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Spatiotemporal and foot kinematic differences during gait in individuals with cavus foot

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Cavus foot, defined by a high medial arch, alters plantar pressure distribution and gait biomechanics, often leading to increased forefoot and heel loading, joint stiffness, and musculoskeletal complications. However, specific kinematic differences compared to normal feet remain underexplored. This study aims to analyse gait kinematics differences in subjects with cavus foot versus those with normally aligned feet. A case-control study was carried out in 100 subjects (50 with bilateral cavus foot and 50 with neutral foot) using the PODOSmart® system, which consists of one pairs of smart insoles, which are available in six sizes covering European sizes 36 to 47, to measure spatiotemporal parameters and segmental foot kinematics with a sampling frequency of 208 Hz. spatiotemporal Kinematic gait analysis showed statistically significant differences ($p = 0.003$) in the case group, with a shorter duration of the taligrade phase of gait in both the left and right feet. The subject with pes cavus showed rapid heel contact, presenting a shorter duration of the taligrade phase of gait compared to subjects with normal feet, which is related to the supination characteristic of this deformity.

Keywords Cavus foot, Gait patterns, Musculoskeletal diseases, Stance phase gait, Foot

The human foot exhibits considerable variability in its morphology, resulting in different foot types, including cavus foot. These morphological differences can significantly influence foot functionality, particularly in relation to its biomechanical behaviour during gait[1–3]. Cavus foot is characterized by a high longitudinal arch, which gives the foot a concave appearance and leads to abnormal load distribution during walking, potentially predisposing individuals to various musculoskeletal pathologies[4–6]. Individuals with cavus foot show a higher incidence of injuries to the soft tissues and lateral structures of the foot, as well as to the ankles and foot bones[1].

This alteration can generate areas of excessive pressure, which in turn contributes to pain and the development of various podiatric pathologies, such as claw toe deformity, hammer toes, and plantar ulcers[1,7]. Its incidence is 2–7% in children, but it has been estimated that around 10–15% of the adult population has cavus foot, so its presence increases with age[8,9], and a significant proportion of them experience pain due to concentrated loads in areas such as the forefoot[10–13].

The analysis of plantar pressure distribution has been a key area in cavus foot research. Compared to neutrally aligned feet, cavus foot show a reduced contact area in the midfoot, resulting in increased pressure in the forefoot and heel[9,14,15]. Some studies[3,10] have observed that cavus foot exert greater pressure on the metatarsal area, particularly under the heads of the second and third metatarsals. The modified distribution of plantar pressure can have consequences for the individual, affecting both injury prevention and the improvement and proper functioning of orthopaedic treatment.

In addition to changes in plantar distribution, understanding the kinematic differences in gait between different foot types is essential to understand the functional implications of cavus foot[16]. Gait kinematics in individuals with cavus foot differ from those of individuals with normal feet[12,17], affecting parameters such as joint

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range of motion, speed, and amplitude of movement. These individuals often present increased gait rigidity due to limited pronation and rearfoot inversion at initial contact, together with abnormal force distribution during stance phases, which predisposes them to injury and impairs their quality of life[18,19]. This is the importance of kinematic analysis in the evaluation of the cavus foot, to detect gait alterations that are not always evident in a conventional biomechanical examination[5,20]. The information obtained from this analysis can be used to design more effective treatments aimed at improving the altered parameters[5,12,20–22].

This examination, using advanced techniques and systems, allows us to identify the morphological and functional characteristics unique to the cavus foot and compare them with those of a normal (neutral) foot[10,21,23,24]. However, despite the importance of this topic and its clinical impact, there are few studies and information available that help us kinematically distinguish one foot from another. Most existing studies have focused on general biomechanical aspects without delving into specific movement variations[25–27]. Therefore, it is essential to conduct detailed research that analyses differences in kinematic variables between these two foot types, in order to improve diagnosis, treatment, and prevention of associated pathologies. This study differs from previous research by utilizing an advanced portable system (PODOSmart®) that enables detailed and functional analysis of gait phases and kinematic angles in individuals with cavus foot. This approach allows detection of subtle alterations and provides more precise clinical information, with potential impact on designing personalized treatment strategies. Thus, this study aims to analyse foot kinematics differences during gait in individuals with cavus foot compared to subjects with normal feet.

Materials and methods

Study design

This case-control study consisted of 100 subjects (80 women and 20 men), ranging in age from 18 to 65 years, with a mean age of 24.44 years. Subjects were included in the study using a non-randomized consecutive design carried out at a biomechanical center between November 2024 and February 2025, among patients attending routine assessments. The case group consisted of 50 subjects with bilateral cavus foot and the control group of 50 individuals with neutral feet; all subjects met the inclusion and exclusion criteria. The inclusion criteria common to both groups were individuals between 18 and 65 years of age, healthy with no general illnesses, without systemic diseases, musculoskeletal disorders, or foot pathologies, with no previous surgeries on the lower limbs, able to understand the instructions provided, and who signed the informed consent form. For the cavus foot group, participants were required to present bilateral cavus foot with a positive Coleman test indicating a flexible hindfoot. For the control group, participants were required to have bilateral neutral feet, clinically defined as the absence of any structural deformity, pain, or functional limitation, and confirmed by visual assessment of hindfoot alignment within normal angular limits during standing. The exclusion criteria were the presence of neurological diseases or musculoskeletal disorders, current pharmacological treatment that could influence gait, pregnancy or breastfeeding, failure to sign the informed consent form, inability to understand the study instructions, or, in the case of the cavus foot group, a negative Coleman test (no correction on the block) with a rigid phase pathology.

Procedure

The study was conducted by an experienced podiatrist specializing in biomechanics. First, each subject was interviewed to inquire about their medical history and general health status in order to record demographic data and verify compliance with the inclusion and exclusion criteria. Subsequently, the individuals were weighed and measured; they had to be barefoot and dressed in light clothing. The Coleman test[28] was then performed to discriminate or include cases. The participant stood barefoot on a wooden block (2.5–3 cm thick) with the heel and lateral border of the foot elevated, while the first metatarsal and medial forefoot were allowed to drop freely. A positive test (indicating flexible hindfoot varus) was defined as correction of the varus deformity to neutral or valgus alignment upon weight-bearing on the block, confirming the varus was secondary to forefoot pronation[29].

Gait analysis was performed using the PODOSmart® system (Digitsole SAS, Nancy, France), which consists of one pairs of smart insoles, each weighing 66 g. Each insole contains an inertial measurement unit that captures spatiotemporal and kinematic data with a sampling frequency of 208 Hz[30]. The subjects wore their own footwear, this approach was chosen to capture gait characteristics under habitual, everyday conditions, as footwear significantly influences gait patterns. Participants' shoes were carefully inspected to ensure they were in good condition and free from structural alterations or excessive wear that could affect gait performance or data accuracy. PODOSmart® insoles were fitted onto these. To perform the analysis, participants walked linearly for a distance of 6 m in a larger room to ensure they had comfortable space. A practical test was first conducted to verify that everything was correct and that the patient felt comfortable and familiar with the procedure. Then, the actual analysis began. Data were recorded as the average values across multiple gait cycles during the 6-meter walking distance. On average, each participant completed approximately 10 to 12 gait cycles per trial, with 3 trials performed, and the mean values used for analysis.

The following gait variables were analysed for each foot: contact time (ms), flying time (ms), taligrade (ms), plantigrade (ms), digitigrade (ms), foot progression angle (°), clearance (cm), angle of attack (°), walking speed (km/h), stride length (m), cadence (steps/min), heel strike (°), toe strike (°), heel off (°), toe off (°) and propulsion ratio (%).These variables were defined and calculated based on the PODOSmart® software algorithms integrated within the system, which automatically processed the sensor data to provide spatiotemporal and kinematic gait parameters. Data extraction and analysis were performed using the PODOSmart® proprietary software.

Sample size calculation

The confidence levels, potential equally sized groups, and sample size estimation were evaluated using Epidat version 4.2 software (Consellería de Sanidade, Xunta de Galicia, Spain; Pan American Health Organization (PAHO-WHO); University CES, Colombia). Additionally, an 80% statistical power analysis with a type I error of 5% ($\alpha = 0.05$), a type II error of 20% ($\beta = 0.20$), and a two-tailed test were conducted to ensure statistical reliability. Ultimately, a total sample of 100 subjects was selected. The groups were categorized as follows: 50 neutral foot subjects and 50 cavus foot subjects.

The sample size estimation was informed by previous studies analysing kinematic parameters in foot deformities[31]. These studies provided relevant estimates of means and standard deviations for similar biomechanical variables, which guided the assumptions used in our sample size calculation. Specifically, expected differences and variability in gait parameters from these prior works supported selecting a total sample size of 100 subjects (50 per group) to achieve adequate statistical power (80%) and significance ($\alpha = 0.05$).

Ethical and legal considerations

This research was conducted following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines[32]. Approval was obtained from the Research Ethics Committee of the University of A Coruña (Ferrol, Spain) for this study, consent no. 2024-0033. This study complied with all the ethical standards included in the declaration of Helsinki and Organic Law 3/2018 on the protection of personal data and guarantee of digital rights[33].

Statistical analysis

The normality of all gait variables was assessed using the Kolmogorov-Smirnov test ($p > 0.05$) to determine the appropriate statistical tests. Independent t-tests were performed for variables that followed a normal distribution. For non-parametric data, the Mann–Whitney U test was used to compare groups with and without cavus foot. The independent variables are shown as mean, ranges of minimum to maximum and standard deviation (SD) values for the descriptive data analysis. Concerning the categorical variables, they were presented as percentages and absolute values. Statistical significance was set at a p-value less than 0.05 with a 95% confidence interval. All statistical analyses were carried out using SPSS 19.0 software.

Results

Sociodemographic data

The study included 100 participants (50 with cavus foot, 50 with neutral foot) with a mean age of 24.44 ± 7.41 years (range: 18–54). A sex imbalance was noted, with females comprising 80% of the total sample (76% cavus foot, 84% neutral foot; $p = 0.662$). Both groups exhibited similar BMI values (cavus: 23.59 ± 3.80 kg/m^2; neutral: 23.35 ± 3.53 kg/m^2; $p = 0.662$). Table 1 describes the main characteristics of all the subjects who participated in the study.

Main outcome measures data

The Mann-Whitney U test showed statistically significant differences in the taligrade phase for both the right and left feet ($p = 0.003$) in both groups, with the cavus foot group having a shorter taligrade duration compared to the control group. The remaining variables showed no significant differences between groups (Table 2).

Discussion

The objective of this study was to analyse foot kinematics during gait in individuals with cavus foot compared to subjects with normal feet using the PODOSmart® system. Participants were consecutively recruited which may explain the predominance of women (80%) in the sample. These data are consistent with previous literature suggesting a higher likelihood and incidence of structural foot abnormalities in women due to ligament laxity, footwear type, or hormonal changes[34–36]. Although the sex distribution was unbalanced, statistical analysis showed no significant difference between groups ($p = 0.662$), indicating that gender did not act as a confounding factor in group assignment. On the other hand, both groups presented BMI values within the normal range (case group: 23.59 ± 3.80 kg/m^2; control group: 23.35 ± 3.53 kg/m^2), with no statistically significant difference between them. This suggests that the kinematic differences observed are not attributable to weight-related mechanical

Characteristics	Total sample ($n = 100$) Mean ± SD (range)	Case group ($n = 50$) Mean ± SD (range)	Control group ($n = 50$) Mean ± SD (range)	p-value
Age (years)	24.44 ± 7.41 (18–54)	23.24 ± 5.05 (18–40)	25.64 ± 9.12 (18–54)	0.471†
Weight (kg)	65.16 ± 11.58 (40–92)	64.64 ± 12.13 (40–92)	65.68 ± 11.06 (45–89)	0.730†
Height (m)	1.67 ± 0.08 (1.50–1.84)	1.65 ± 0.08 (1.50–1.84)	1.68 ± 0.08 (1.55–1.82)	0.240†
BMI (kg/m^2)	23.47 ± 3.66 (14.2–32.8)	23.59 ± 3.80 (14.2–32.8)	23.35 ± 3.53 (17.9–30.5)	0.679†
Sex, male/female (%)	20/80 (20%/80%)	12/38 (24%/76%)	8/42 (16%/84%)	0.320†
Foot Size (EU)	38.84 ± 2.36 (36–45)	38.80 ± 2.73 (36–45)	38.88 ± 1.99 (36–42)	0.364†

Table 1. Main characteristics of the total sample with or without bilateral cavus foot. *Kg* kilogram; *m* meter, *m2* square meter, *%* percentage, *SD* standard deviation, *N* number. †Mann-Whitney U test was used. In all the analyses, $p < 0.05$ (with a 95% confidence interval) was considered statistically significant (bold).

Characteristics	Total sample ($n=100$)	Case group ($n=50$)	Control group ($n=50$)	
	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	*p*-value
Contact time (right foot) ms	687.3 ± 58.31 (558–903)	669.20 ± 57.77 (558–784)	687.40 ± 58.31 (609–903)	0.307
Contact time (left foot) ms	680.22 ± 56.45 (557–875)	671.60 ± 56.55 (557–784)	688.84 ± 55.57 (615–875)	0.416
Flying time (right foot) ms	423.06 ± 34.06 (283–489)	421.48 ± 25.09 (350–459)	424.64 ± 41.33 (283–489)	0.490
Flying time (left foot) ms	421.58 ± 33.61 (292–486)	418.80 ± 26.68 (344–470)	424.36 ± 39.44 (292–486)	0.288
Taligrade (right foot) ms	95.80 ± 15.47 (67–149)	90.80 ± 14.88 (67–122)	100.80 ± 14.53 (77–149)	**0.003**
Taligrade (left foot) ms	97.04 ± 19.83 (11–152)	91.20 ± 22.13 (11–126)	102.88 ± 15.33 (74–152)	**0.003**
Plantigrade (right foot) ms	335.16 ± 52.72 (222–500)	337.24 ± 59.73 (222–500)	333.08 ± 45.16 (268–473)	0.581
Plantigrade (left foot) ms	337.12 ± 49.06 (249–466)	330.32 ± 54.54 (249–466)	343.92 ± 42.37 (275–436)	0.116
Digitigrade (right foot) ms	244.86 ± 34.54 (110–317)	241.12 ± 42.55 (110–317)	248.60 ± 23.91 (210–303)	0.591
Digitigrade (left foot) ms	244.24 ± 29.45 (112–295)	245.76 ± 35.63 (112–295)	242.72 ± 21.87 (204–286)	0.195
Foot progression angle (right foot)°	9.19 ± 15.10 (-3.60–17.50)	7.19 ± 4.26 (-2.60–13.20)	11.19 ± 20.84 (-3.60–17.50)	0.978
Foot progression angle				
(left foot)°	3.57 ± 6.48 (-7.10–31)	2.22 ± 5.01 (-7.10–12.70)	4.92 ± 7.49 (-4.20–31)	0.144
Clearance (right foot) cm	1.05 ± 0.54 (0.30–3.10)	1.01 ± 0.48 (0.30–2.70)	1.10 ± 0.60 (0.50–3.10)	0.750
Clearance (Left foot) cm	1.20 ± 0.54 (0.30–3.50)	1.12 ± 0.46 (0.40–2.10)	1.30 ± 0.61 (0.30–3.50)	0.106
Angle of attack (right foot)°	29.47 ± 29.01 (13.40–37.90)	25.45 ± 5.33 (13.60–37.30)	33.49 ± 40.49 (13.40–37.90)	0.869
Angle of attack (Left foot)°	26.38 ± 4.49 (13.60–34.80)	26.35 ± 4.37 (15.90–32.40)	26.42 ± 4.66 (13.60–34.80)	0.901
Walking speed (Km/h)	4.44 ± 0.58 (2.90–5.60)	4.51 ± 0.63 (2.90–5.60)	4.37 ± 0.53 (3.00–5.30)	0.281
Stride length (right foot) cm	134.18 ± 14.21 (104–165)	134.52 ± 14.89 (104–164)	133.84 ± 13.63 (106–165)	0.590
Stride length (left foot) cm	134.98 ± 14.03 (100–164)	135.64 ± 15.62 (100–163)	134.32 ± 12.36 (112–164)	0.392
Cadence (Step/min)	109.04 ± 17.78 (11–156)	112.16 ± 12.64 (90–156)	105.92 ± 21.43 (11–134)	0.498
Heel strike (right foot) °	− 14.64 ± 5.18 (-29.70–0.40)	− 14.66 ± 5.54 (-29.70–0.40)	− 14.63 ± 4.85 (-24.10 - -1.90)	0.730
Heel strike (Left foot)°	− 12.90 ± 4.65 (-29.00 - -1.80)	− 12.67 ± 4.90 (-29.00 - -5)	− 13.14 ± 4.42 (-20.60 - -1.80)	0.288
Toe strike (right foot)°	− 8.61 ± 3.83 (-22.40 - -0.60)	− 8.78 ± 3.97 (-22.40 - -2.80)	− 8.44 ± 3.71 (-14.90 - -0.60)	0.956
Toe strike (left foot)°	− 7.79 ± 3.69 (-20.30–1.60)	− 7.43 ± 3.87 (-20.30–1.60)	− 8.15 ± 3.50 (-16.90 - -1.60)	0.136
Heel off (Right foot)°	-6.40 ± 3.37 (-17.90–0.50)	-6.37 ± 3.42 (-17.90 - -1)	-6.43 ± 3.36 (-13.60–0.50)	0.679
Heel off (Left foot)°	-6.59 ± 3.47 (-18.80–0.40)	-6.59 ± 3.47(-18.80 - -1.80)	-6.54 ± 3.49(-13.50–0.40)	0.741
Toe off (Right foot)°	-1.39 ± 6.43 (-13.30–29.00)	-0.87 ± 7.23 (-12.00–29.00)	-1.92 ± 5.54 (-13.30–9.00)	0.581
Toe off (Left foot)°	-5.20 ± 3.48 (-14.50–2.00)	-5.48 ± 3.49 (-10.70–2.00)	-4.93 ± 3.47 (-14.50–0.70)	0.230
Propulsion ratio (Right foot)%	11.76 ± 9.58 (-6.00–32.00)	12.36 ± 9.85 (-6.00–32.00)	11.16 ± 9.91 (-6.00–28.00)	0.760
Propulsión ratio (Left foot)%	11.76 ± 10.88 (-12.00–36.00)	10.48 ± 12.07 (-12.00–36.00)	13.04 ± 9.49 (-7.00–28.00)	0.197

Table 2. Main outcome measurements of kinematic analysis of total sample. *ms* meters per second, *SD* standard deviation. †Mann-Whitney U test was used.In all the analyses, $p < 0.05$ (with a 95% confidence interval) was considered statistically significant (bold).

loading. This finding contrasts with previous studies reporting higher BMI values primarily in individuals with flat feet, suggesting that cavus foot may be more related to intrinsic structural factors than to body mass[31]. The similarity in shoe sizes between the groups also suggests that differences in arch morphology are independent of foot dimensions.

The results of our research showed significant differences between both groups, in the taligrade phase in both the left and right feet, with a reduction in the duration of this phase observed. This indicates that heel contact in the case group occurs more quickly compared to a normal foot, which coincides with the stiffness and supination characteristic of the hindfoot in this deformity[14,16,25]. Biomechanically, hindfoot stiffness and supination limit the foot's ability to absorb impact through pronation. This reduction in functional pronation results in a more abrupt and quicker heel contact, shortening the taligrade phase and increasing lateral loading of the foot. This explains the higher incidence of lateral pain and the sensation of instability described in patients with cavus foot. The stiffness also limits initial dorsiflexion, affecting the gait cycle by reducing the support time during initial contact, requiring proximal dynamic compensations to maintain stability and walking efficiency. This could explain the higher incidence of lateral pain, generated by this structural rigidity and decreased pronatory capacity, which conditions the hindfoot varus situation, generating more pressure and therefore pain in the lateral area of the foot.

On the other hand, the instability presented by subjects with a cavus foot is also supported by our findings. The decreased duration of the taligrade phase reduces the time and area of support during initial contact, limiting postural stability. This aligns with studies showing that cavus feet have reduced plantar contact and altered center of pressure trajectories during gait, which can increase the risk of imbalance and falls[9,12,17,37]. Therefore, the kinematic patterns observed in our study provide objective evidence that cavus foot contributes to functional instability during walking. This difference in the taligrade phase is also justified by the study by Buldt et al.[20], who observed that the cavus foot limits dorsiflexion during the initial contact, which could explain the shorter

duration of the taligrade phase in our sample. These results coincide with the observations of Hillstrom et al.[3] where the rigid structure and the elevated arch limit pronation during the initial contact, which could explain why the flight phase was similar in a cavus foot as in a neutral foot. On the other hand, similar to the study by Buldt et al.[5,20], no differences were observed in the plantigrade phase. This leads us to believe that the pronation limitation in cavus foot reported by Buldt et al. may be compensated by other proximal structures (hip, knee), these compensations allow the foot to achieve normal plantigrade positioning despite hindfoot rigidity.

However, no significant differences were found in the other parameters analysed, which may indicate the presence of compensations at proximal joints and contralateral limbs, aimed at maintaining the most functional gait possible despite the foot deformity. These results are consistent with previous research[9] on mild/moderate cavus foot, which observed that despite altered plantar pressures, subjects maintained normal spatiotemporal parameters, which could be due to dynamic compensations. This may indicate that not only the presence of cavus foot determines the functional impact, but that it depends more on the severity of the deformity and individual compensatory capacity.

Although the forefoot in cavus foot presents kinematic alterations[20] our results did not find significant alterations in the toe-off angle, possibly due to differences in the severity of the deformity or individual compensations, to maintain push-off efficiency. This highlights the importance of assessing not only the hindfoot but also forefoot dynamics.

Our study has limitations. First, the sample should have been more balanced in terms of sex, with more women than men in this case. Therefore, the results obtained cannot be generalized. Therefore, in future studies it would be interesting to analyse the adaptations in the kinematics of the cavus foot that may occur specifically by sex, ensuring equitable representation to generalize conclusions. In our study, we did not take into account the severity of the cavus foot deformity. We included subjects with a positive Coleman test, that is, a flexible degree of the deformity. Therefore, in future studies it would be interesting to perform a subgroup analysis, studying the differences between etiologies or by severity, classifying subjects according to radiological criteria to analyse more subtle differences. Furthermore, musculoskeletal biomechanical data, such as electromyography, which would be useful for analysing muscle activity during gait phases, were not analysed. This makes it difficult to draw conclusions about the effects of cavus foot on gait parameters. Another limitation concerns the 6-meter walking distance used for gait assessment. Although this distance was chosen for practical and space reasons, it may not fully capture a steady-state gait pattern. Previous studies analysing gait parameters with pressure walkways or inertial systems have used both shorter distances and longer distances, most commonly around 10 m[38–40]. Therefore, while 6 m is within a practical and validated range, future studies could benefit from using longer walking paths to ensure stable gait cycles and minimize acceleration and deceleration effects.

However, this research provides useful information for clinical practice when implementing and personalizing orthotic treatment for this type of patient, with the goal of improving instability and initial contact, as well as recommending exercises to mitigate the excessive supination characteristic of this type of foot. Furthermore, this study highlights the importance for further research to better understand the biomechanical and neuromuscular mechanisms underlying cavus foot. Specifically, future studies should include electromyography to analyse muscle activation patterns, use larger and more balanced samples to explore sex differences, and employ longer walking distances to capture steady-state gait. Such investigations would provide more detailed insights into compensatory strategies, gait adaptations, and clinical management, ultimately informing more targeted interventions and improving patient outcomes.

Conclusion

The results of this study show changes in the kinematic gait analysis between subjects with cavus foot and individuals with normal foot, specifically a shorter duration of the taligrade phase of gait in the cavus foot compared to the normal foot. This indicates that heel contact in the cavus foot occurs more quickly, which coincides with the stiffness and supination characteristic of the hindfoot in this deformity. However, as only this parameter showed a significant difference, it suggests that kinematic alterations in cavus foot may be subtle and potentially compensated by dynamic mechanisms.

Data availability

The dataset supporting the conclusions of this article is available in the daniellopez@udc.es in the Research, Health and Podiatry Group. Department of Health Sciences. Faculty of Nursing and Podiatry. Universidade da Coruña, Industrial Campus of Ferrol. Spain.

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Declarations

Competing interests
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