-based CODD to individualise training and provide appropriate training stimuli for each athlete. The results revealed significant between-group differences in movement efficiency after four and eight weeks of training, with players in the intervention group demonstrating the greatest ability to compensate for their individual linear and multidirectional speed demands. In other words, these players were the most efficient across all assessed movement directions. These findings are consistent with the initial hypothesis and previous studies (Barrera-Domínguez, Jones, et al., 2024), which recommended specific training according to each player's individual speed requirements.

In addition to improving athletes' efficiency in multidirectional movements, *Study 10* demonstrated a large improvement in both linear and multidirectional speed performance after eight weeks of individualised horizontal force-oriented training based on CODD, with an average performance improvement of 4.02% (ES =1.23; p <0.01), and up to a 7.42% enhancement in 180º COD performance (ES =1.72; p <0.01). However, training programs with a horizontal force orientation in basketball players have not shown a significant effect on COD performance (Aztarain-Cardiel et al., 2022; Sánchez-Sabaté et al., 2024). This may be attributed to their lack of individualisation, as they were not adjusted to the specific needs of each player (Barrera-Domínguez, Martínez-García, et al., 2024). Generalised training programs without individual adaptation may fail to provide an effective stimulus for a group of athletes with differences in COD mechanics and performance, and therefore with different training needs (Barrera-Domínguez, Jones,

et al., 2024). In this regard, the non-responder analysis —athletes were labelled as non-responders if they did not get a post-intervention performance increase greater than 2CV— revealed that individualised training protocols resulted in a higher proportion of athletes responding positively to training (78% of responders) compared to the non-individualised group (36% responders). This evidence suggests that individualised training approaches not only achieve faster and more substantial performance improvements, but also result in fewer non-responders to training. The present findings indicate that this individualised CODD-based training approach emerges as a quick and straightforward method to accurately assess and determine each athlete's specific speed requirements across multiple cutting angles relevant to the sporting context. This facilitates the design of a training program focused on improving each athlete's specific speed demands. Therefore, it uses would be recommended to maximise COD performance in the shortest possible time.

Finally, it is well documented that a short-term intervention (4 to 8 weeks) involving strength or ballistic training programs can significantly improve physical performance in male team sport players (Keller et al., 2020; Pleša et al., 2024). Regardless of the strength orientation trained, male youth team sports players demonstrated improvements in jumping and COD performance within four weeks of training (Keller et al., 2020). Similarly, Pleša et al. (2024) reported significant gains in jump and COD performance among highly trained basketball players after just five weeks of individualised training based on the dynamic strength index. Thus, these findings suggest that significant improvements in physical performance can occur within the first month of training. However, the results of this doctoral thesis only partially align with these findings. Significant improvements in vertical jump performance (≥7.29%, d ≥1.47, p <0.01) were observed after four weeks of individualised training. Nevertheless, neither linear nor COD performance showed significant changes at this time point, although a trend towards improvement was evident (≥1.00%, d ≥0.23, p≥ 0.32). Thus, it was found that the timing of performance improvements depends on the specific skill targeted. In this regard, performance improvements in jumping actions occurred earlier than in speed and COD actions. This discrepancy may be attributed to the complexity of COD movements, which integrate multiple abilities —such as acceleration, deceleration and reacceleration— while interacting different force orientations (Dos'Santos, Comfort, et al., 2018). Consequently, longer training durations, at least 6 weeks (Barrera-Domínguez, Martínez-García, et al., 2024), may be necessary to obtain significant improvements in COD performance; compared to vertical jump performance, which responded significantly after just four weeks of training (Barrera-Domínguez et al., 2023). These findings were consistent with a recent meta-analysis on the combined effects of training on COD speed, which concluded that a minimum intervention period of six to eight weeks was necessary to achieve significant improvements in performance (Falch et al., 2019).

Conclusions

In conclusion, and in order to synthesise all the results of each of the eleven studies included in this doctoral thesis, the main findings in response to the initial aims will be presented below.

Aim 1. To identify the key factors influencing COD performance in basketball players.

- ***Conclusion 1A.*** The anthropometric variables evaluated showed no influence on COD performance in basketball players, regardless of the cutting angle or gender. Fat mass percentage was the only variable that showed a significantly large effect on COD performance at 45° in male basketball players. Therefore, it can be concluded that these variables do not have a relevant impact on COD performance in basketball players, except for fat mass. Specifically, lower fat mass in male players is associated with better performance in velocity-oriented COD actions.
- ***Conclusion 1B.*** The functional movement variables evaluated showed no relationship with COD performance at different cutting angles in male athletes. However, for female athletes, dynamic balance was found to be determinant at all cutting angles, while ankle mobility showed a significantly large relationship with COD at 45°. Therefore, it is important to take into account the gender and the characteristics of athletes when looking for relationships between these abilities and improving COD performance in basketball players.
- ***Conclusion 1C.*** Strength variables, regardless of muscle action, manifestation or force orientation assessed, showed the strongest relationship with COD actions in both genders. Among muscle actions, eccentric strength demonstrated the strongest relationship with COD performance at all cutting angles, particularly the rate of eccentric force development. However, the fastest basketball players in terms of changing direction exhibited a lower eccentric/concentric force ratio. In other words, having high levels of concentric strength relative to the athlete's own eccentric strength is also a key determinant for optimal performance in these actions. Therefore, a higher rate of eccentric force development while maintaining

a balanced eccentric/concentric force ratio is essential for achieving an optimal performance in COD actions.

- ***Conclusion 1D.*** On the other hand, although all the strength variables were related to COD performance in both genders, differences were mainly found in contraction rate and force orientation between genders. Strength variables with a long SSC and a vertical force orientation were the most important determinants of COD performance in female athletes. In their male counterparts, strength variables with a short SSC and a horizontal force orientation were the key determinants of COD performance. Once again, these findings highlight the importance of avoiding generalisations and considering gender-related and players characteristics to enhance COD performance.
- ***Conclusion 1E.*** The performance variables influencing COD, measured through execution time and CODD, are different. Therefore, these two methods of assessing COD are not measuring exactly the same thing. The execution time is measuring the performance in these actions, while CODD evaluates the efficiency of the athletes in the COD skill.
- ***Conclusion 1F.*** While age category and gender showed significant differences in performance across all physical abilities analysed, inter-limb asymmetries had no effect on sport performance of basketball and handball players. These findings confirm that asymmetries are largely independent of athletic performance; whereas gender and age directly influence athletes' physical performance.

Aim 2. To standardise and improve the accessibility of linear and multidirectional speed assessment for sports professionals.

- ***Conclusion 2A.*** To effectively assess COD speed, the testing protocol should be short in duration (i.e., less than 5 seconds or covering a distance of 10 metres), and include a single cut. Furthermore, given the strong dependence of the cutting angle on COD performance, the multidirectional demands of basketball, and the requirement to be equally proficient at turning in both directions across a wide range of angles, it is highly recommended to assess athletes ability through multiple COD tests with a single COD at various angles and with both legs, to create an individual COD angle profile for each basketball player.
- ***Conclusion 2B.*** The execution time in COD tests and the CODD assess different aspects of the athletes' COD ability. The CODD is a validated measure for assessing an athlete's efficiency in these actions, but it is recommended to assess performance through execution time in simple COD tests with a single cut at different angles. Therefore, for a better understanding and comprehension of the athlete's COD ability, it is advisable to analyse and combine both metrics.
- ***Conclusion 2C.*** The CODD provides valuable information about the relationship between linear speed and COD ability for each athlete, identifying individual strengths and weaknesses in these skills. Furthermore, the CODD thresholds identified allow for the classification of basketball players, the sharing and comparison of standardised data with other samples, improved management and

monitoring of each player's performance and, most importantly, the development of training programs focused on the athlete's individual weaknesses and needs.

- ***Conclusion 2D.*** Asstrapp is a highly valid and reliable tool for measuring COD test execution time. Moreover, Asstrapp is an affordable and accessible sports assessment tool for all coaches. It is an easy and quick tool to use, it is more portable than traditional laboratory instruments and has the advantage of providing real-time feedback. For all these reasons, this app is recommended to any sports professional to assess, quantify and train COD.

Aim 3. To analyse the effect of different individualised training approaches on physical performance in basketball players.

- ***Conclusion 3A.*** Although there are a wide variety of training approaches, such as plyometric, strength, speed or combined training, for the improvement of COD performance, our meta-analysis study revealed that combined plyometric and strength exercises including a vertical and horizontal force orientation within the training program was the most effective method for the improvement of COD performance in basketball players. This training methodology, over six weeks and three sessions per week, seems to be the minimum recommended stimulus.
- ***Conclusion 3B.*** Each individualised training programs were effective in improving the variable on which the training was based (i.e., vertical force-velocity profile and CODD). These findings indicate that the improvements are mostly specific to the variable used to individualise training. So, it is important to know which sport performance variable each athlete needs to work on to individualise training.
- ***Conclusion 3C.*** The improvements in sports performance following the individualised training approaches were of greater magnitude than those found in previous literature with general, non-individualised training. These improvements were specific to the force orientation trained during the interventions. That is, more substantial performance improvements were observed in vertical variables among players who underwent training based on the F-V profile, and in the horizontal variables for those trained based on the CODD.
- ***Conclusion 3D.*** Both individualised training approaches led to performance improvements in all measured outcomes after 8 weeks. Furthermore, significant changes in vertical jump performance were observed earlier (at four weeks) than in linear and multidirectional speed (at eight weeks). So, it can be deduced that changes in vertical jump performance occur earlier compared to changes in COD performance, with four weeks of training being insufficient to find significant changes in multidirectional speed performance.
- ***Conclusion 3E.*** Basketball-specific training without individualisation was insufficient to improve physical performance, as more than 60% of athletes in this group were classified as non-responders to the training stimulus. Therefore, it is of vital importance that individualised training stimuli are implemented, adapting training programs to the physical needs of each athlete in order to optimise the responsiveness of each player to specific training variables.

CONCLUSIONES

En conclusión y con el fin de sintetizar todos los resultados de cada uno de los once estudios incluidos en la presente tesis doctoral; a continuación, se van a exponer los principales hallazgos como respuesta a los objetivos planteados inicialmente.

Objetivo 1. Determinar los factores determinantes en el rendimiento de las acciones de COD en jugadores de baloncesto.

- ***Conclusión 1A.*** Las variables antropométricas evaluadas no mostraron influencia alguna sobre el rendimiento de las acciones de COD en jugadores de baloncesto independientemente del ángulo de corte y del género de los jugadores. Fue, exclusivamente, el porcentaje de masa grasa la única variable que mostró un efecto significativamente grande en el rendimiento del COD a 45º en jugadores de baloncesto masculinos. Por lo que se puede concluir que estas variables no tienen un peso relevante en el rendimiento del COD en jugadores de baloncesto, a excepción de la masa grasa; a menor masa grasa en jugadores masculinos, mayor rendimiento en acciones de COD orientados a la velocidad.
- ***Conclusión 1B.*** Las variables de movimiento funcional evaluadas no mostraron relación alguna con el rendimiento de los COD a diferentes angulaciones de corte en deportistas masculinos. Sin embargo, para las deportistas femeninas el equilibrio dinámico mostró ser determinante ante cualquier angulación de corte, mientras que se encontró una relación significativamente grande entre la movilidad de tobillo y el COD a 45º. Por ello, es importante tener en cuenta el género y las características de los deportistas a la hora de buscar relaciones entre estas habilidades y mejorar el rendimiento de los COD en jugadores de baloncesto.
- ***Conclusión 1C.*** Las variables de fuerza, independientemente de la acción muscular, la manifestación o la orientación de la fuerza evaluada, fueron las que mayor relación mostraron con las acciones de COD en ambos géneros. Con relación a las acciones musculares, fue la excéntrica la que mostró mayor relación con el

rendimiento del COD a cualquier angulación, específicamente la aplicación de fuerza excéntrica rápida. Sin embargo, los jugadores de baloncesto más rápidos cambiando de dirección mostraron una menor ratio de fuerza excéntrica/concéntrica. Es decir, tener altos niveles de fuerza concéntrica en relación a la fuerza excéntrica del propio deportista también es determinante para un óptimo rendimiento en estas acciones. Por ello, el desarrollo de la fuerza excéntrica rápida a la misma vez que se mantiene equilibrado la ratio de fuerza excéntrica/concéntrica es de vital importancia para un óptimo rendimiento en acciones de COD.

- ***Conclusión 1D.*** Por otro lado, aunque todas las variables de fuerza mostraron relación con el rendimiento de los COD en ambos géneros, principalmente se encontraron diferencias en la velocidad de contracción y la orientación de la fuerza entre géneros. Siendo las variables de fuerza con un SSC largo y una orientación vertical de la fuerza las que determinaron en mayor medida el rendimiento del COD en deportistas femeninas, mientras que fue la fuerza con un SSC corto y con una orientación horizontal la que mayoritariamente determina el rendimiento en acciones de COD en deportistas masculinos. De nuevo, estos hallazgos resaltan la importancia de no generalizar y tener en cuenta el género y características de la muestra para la mejora del rendimiento en los COD.
- ***Conclusión 1E.*** Las variables de rendimiento que afectan al COD, medido a través del tiempo de ejecución y del CODD, son diferentes. Por lo que ambos métodos de evaluar los COD no están midiendo exactamente los mismo. El tiempo de ejecución está midiendo el rendimiento en estas acciones, mientras que el CODD evalúa la eficiencia de los deportistas en la habilidad de COD.
- ***Conclusión 1F.*** Mientras que la categoría de edad y el género sí que mostró diferencias significativas en el rendimiento en todas las capacidades físicas analizadas, las asimetrías entre piernas no mostraron ningún efecto en el rendimiento de los jugadores de baloncesto, ni balonmano. Estos hallazgos confirman que las asimetrías son en gran medida independientes al rendimiento deportivo; mientras que el género y la edad sí que influyen directamente en el rendimiento físico de los deportistas.

Objetivo 2. Estandarizar y hacer más accesible la evaluación de la velocidad lineal y multidireccional a los profesionales del deporte.

- ***Conclusión 2A.*** Para evaluar eficazmente la velocidad de los COD, el protocolo de las pruebas debe ser de corta duración (i.e., menos de 5 segundos de duración o 10 metros de recorrido), e incluir un solo corte. Además, debido la gran dependencia del ángulo de corte en el rendimiento de los COD, a los requerimientos multidireccionales asociados al baloncesto, y el requisito de ser igualmente competente girando a ambos lados a través de un amplio espectro de ángulos; es altamente recomendable evaluar a los deportistas esta habilidad a través de varias pruebas de COD con un solo COD a varias angulaciones y con ambas piernas, para

crear un perfil de COD en base a la angulación de corte para cada jugador de baloncesto.

- ***Conclusión 2B.*** El tiempo de ejecución en las pruebas COD y el CODD evalúan diferentes aspectos dentro de la habilidad de COD de los deportistas. El CODD es una medida validada para evaluar de eficiencia de los deportistas en estas acciones, pero se recomienda evaluar el rendimiento a través del tiempo de ejecución en pruebas de COD simples con un solo corte a diferentes angulaciones. Por ello, para una mejor comprensión y entendimiento de la capacidad de COD del deportista se recomienda analizar y mezclar ambas métricas.
- ***Conclusión 2C.*** El CODD proporciona una gran información sobre la relación entre la velocidad lineal y el COD de cada atleta, identificando los puntos fuertes y débiles individuales de cada deportista en estas habilidades. Además, los umbrales de CODD encontrados permiten clasificar a los jugadores de baloncesto, compartir y comparar datos estandarizados con otras muestras, mejorar la gestión y el seguimiento del rendimiento de cada jugador y, lo que es más importante, proponer programas de entrenamiento que se focalicen en las debilidades y necesidades individuales del deportista.
- ***Conclusión 2D.*** Asstrapp es una herramienta muy válida y fiable para medir el tiempo de ejecución de las pruebas de COD. Además, Asstrapp es un instrumento de evaluación deportiva asequible y accesible para todos los entrenadores, una herramienta fácil y rápida de usar, es más portátil que los instrumentos de laboratorio tradicionales y tiene la ventaja de que ofrece un feedback inmediato. Por todas estas razones, esta app se recomienda a cualquier profesional del deporte para evaluar, cuantificar y entrenar los COD.

Objetivo 3. Analizar el efecto de diferentes aproximaciones de entrenamiento individualizado sobre el rendimiento físico en jugadores de baloncesto.

- ***Conclusión 3A.*** Aunque existen una gran variedad de propuestas de entrenamiento, tales como entrenamiento pliométrico, de fuerza, de velocidad o combinado, para la mejora del rendimiento en acciones de COD, el estudio de meta-análisis reveló que un entrenamiento pliométrico junto a ejercicios de fuerza que combinen una orientación de la fuerza vertical y horizontal dentro del programa de entrenamiento fue lo más efectivo para la mejora del rendimiento del COD en jugadores de baloncesto. Esta metodología de entrenamiento con una duración de seis semanas, y tres entrenamientos a la semana parece ser la duración y frecuencia mínima recomendable.
- ***Conclusión 3B.*** Cada uno de los programas de entrenamiento individualizado fue eficaz en la mejora de la variable en la que se basaba el entrenamiento (i.e., el perfil fuerza-velocidad vertical y el CODD). Estos hallazgos indican que las mejoras son específicas mayoritariamente a la variable que se usa para individualizar el entrenamiento. Por lo que es importante conocer que variable de rendimiento necesita trabajar cada deportista e individualizar el entrenamiento en base a ello.

- ***Conclusión 3C.*** Las mejoras en el rendimiento tras las propuestas de entrenamiento individualizadas fueron de mayor magnitud a las encontradas en la literatura previa con entrenamientos generales sin individualizar. Estas mejoras fueron específicas a la orientación de la fuerza trabajada durante las intervenciones. Es decir, se observaron mayores ganancias en las variables verticales entre los jugadores que se sometieron a un entrenamiento basado en el perfil F-V, y en las variables horizontales para aquellos entrenados en base al CODD.
- ***Conclusión 3D.*** Ambos enfoques de entrenamiento individualizado condujeron a mejoras en el rendimiento en todos los resultados medidos después de 8 semanas. Además, se observaron cambios significativos en el rendimiento del salto vertical antes (a las cuatro semanas), que en la velocidad lineal y multidireccional (a las ocho semanas). Por lo que se podría determinar que los cambios en el rendimiento de las acciones de salto vertical ocurren antes en comparación con los cambios en el rendimiento de los COD, siendo cuatro semanas de entrenamiento insuficientes para encontrar cambios significativos en el rendimiento de la velocidad multidireccional.
- ***Conclusión 3E.*** El entrenamiento específico de baloncesto sin individualización fue insuficiente para mejorar el rendimiento físico, ya que más del 60% de los atletas de este grupo fueron clasificados como no respondedores al propio entrenamiento. Por ello, es de vital importancia que se implementen estímulos de entrenamiento individualizados, adaptando los programas de entrenamiento a las necesidades físicas de cada deportista para optimizar la capacidad de respuesta de cada jugador a variables de entrenamiento específicas.

LIMITATIONS AND FUTURE DIRECTIONS

"Science builds the future
with questions we do not yet know
and answers we cannot yet imagine."

Unknown –

LIMITATIONS

Despite the interesting findings provided in this doctoral thesis, it is not exempt from limitations that must be taken into consideration when interpreting the results and extrapolating them to the context of each professional. For this reason, the specific limitations of the eleven studies included were mentioned in each of them, and the main general limitations to be considered in this doctoral thesis were presented below:

Firstly, caution should be exercised due to the sample used in most studies which was composed entirely of non-professional senior basketball players, due to the impossibility of accessing players of a higher competitive level. This implies that the results of all studies can serve as a reference in a population with similar characteristics, but caution is recommended when attempting to extrapolate these results to other competitive levels or sports. Despite the calculation of sample size to achieve maximum possible statistical power in each study, limitations in statistical analysis due to sample precluded the investigation of playing position or gender in some studies. Even so, the included studies represent an initial approximation to most of the topics they address, so that future research will be able to provide even more comprehensive knowledge.

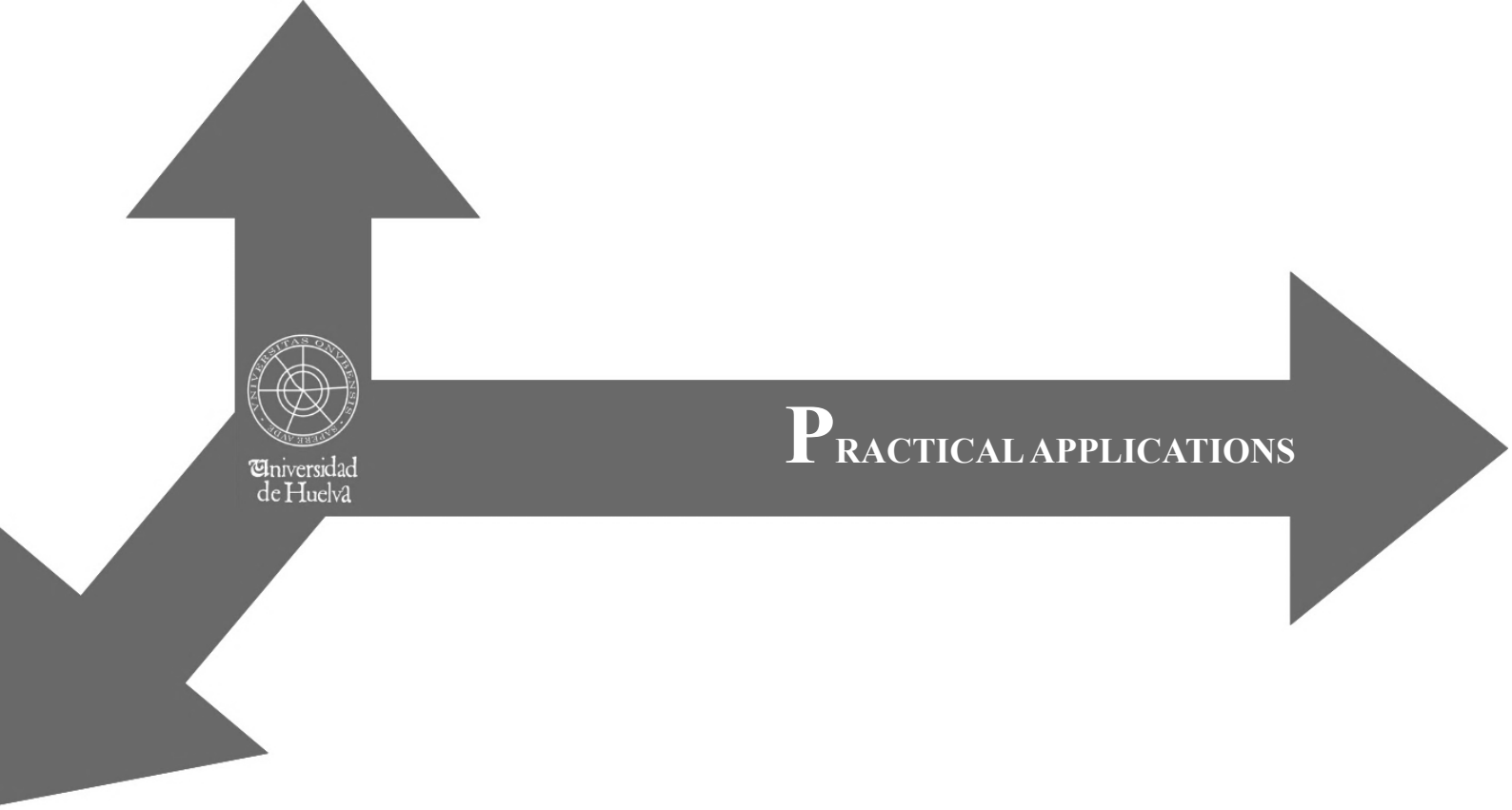
Finally, it is important to highlight that the proposal of a general and gold-standard COD assessment for all sport contexts is assumed to be impossible due to the multitude of variables that influence the performance of these tests as discussed throughout the thesis. However, the recommended COD assessment proposal represents the most coherent approach based on the results of the present thesis and the current scientific literature. Furthermore, the implementation of a standardised battery of COD tests in future scientific studies will be very useful to advance the knowledge of this skill.

FUTURE DIRECTIONS

From the results obtained in this doctoral thesis, new ideas and research questions have arisen that can undoubtedly continue to further advancing scientific knowledge about the topic of study. The most relevant ones are presented below:

Firstly, it is recommended that future cross-sectional studies using the standardised assessment proposed in this thesis to further examine the determining factors on COD performance at different angulations, facilitating the comparison of data across studies. In this way, conducting systematic reviews with meta-analyses would be beneficial, as they allow for a precise comparison of data. Moreover, the recommended tests for evaluating COD actions can be segmented into different phases. Therefore, it is recommended to use assessment tools that allow analysing performance in each of phase and identifying the key determinants of COD performance in each phase. Secondly, COD actions in real game situations are not always performed without fatigue. Therefore, it is recommended to analyse the effect of fatigue on these actions. Another important aspect derived from this thesis is the classification of athletes based on CODD, a novel approach that should be further investigated in future scientific studies involving samples of multiple competitive levels and sports.

Finally, training individualisation is one of the key principles of training that the results of this thesis have shown to be decisive in the adaptations of athletes after an intervention. To date, the effect of different individualised training approaches on sports performance of basketball players is an area that has been little studied in the current scientific literature. Therefore, scientists and sport professionals are strongly encouraged to focus on the training individualisation for future scientific research.



PRACTICAL APPLICATIONS

Finally, the practical applications and take-home messages extracted from the results and findings of the present doctoral thesis were collected as recommendations for any sport professional who seeks to get a better understanding of multidirectional actions in team sports and, thus, to improve the performance of their athletes.

- ***Determinant factor in COD performance.*** This doctoral thesis highlights the importance of lower limb strength in COD actions, identifying this physical capacity as the most influential factor in COD performance among basketball players. Furthermore, delving into different muscle actions and force manifestations, it appears that rapid eccentric muscle action (<40 ms) is the most decisive capacity, regardless of cutting angle or athlete characteristics. However, it is recommended to avoid generalisation and to carefully analyse the cutting angles and the specific characteristics of the athletes whose performance is intended to be improved. The determining variables for each athlete will depend on their gender and skill level, emphasising the need for individualised assessments and training approaches.

Regarding the cutting angle targeted for performance improvement, it was observed that the velocity-oriented COD (<90º cut) are predominantly influenced by maximum concentric strength. Conversely, performance in strength-oriented COD actions (>90º cut) is more closely related to isometric and eccentric strength of the athletes. For this reason, it was recommended to implement specific training for the different muscular actions and force manifestations based on the cutting angle that needs to be improved. This approach ensures that the training is aligned with the demands of the desired COD performance.

Additionally, differences in the determinants of COD performance have been observed between genders. In this sense, male basketball players demonstrated a stronger relationship between horizontal force with a short SSC (<250 ms) and, both linear and multidirectional speed actions. Conversely, in female athletes, vertical force with a long SSC was the most determinant factor in speed actions. Based on these findings, it was recommended to pay attention to gender and the specific characteristics of each athlete

when seeking to establish a relationship between different physical abilities and COD actions at different angles. This individualised approach can enhance training specificity and optimise performance outcomes.

Therefore, the previous points may serve as a reference or guideline; however, due to the complexity and multidirectional nature of COD actions, the findings from the most recent scientific literature strongly recommend avoiding generalisations about the determinants of COD performance. Instead, it is crucial to analyse these factors specifically, based on the characteristics of each athlete and the COD actions targeted for improvement.

- ***Standardisation of COD assessment.*** In order to deepen the understanding and development of any athletic skill, one of the most important aspects is having a standardised assessment of that skill. It enables the analysis of results and the identification of new insights. Until now, such standardisation did not exist for the COD skill among sport professionals. This lack of standardisation has led to the use of different COD tests in previous scientific studies, making cross-study comparisons difficult and hindering the advancement of scientific knowledge on the topic. However, based on the findings of the present doctoral thesis, along with the recent scientific studies, it is recommended to implement short duration testing protocols (i.e., less than 5 seconds or over 10 metres), with a single cut at different angles to effectively evaluate COD speed. This approach facilitates the creation of a COD angle profile based on the individual needs of each basketball player.

- ***Analysis of execution time and CODD.*** Traditionally, execution time in a COD test has been used as a measure of performance. Despite being a valid metric, it may obscure the influence of other physical attributes, such as the athlete's linear speed. Therefore, it would be recommended to complement this measurement unit with the CODD —extracted from the execution time in a linear speed test and a COD test with the same total distance covered—. The combination of both metrics, execution time and CODD, provides sports professionals with a more comprehensive assessment of their athletes' performance and efficiency in multidirectional actions. This approach not only allows to classify athletes based on their performance and track progress over time, but also equips strength and conditioning coaches with the necessary information to identify individual needs and limitations in multidirectional actions. Consequently, this enables the development of more specific and individualised training programs aimed at optimizing performance in these actions more efficiently.

- ***Asstrapp validation.*** The limitations of current technology for assessing execution time and CODD in speed tests have made it almost inaccessible for sports professionals in daily practice. High cost, lack of portability, or significant time requirements for evaluation are the major barriers to monitoring speed performance in team sports. For this reason, the development of an innovative AI-based technology became essential to evaluate any speed test in a valid and reliable manner, without the constraints of the current tools. Asstrapp, a mobile application currently available on the iOS operating system, has proven to be a valid and reliable tool that is accessible for

coaches. It is cost-effective, portable, user-friendly, and provides real-time feedback. For these reasons, Asstrapp is recommended for sports professionals to effectively evaluate, quantify, and train COD actions.

- ***Training individualisation.*** Despite extensive scientific literature analysing the effect of multiple training methodologies, either in isolation or combined, the findings of this doctoral thesis highlight the importance of designing specific and individualised training stimuli to maximise performance gains. In this context, a targeted approach to force orientation, aligned with the intended improvement, along with a training methodology that emphasises the athletes' physical needs and proper management of other variables influencing training load, seems to be the best strategy for optimising athletic performance. Therefore, strength and conditioning coaches are strongly encouraged to design individualised training programs based on CODD for the improvement of multidirectional performance or using any other variable according to the needs of each athlete.

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