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Design and implementation of a pneumatic machine for ergonomic greenhouse planting

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ABSTRACT

The continuous development of greenhouse agriculture requires technological innovations to optimize labour-intensive tasks such as crop planting. In Almeria, Spain, greenhouse planting is traditionally performed manually using an iron lance, a process that imposes a high biomechanical load and often leads to musculoskeletal disorders among agricultural workers. This study presents the design, development, and validation of a pneumatic system attachable to a conventional agricultural cart, designed to facilitate hole opening in the soil for planting. The system operates using compressed air to drive a pneumatic actuator that perforates the soil with dimensions suitable for plant root balls. Experimental validation results demonstrate that the system tool operates with optimal depth characteristics and high precision. The biomechanical analysis shows a significant reduction in the effort required by workers—exceeding 50 %—as well as improved stability in the applied force, leading to a more even distribution of exertion. This minimizes biomechanical impact, reduces the risk of musculoskeletal injuries, and enhances productivity. The designed system is efficient and represents a significant ergonomic advancement in agriculture, providing an accessible and cost-effective solution to improve working conditions and reduce health risks in the agricultural sector.

1. Introduction

Greenhouse-intensive agriculture is expanding rapidly worldwide. Southeastern Spain, particularly the province of Almeria, leads the production of horticultural crops using greenhouse systems [1,2]. Greenhouses in Almeria cover 33,402 hectares, representing 86 % of the total greenhouse area in Andalusia [3]. The high profitability achieved through this production system is mainly due to the implementation of highly efficient technologies at all cultivation stages, such as drip irrigation systems, climate control, integrated pest management, and automation. The primary greenhouse crops in southeastern Spain, based on production volume, include peppers, tomatoes, cucumbers, zucchini, watermelon, and eggplant [3], all of which require the introduction of root balls during planting.

In most greenhouses in Almeria, the process begins with the transplantation of seedlings from professional nurseries, which specialize in producing high-quality plants with guaranteed vegetative and sanitary standards. These nurseries use advanced seeders capable of performing multiple sowing operations simultaneously, achieving high efficiency [4,5]. Transplanting of the seedlings into the seedling trays which are then taken to the production site uses transplanting machines with various levels of technology from manual to fully automated [6]. However, when planting takes place inside the greenhouse, it is done manually after soil preparation, making it one of the most labour-intensive processes [7]. Due to the configuration of the greenhouse interior where the aisles between crop rows are narrow and the precise location of the planting site due to the drippers, commercial automatic transplanting machines used in outdoor cultivation cannot be used. Furthermore, robots have multiple degrees of freedom to perform movements, making them complex systems that require a high initial investment [8].

Greenhouse crop planting is a simple but crucial process to ensure proper plant development (Fig. 1) [9]. First, the soil is prepared by applying irrigation before planting. Then, a hole is made using an iron

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Fig. 1. Planting process. (a) Hole preparation, (b) Inserting the plant and compacting the soil to secure it.

lance. This hole must be deep and wide enough to accommodate the plant's root ball, ensuring the roots have enough space to grow and develop. The root ball containing the plant is carefully inserted, ensuring that the plant remains upright and at the correct depth to facilitate rooting. Finally, the surrounding soil is compacted around the plant to secure it properly, preventing tilting or exposure to damage while enhancing water and nutrient absorption [10].

Soil management is a critical factor for optimal greenhouse crop development. The use of sand-covered soil in southeastern Spanish horticultural production has significantly contributed to its technical, social, and economic advancement in recent decades. Today, 83 % of greenhouses in Almeria use sand-covered soil, surpassing alternative techniques such as substrate and hydroponic cultivation (rock wool, perlite, coconut fibre) at 7 %, and natural soil at 10 % [11]. Fig. 2 illustrates the configuration of sand-covered soil with two different compositions, representing the typical sand-covered soil and the most common variation of Almeria region.

The task of digging holes using a lance or similar tool imposes a significant biomechanical burden on the musculoskeletal system due to the repetitive impact against the soil, the hardness of the terrain, and the tool's weight [12,13]. Each impact against the surface transmits force to the hands, wrists, and forearms [14,15], potentially leading to repetitive microtraumas that can result in conditions such as tendinitis or carpal tunnel syndrome due to sustained pressure on the wrist [16]. Additionally, the weight of the lance increases strain on the shoulder and back, promoting muscle fatigue, contractures, and even shoulder tears [17]. The constant effort required to lift and maneuver the tool also affects the lower back, increasing the risk of lower back pain due to intervertebral disc overload and paravertebral muscle strain. In the long term, continuous exposure to these conditions without adequate preventive measures—such as ergonomic tool designs, efficient work techniques, and active rest breaks—can lead to chronic musculoskeletal disorders that compromise agricultural workers' functionality and quality of life.

The integration of robots or robotic arms for agricultural tasks [18] such as automatic seedling, tutoring, phytosanitary treatments, or fruit harvesting [19–22] is an active research area. However, for robots and automation to benefit farmers, their adoption must be economically viable at a commercial level, as current implementations require high investment costs [23–30]. Additionally, farmers need to be educated to overcome technical and cultural resistance to using robots [31,32]. Until then, technological advances that are easy to use, improve productivity, and enhance worker safety at minimal cost should be incorporated. This motivation underpins the design of the tool developed in this study.

The objective of this article is the design, implementation, and experimental validation of a pneumatic attachment that can be installed on a conventional agricultural cart to facilitate the creation of planting holes for greenhouse crops with root balls. This innovative design reduces labour time, production costs, and the risk of musculoskeletal problems by improving worker ergonomics. As part of the system validation, a comparative analysis is conducted on efficiency, economic feasibility, and safety relative to the current planting method. The manuscript continues in the next section with the system design and modelling of the tool. Additionally, the experimental validation method and a biomechanical evaluation using the Rapid Upper Limb Assessment (RULA) method are described. The results and discussion section presents the system's real-world implementation, followed by its validation and comparative analysis against the traditional method, confirming its proposed advantages Finally, the study's key conclusions are outlined.

2. Materials and methods

2.1. System design

According to the agronomic requirements of greenhouse vegetable planting and soil characteristics, the machine's needs were determined, based on a pneumatic actuator based pneumatic system (Fig. 3).

The pneumatic system design includes a Filter (1) to clean atmospheric air, followed by a Compressor (2), which compresses the air, increasing pressure and storing it in an air storage Tank (3). At the tank outlet, a Filter (4), Pressure controller (5), Manometer (6), and Lubricator (7) regulate the compressed air to the required pressure for the pneumatic actuator. To control airflow into the pneumatic actuator and adjust the pneumatic actuator's striking force, Valve (8) and a Pressure controller (10) are installed. A two-position 2/3 valve (9) is used to activate the pneumatic actuator's extension and retraction. During its

Fig. 2. Characteristic greenhouse soil types. (a) Typical sand-covered soil, (b) Sand-covered soil natural of Almeria.

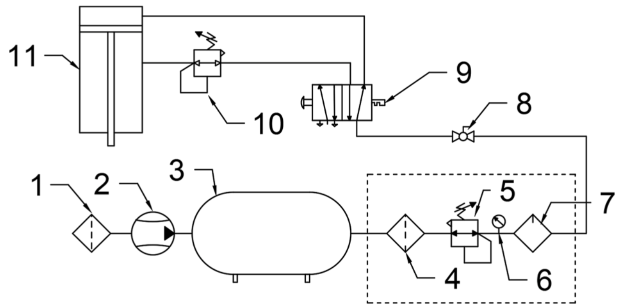

Fig. 3. Pneumatic system diagram: Filter (1), Compressor (2), Tank (3), Filter (4), Pressure controller (5), Manometer (6), Lubricator (7), Valve (8), Valve 2/3 (9), Pressure controller (10), Pneumatic actuator (11).

forward motion, the pneumatic actuator impacts the soil, creating the necessary hole for planting the crop's root ball.

The structural design of this attachment (Fig. 4) was created for easy installation onto manual agricultural carts. It is secured using four bolts and four nuts, allowing farmers to mount it on their cart easily during the planting season. The pneumatic attachment operates by releasing a powerful jet of pressurized air, pushing a cylinder with a tool at its tip shaped to match the plant's root ball, thereby creating a hole in the soil with the correct dimensions for planting.

The machine has been designed to facilitate the drilling of holes in sandy soil, optimizing the plant transplanting process. This system is simple to use, requiring no specialized training for farmers (Fig. 5). The farmer manually moves the cart along the aisle, parallel to the crop row. The system remains idle until the desired transplant hole is reached (Step 1). Once in the desired position, the farmer manually actuates the actuation valve. This action allows compressed air to enter the pneumatic actuator, causing the punch to move downward. It impacts the ground, generating a percussion that initiates the hole formation (Step 2). The farmer then presses the actuation valve again. This second impulse allows the pneumatic actuator to return to its initial position. When the punch is removed from the ground, the planting hole is fully formed, with the appropriate dimensions to accommodate the plant (Step 3). Finally, the farmer moves the cart to the next drilling point, repeating the process at each new transplant position along the crop row (Step 4).

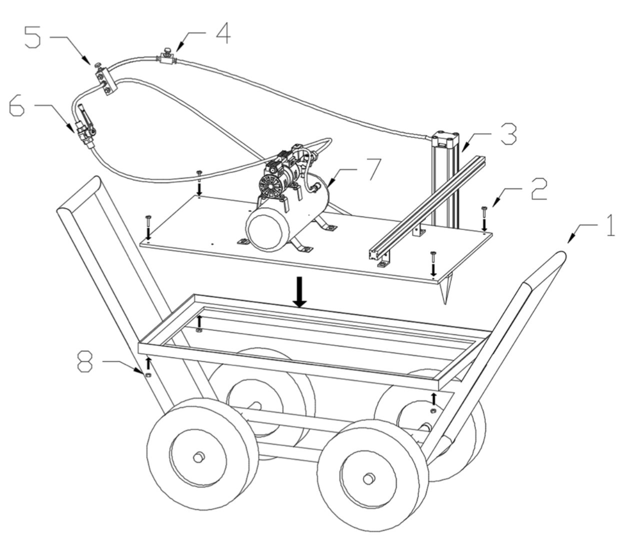

Fig. 4. Planting system design: Agricultural cart (1), Bolts (2), Pneumatic actuator (3), Pressure regulator (4), Actuation valve (5), Ball valve (6), Compressor (7), Nut (8).

2.2. Soil study and farmer requirements

To determine the specific mechanical requirements of the designed tool for hole creation and to enhance worker ergonomics, firstly a study was conducted analysing the two main soil types found in Almeria's greenhouses [33]. Measurements of soil hardness were taken under planting conditions, ensuring the soil was at 100 % moisture to facilitate hole creation for planting (Fig. 6).

Once the cultivation area was confirmed to be in optimal conditions for planting holes, soil hardness measurements were taken using a durometer at different depth levels. The profiles obtained for both soil types are shown in Fig. 7.

The soil profile results show that the sand-covered soil naturally found in Almería has a hard profile with an average strength of 2.1 MPa due to the presence of stones and other impurities in the sand. The typical sand-covered soil has a soft profile with an average hardness of 1.3 MPa. In both types of soil, some areas contain stones, where soil hardness values ranging from 3.2 to 6.6 MPa have been recorded.

2.3. System characterization and validation method

For the experimental validation of the design, a series of test are proposed:

- Test 1: Characterization of the relation between the drilling force applied by the pneumatic actuator and the depth of the planting hole. The objective of this test is to demonstrate the operational efficiency of the tool.
- Test 2: Characterization of the precision of the depth of the planting holes made. The objective of the test is to demonstrate the efficiency of the tool.
- Test 3: Comparative characterization of the efforts made by the farmer during the handling of both tools. In the designed system, the translation effort of the tool is evaluated. In the traditional tool, the drilling effort made by the farmer is evaluated. The objective is to quantitatively compare the possible reduction of the farmer's effort with the designed tool. In addition, a statistical study will be conducted using IBM SPSS Statistics 29.0.2 software. This study analyzes whether there are significant differences between the efforts made by farmers according to the method used. To do this, the Kolmogorov-Smirnova Normality Test and the nonparametric Mann-Whitney U test for independent samples are performed, both with a 95 % confidence level.

2.4. Biomechanical evaluation

The Rapid Upper Limb Assessment (RULA) method is an ergonomic assessment tool designed to identify risks for musculoskeletal disorders (MSDs) in the neck, trunk, and upper extremities during work tasks. This method classifies extremities into two groups: Group A (arm, forearm, and wrist) and Group B (neck, trunk, and legs). The action level is determined by analyzing limb angles, as well as the movements and efforts made by workers.

The postures involved in digging the planting hole were identified by an evaluator trained in occupational risk prevention. According to the authors of the method, postures held for the longest periods of time or with the greatest postural load are visually identified [34]. Therefore, the most repeated postures and those reported by the farmer as most uncomfortable were selected.

To develop the RULA method, images were taken parallel to the farmer's plane of action so that the angles could be measured in their true magnitude. Images were taken from the right side of the worker with the camera. The camera used has a 12-megapixel wide-angle lens with f/1.6 aperture, a 26-mm lens, and sensor-shift optical image stabilization (OIS), as well as a 12-megapixel wide-angle lens with f/2.4 aperture, a 13-mm lens, and a 120° field of view.

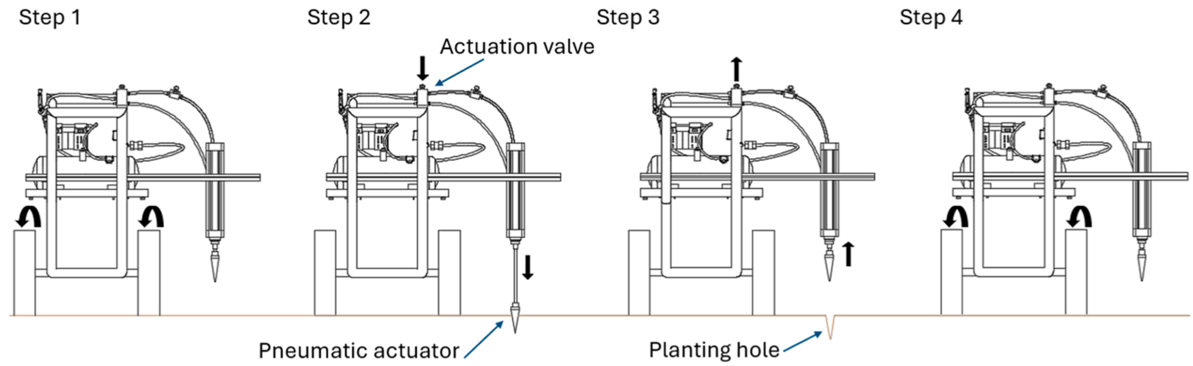

Fig. 5. Operation of the pneumatic system for making the planting hole. Step 1 Moving to the drilling point; Step 2: Activate the pneumatic actuator; Step 3: Return the pneumatic actuator; Step 4: Reposition for next hole.

Fig. 6. Soil condition data collection. (a) Sand-covered soil natural of Almeria, (b) Typical sand-covered soil, (c) Durometer.

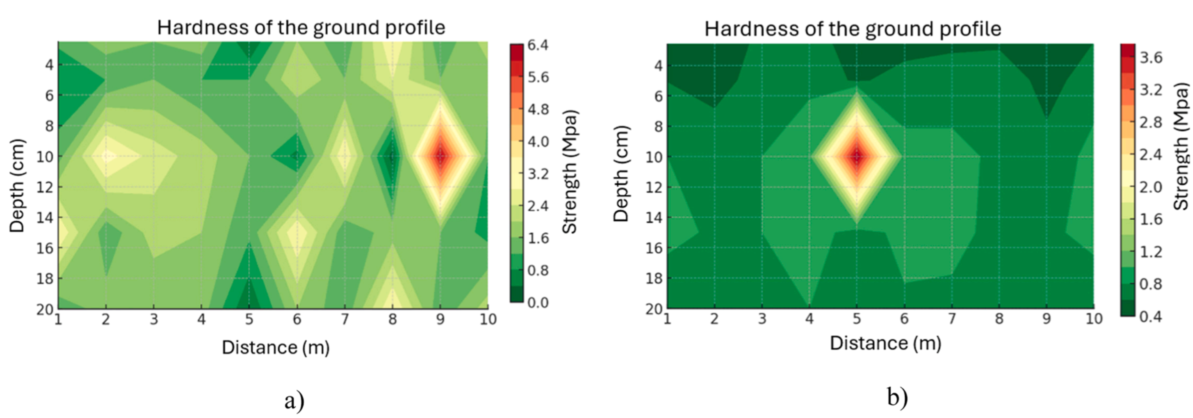

Fig. 7. Soil hardness profiles (a) Sand-covered soil natural of Almeria, (b) Typical sand-covered soil.

The posture assessment was performed using AutoCAD version 2025 to measure the angles of the different body parts. The data obtained were compared with the RULA method tables [35], obtaining a score for group A and another for group B. These scores were corrected according to the repetitiveness of the activity and the weight handled, obtaining scores C and D. From scores C and D, a final score was obtained indicating the risk level. There are four risk levels:

- Level 1 (score 1–2): Acceptable risk.
- Level 2 (score 3–4): Risk may be acceptable; it is necessary to further study.
- Level 3 (score 5–6): Task redesign is required.
- Level 4 (score 7): Urgent changes to the task are required.

3. Results and discussion

The system designed in this study was implemented (Fig. 8) according to prior specifications and dimensions.

The main technical parameters of the system are summarized in Table 1, including dimensions, weight and operating range.

Fig. 8. Implementation of the designed system.

Table 1
Main technical parameters of the system.

Parameters	Values
Dimensions	1200 × 460 × 900 mm
Weight	16 kg
Operating range	5–15.7MPa

Once implemented, the system underwent field validation, where planting holes were made in greenhouse crop rows. A force sensor (Fig. 9a) was installed to measure the impact forces of the pneumatic actuator creating the holes. The installed force sensor has a sensitivity of ±1 Newton and a measuring range of 0 to 3000 N (Fig. 9b). A PhidgetBridge amplifier is installed between the computer and the sensor. This is an interface designed specifically for load cells. This interface improves the load cell signal and delivers a clear and stable digital value. Additionally, hole depth measurements (Fig. 9c) were taken to ensure that the system was capable of producing adequate planting holes.

Firstly, Test 1 validates the performance of the mechanism, planting holes were made along a row in the greenhouse. The data to evaluate the machine are the force of the pneumatic actuator recorded by the force sensor and the depth reached in each hole. The results of the experimental validation are presented in Fig. 10, which shows the relationship between the force of the pneumatic actuator and the depth of the hole. To reduce noise in the force sensor, a band-pass filter was applied in Fig. 10 to improve the representation of the effort generated by the pneumatic actuator. The band-pass filtering process of the data was performed using MATLAB (version R2023a). A total of 26 holes were made in 215 s. Given the automated nature of the mechanism, this could lead into further time reducing, with advantages compared to the traditional method.

Following field testing, in Test 2 the system's accuracy was analysed (Fig. 11). The optimal hole depth was determined to be 8 cm, allowing a variation of ±1 cm without affecting crop development. The error is obtained by dividing the difference between the actual measurement and the optimal measurement of the hole in absolute value divided by the optimal measurement. A 1 cm variation corresponds to a precision error of 12.5 %, with a maximum recorded error of 11.5 %. A larger error in the hole's depth can cause problems in the plant's development. When the hole is too deep, there is a risk that the grafted area will be buried, hindering rooting and proper plant adaptation. On the other hand, when the hole is too shallow, the root ball will not be inserted properly, preventing the sand from compacting properly around the plant, which compromises its grip in the future.

The main limitation of this study's experimental validation is the fact that it considered two soil types representative of the standards found in the Almería region. However, the proposed design was designed with scalability criteria that allow it to be adapted to other soil situations.

Next, in Test 3, measurements were taken of the forces applied by the farmer using both the designed tool and the traditional iron lance. Force sensor was mounted on the cart structure (Fig. 12a) and the traditional lance (Fig. 12b) to measure the effort required during planting. The installed force sensor has a sensitivity of ±0,5 N and a measuring range of 0 to 1000 N (Fig. 12c). An amplifier is installed to obtain a clear and precise signal that is connected to a PicoScope2204A oscilloscope. And the oscilloscope is connected to the computer through which the data processing is done.

The analysis of the force-time graph (Fig. 13) reveals the magnitude and periodicity of biomechanical effort exerted by a farmer using an iron lance. Peak forces reaching 500 N appear at regular intervals, indicating repetitive impact against the soil. Between impacts, force values drop to approximately 15 N, representing the weight of the tool. This cyclical

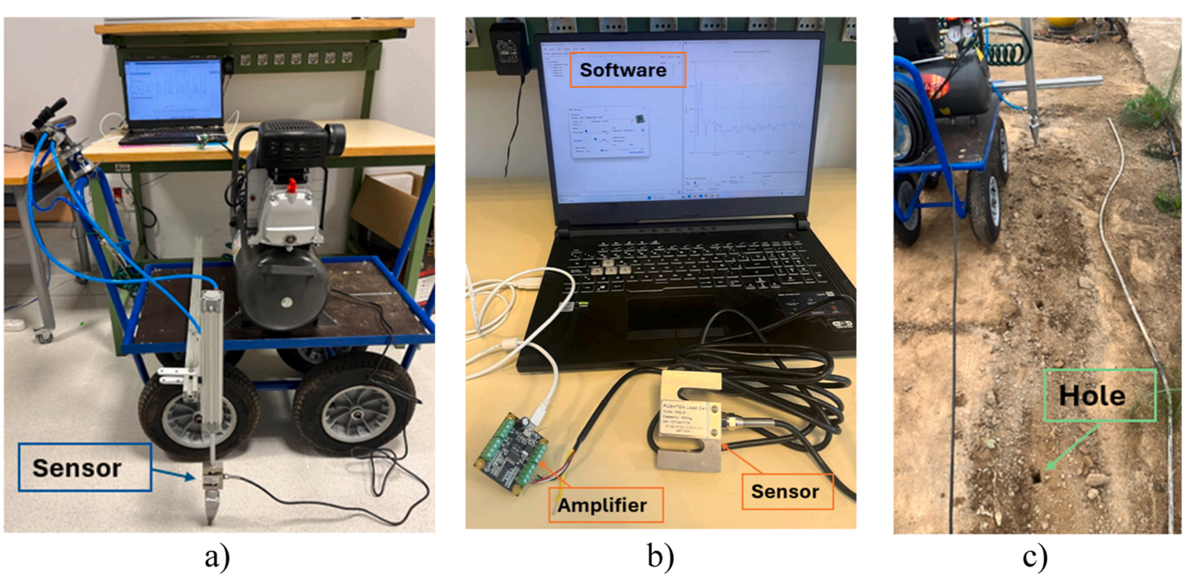

Fig. 9. Validation and characterization system for the implemented system. (a) Force Sensor, (b) Measuring equipment, (c) Planting holes.

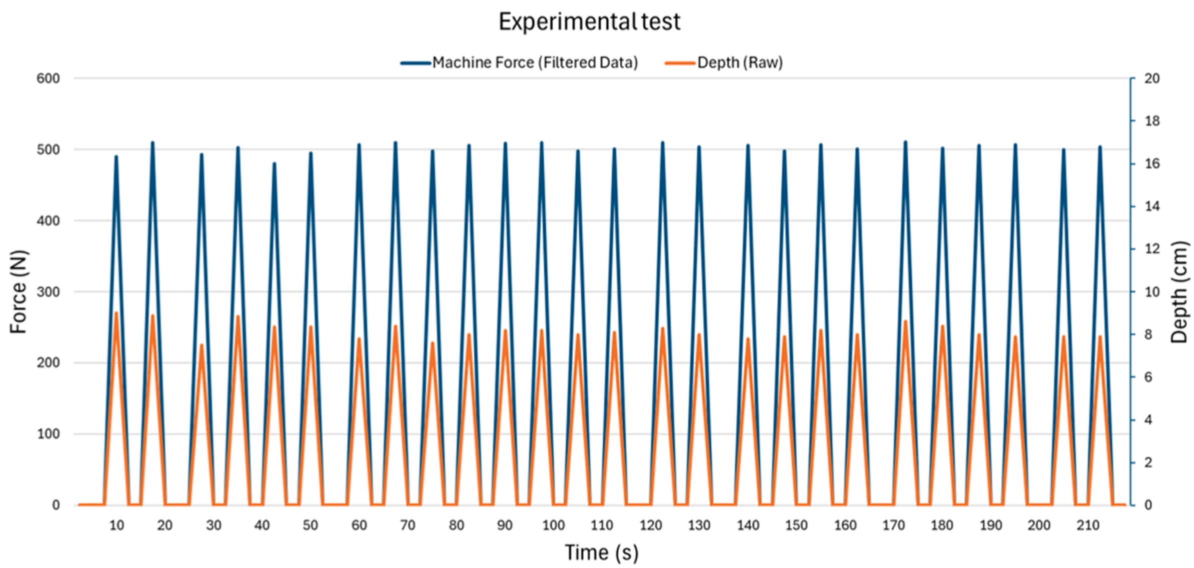

Fig. 10. Experimental validation of the pneumatic system.

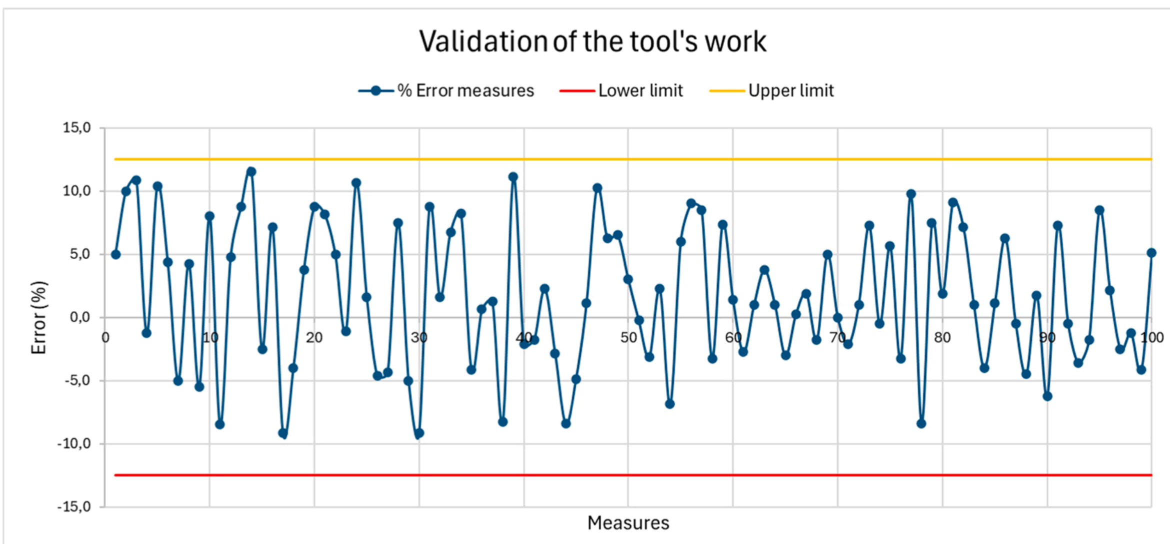

Fig. 11. Experimental validation of system precision, checking the error obtained in the planting hole depth.

pattern suggests a constant work rhythm, imposing high intermittent mechanical loads on the upper limbs and lower back. The force transmission through the hands, wrists, and spine may lead to cumulative microtraumas, increasing the risk of musculoskeletal injuries such as tendinitis, epicondylitis, and lower back pain. By contrast, using the designed system, force peaks were significantly reduced to below 200 N. Moreover, force application was more stable, showing a smoother, continuous pattern that suggests a more uniform distribution of effort and a reduction in biomechanical impact. This improved distribution decreases exposure to repetitive microtraumas and reduces the risk of musculoskeletal disorders, ultimately improving worker efficiency, safety, and productivity.

The results of the statistical analyses performed show that the data do not follow normality according to the Kolmogorov-Smirnova normality test because its significance is <0.05. Since the data do not present normality, non-parametric statistics must be applied. In the non-parametric Mann-Whitney U test for independent samples, a significance level (p) <0.01 was obtained. This significance value is <0.05, therefore, there are significant differences in the effort made by the farmer between the traditional method and the method proposed with the pneumatic system (Fig. 14). From this method it is concluded that there is a greater effort on the part of the farmer when the traditional system is applied, given the experimental results analyzed.

The RULA method is used to assess the postural load to which the worker is subjected during the task of digging the planting hole. The results obtained allow the identification of the ergonomic risk levels associated with both procedures: the traditional method and the method proposed using the pneumatic machine. Fig. 15 presents the images captured by the evaluator, used to analyze the angles formed by the different parts of the body with respect to the references established by the RULA method. Fig. 15a shows the measurements taken of the worker performing the task using the traditional method, while Fig. 15b shows the measurements corresponding to the worker using the method assisted by the designed machine.

Table 2 presents the angles measured for each posture analyzed using the RULA method, as well as the scores obtained in the different evaluation stages (sections C and D) and their corresponding risk level. In the case of the traditional method, a high score is observed in section C,

Fig. 12. Installation of force measurement sensors. (a) Traditional tool, (b) Designed system (c) Measuring equipment.

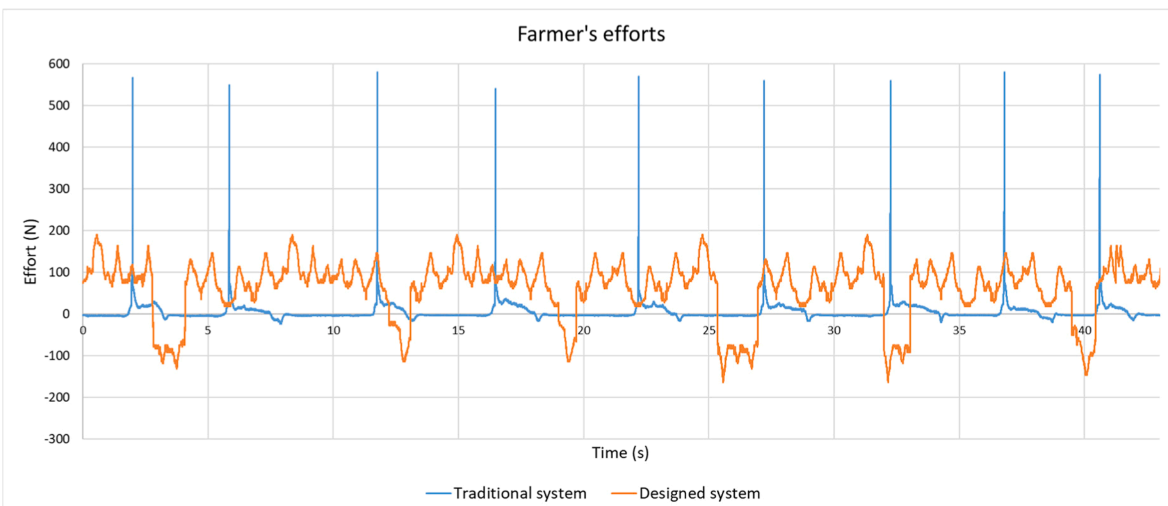

Fig. 13. Comparative validation of the designed system, showing the efforts required by the farmer according to each method.

above 7, as well as a score above 7 in section D, which leads to a final score of 7. This value is associated with a high risk level, so urgent changes in the performance of the task are required. In contrast, the proposed method, which incorporates the pneumatic system, presents scores of 4 in section C and 3 in section D, obtaining a total score of 3. This result corresponds to a risk level of 2, considered acceptable, although a more detailed analysis is recommended to confirm its long-term ergonomic viability. Therefore, this study demonstrates that the proposed method, based on the use of a pneumatic machine, is more ergonomically beneficial, as it significantly reduces the risk of musculoskeletal disorders in farmers.

From the results obtained in the different analyses, Table 3 shows how in the traditional method, the farmer makes efforts of up to 587 N, higher than the 189 N recorded during the use of the pneumatic system by the farmer. Furthermore, it has been shown that, once the pressure of the pneumatic system is regulated, it offers greater precision and regularity in the preparation of the planting holes, presenting a lower error and reduced variance. These results are due to the fact that the farmer cannot maintain a constant effort during a high number of repetitions, such as those required in greenhouse planting activity. Furthermore, the analysis of the risk of musculoskeletal disorders using the RULA method indicates that the pneumatic system presents a risk level 3, which implies a less dangerous situation compared to the traditional method, which presents a risk level 7.

In ergonomic terms, the difference between the two methods is substantial and has been corroborated theoretically and experimentally. Using the sensor values, Fig. 13 shows the effort required by the operator during the task with both systems. It has been found that the traditional method requires approximately 67 % greater effort than the pneumatic system. This difference directly impacts the stress on the main muscle groups and joints involved, especially in the lumbar region, shoulders, and wrists. Postural analysis using the RULA method confirms this improvement, showing a reduction in risk level from 7 to 3 when using the pneumatic system. This reduction implies a lower sustained biomechanical load, a more neutral posture, and a significant reduction in the risk of developing musculoskeletal disorders associated with repetitive greenhouse work.

4. Conclusions

The functional validation of the designed tool under field conditions demonstrates its ability to efficiently perforate the soil in greenhouse crop rows, achieving an optimal hole depth of 8 cm while allowing a maximum variation of ±1 cm without negatively affecting crop

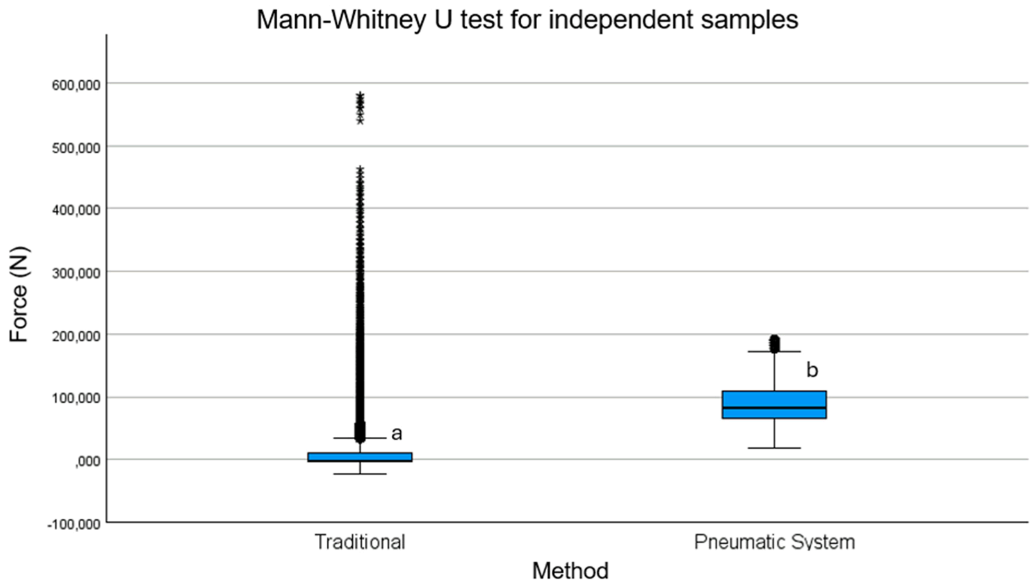

Fig. 14. Result of the farmer's force according to the method used. Different letters indicate significant differences ($p < 0.05$; Mann-Whitney U test for simple independent variables).

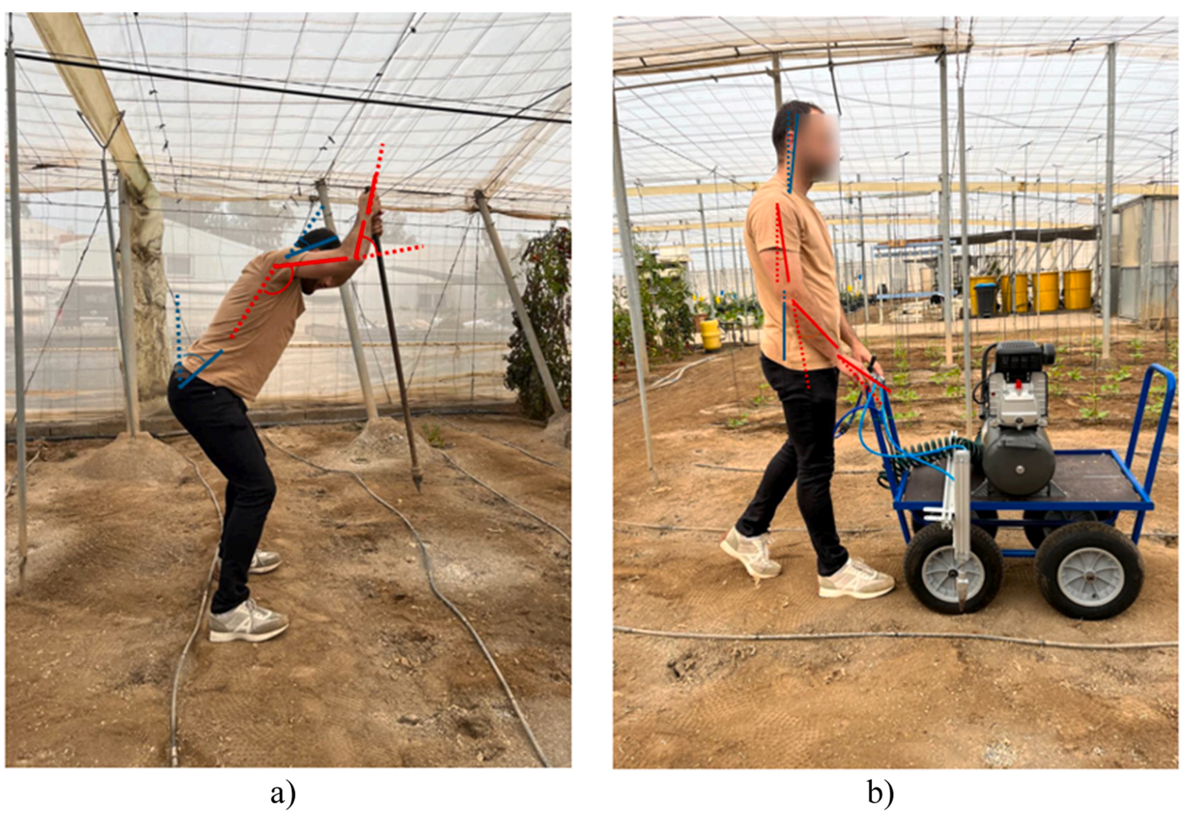

Fig. 15. Analysis of the RULA method, study of postural loading in both methods. a) Traditional method. b) Pneumatic system.

Table 2
Results of RULA method.

Evaluated method	Angles					Scores				
	Arm	Forearm	Wrist	Neck	Truck	A	B	C	D	Risk level
Traditional	>90°	55°	0°	29°	48°	5	4	>7	>7	7
Pneumatic system	16°	36°	9°	3°	0°	2	1	4	3	3

Table 3
Comparative table of the analyses performed.

	Traditional method	Pneumatic system
Maximum effort made by the farmer (N)	587	189
Maximum error recorded (%)	27.5	11.5
Variance	58.6	30.8
Risk Level Rula method	7	3

development. The experimental results indicate a maximum error of 11.5 %, confirming an acceptable level of precision for the planting process. As a limitation of the study, the experimental validation considered two representative soil types in the Almería region. However, the proposed system was designed with scalability criteria in mind, adapting the power required in the compressor and pneumatic actuator, allowing its use in other soil types. From a biomechanical perspective, a comparative analysis between the traditional iron lance and the newly developed system reveals a significant reduction in the magnitude of forces applied by the worker. The peak forces required for hole creation decreased from 500 N to 200 N, demonstrating a substantial reduction in the physical effort needed for planting tasks. Additionally, the force application became more stable, avoiding abrupt variations and ensuring a more uniform distribution of exertion. This improvement minimizes the biomechanical impact on the upper limbs and lumbar region, significantly reducing muscle strain and fatigue. The results of the RULA method also indicate a notable decrease in exposure to repetitive microtraumas, lowering the risk of developing musculoskeletal disorders such as tendinitis, epicondylitis, and lower back pain. By alleviating the physical burden associated with manual planting, this system contributes to the prevention of occupational injuries in the agricultural sector. Overall, the validated tool proves to be an efficient, ergonomic advancement, offering a practical and cost-effective solution to improve working conditions in greenhouse agriculture. Its implementation enhances worker safety and productivity, making it a valuable innovation for reducing the physical strain and health risks associated with manual planting processes.

Ethics Statement

Not applicable: This manuscript does not include human or animal research

CRediT authorship contribution statement

Antonio García-Chica: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rosa María Chica:** Visualization, Validation, Resources, Investigation, Funding acquisition, Conceptualization. **Julio J. Caparros-Mancera:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Antonio Gimenez:** Validation, Supervision, Software, Resources, Project administration, Funding acquisition. **J.L. Torres-Moreno:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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