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ORIGINAL

Design, Construction and Testing of a Prototype of Transradial Hand Prosthesis with Two Degrees of Freedom Cable-Controlled and Voice-Activated

Diseño, Construcción y Pruebas de un Prototipo de Prótesis de Mano Transradial de Dos Grados de Libertad Controlado por Cables y Activado por Voz

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ABSTRACT

This study focuses on the design, construction, and testing of a transradial hand prosthesis with two degrees of freedom, controlled by cables and activated by voice, aimed at improving the daily task performance of individuals with motor disabilities. A descriptive study with a quantitative approach was conducted, utilizing anthropometric measurements of hands taken from students at the Escuela Superior Politécnica de Chimborazo. The resulting prototype features a cable-actuated mechanism, with individual mechanical fingers, and is made from polylactic acid (PLA). The primary function of the prosthesis is the opening and closing motion of the fingers. Through direct and inverse kinematic analysis, the position of each finger was determined, and their respective velocities and accelerations were calculated. The maximum speed achieved by the thumb was 0,057 mm/s, while the other fingers reached a speed of 0,62 mm/s. The thumb's acceleration was 1,179 mm/s^2, while the other fingers had an acceleration of 0,35 mm/s^2. In practical tests with various objects, the prosthesis was able to lift a maximum weight of 220 grams, with the ideal weight for optimal performance ranging between 100 and 120 grams.

Keywords: Elastomer; Rope Mechanism; Transradial Prosthesis; Stylized Prototype.

RESUMEN

Las prótesis diseñadas para recuperar la funcionalidad parcial de una extremidad han sido clave en el avance de la medicina, destacándose los mecanismos antropomórficos que, además de resolver el problema estético, mejoraron la funcionalidad mediante nuevas taxonomías de agarre. El objetivo de esta investigación fue desarrollar un prototipo de prótesis de mano transradial de dos grados de libertad, controlada por cables y activada por voz, para mejorar la interacción en tareas cotidianas de personas con discapacidad motora. La metodología utilizada fue un estudio descriptivo con muestreo poblacional y enfoque cuantitativo, tomando medidas antropométricas de manos de estudiantes de la Escuela Superior Politécnica de Chimborazo. El prototipo resultante fue una prótesis accionada por cuerdas, con dedos individuales de accionamiento mecánico, fabricada en ácido poliláctico (PLA), cuyo objetivo principal era realizar el movimiento de apertura y cierre de los dedos. Mediante análisis cinemático directo e inverso, se determinó la posición de cada dedo y se calcularon las velocidades y aceleraciones, encontrando que el pulgar alcanzó una velocidad máxima de 0,057 mm/s, mientras que los otros dedos llegaron a 0,62 mm/s. La aceleración del pulgar fue de 1,179 mm/s^2, y la de los otros dedos de 0,35 mm/s^2. En las pruebas con objetos, se logró levantar un peso máximo de 220 gramos, con un peso ideal para su correcto funcionamiento entre 100 y 120 gramos.

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Palabras clave: Elastómero; Mecanismo de Cuerdas; Prótesis Transradial; Prototipo Estilizado.

INTRODUCTION

The models or prostheses created to restore the performance of a single limb partially have symbolized a requirement that has single limb has symbolized a requirement that has promoted significant progress in the evolution of anthropomorphic mechanisms. These have resolved the aesthetic aspect and expanded the taxonomies of gripping, significantly improving their functionality.(1) Currently, research and development in this field are focused on achieving two fundamental properties: optimizing their usefulness for lifting loads or performing power grips and ensuring their accessibility in terms of cost.

In October 2010, in Taiwan, Takashi Sonoda and Ivan Godler created a robotic hand powered by a chain drive system to move their fingers, performing a cylindrical and pincer grip.(2) One of the oldest and most frequently employed methods in the field of prosthetics to achieve flexion-extension movement in the fingers is achieved through cables and pulleys. In most situations, the pulleys are located at the joints. A cable flows through them, one end of which is fixed to a phalanx, usually, the last (distal) phalanx, while the other end of the cable is linked to the output of the actuation system or, if not, to the reduction system. When a load is applied from the actuation system to the cable, the cable slides through the pulley and moves the phalanx and, consequently, the finger joint.(3)

Mark R. Cutkosky, a professor at Stanford University, conducted a study on the various taxonomies of grasping function based on tasks performed in the manufacturing environment, as well as the constraints and simplifications carried out in the design of robotic hands.(4)

In cases where the grasping is exact, the importance of the force exerted is reduced, and more skill is discussed. The precision grip consists mainly of fingertip contact, requiring primarily wrist movement.(4) Power gripping is distinguished from power gripping.

The power grip is distinguished by a mode of gripping that values security and stability, employing a larger contact surface, particularly at the phalanges of the fingers, to ensure more solid control over larger or heavier objects. This anchorage involves the fingers, palm, and thumb, distributing the pressure effectively and enhancing the gripping force. It is perfect for large objects that demand precise and solid handling, such as tools or weights, where stability and slip prevention are essential to prevent undesirable movements.(4)

METHOD

Anthropometry of the hand

Studying the proportions and dimensions of the human hand is essential to understanding morphological variations within the human species. To obtain accurate measurements, the length of the hand should be taken from the base of the wrist to the tip of the middle finger, considering that this measurement corresponds to the total length of the hand. In addition, other measurements, such as the width of the palm, which is determined from the edge of the palm at the base of the fingers to the opposite side of the hand, must be taken into account. The measurement of individual fingers, such as the length of the middle finger and thumb, is also relevant for the analysis of the relationship between the different segments of the hand.(5) To carry out the most authentic and appropriate design for the population of Ecuador, the students of the Higher Polytechnic School of Chimborazo were studied as a sample, from which the following data were obtained:

Figure 1. Taking anthropometric hand measurements

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The measurement is made to a random person from the Higher Polytechnic School of Chimborazo, the age ranges are from 21 years old and the measurements were taken from a man, where the following values are given as a result.

Table 1. Anthropometric hand measurements

Parameters	Reported values
Hand length	194,61 mm
Palm length	105,41 mm
Hand width without thumb	96,65 mm
Hand width with thumb	105,72 mm

Table 2. Finger measurements

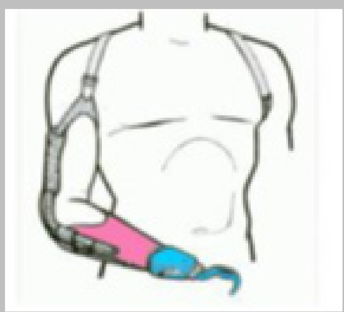
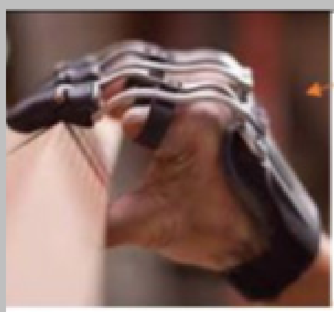
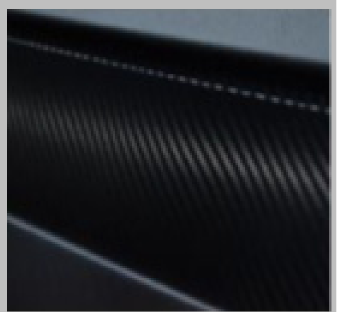
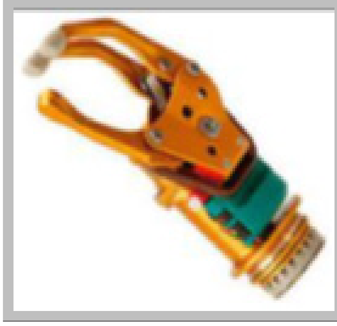
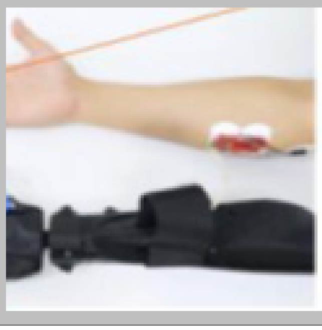
	Phalange lengths mm		
	Proximal Phalanx	Medial Phalanx	Distal Phalanx
	42±10	26±5	27±3
Little finger	56±11	32±6	27±3
Ring	60±13	35±8	28±2
Middle	56±11	34±7	28±3
Index	45±6	NA	38±4

This type of data is crucial in the design of prostheses, ergonomic tools, and biomedical devices, as it provides accurate parameters for adapting artificial structures to the average dimensions of the human hand. The information can be used to improve the functionality and comfort of prostheses and exoskeletons, ensuring that the design respects the natural proportions of the hand.

Prosthesis specifications

For the prosthesis to be considered as a prototype that can meet the client's needs, an analysis of alternatives was carried out using a morphological matrix as shown in the following table:

Table 3. Analysis of alternatives

Models	Type	Drive	Materials
1	Hook	Support	Synthetic fibres
			
2	Clamp	Prensil	nylon
			

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3	Transradial	Pulley drive	PLA o TPU
			

The result was a mechanically operated, string-driven prosthesis with individual fingers made of polylactic acid (PLA) material.

Functional analysis

The primary function of the prosthesis is to perform the initiating or closing movement, while the secondary functions will facilitate this movement. Once the work to be carried out by the prosthesis has been established, with its corresponding primary and secondary functions, a schematic of the tasks assigned to levels 0 for the primary function and 1 for the secondary functions is drawn up.

Two types of inputs and outputs shall be provided for each table of the functionality diagrams: control and energy. These inputs shall be located according to the machine's function. In the case of this transradial prosthesis, the level 0 functional diagram is shown in the following diagrams.[6]

Diagram of the main function of the prosthesis

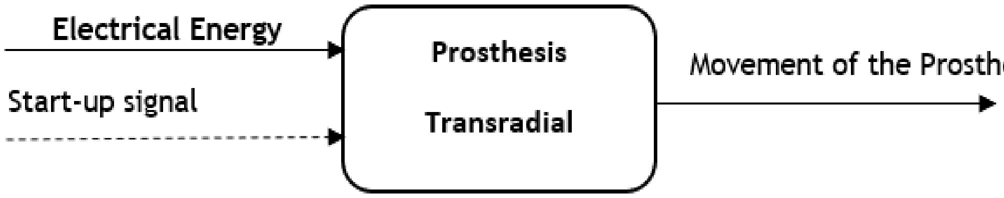


Figure 2. Diagram of the main function of the prosthesis

Functional Description Diagram[6]

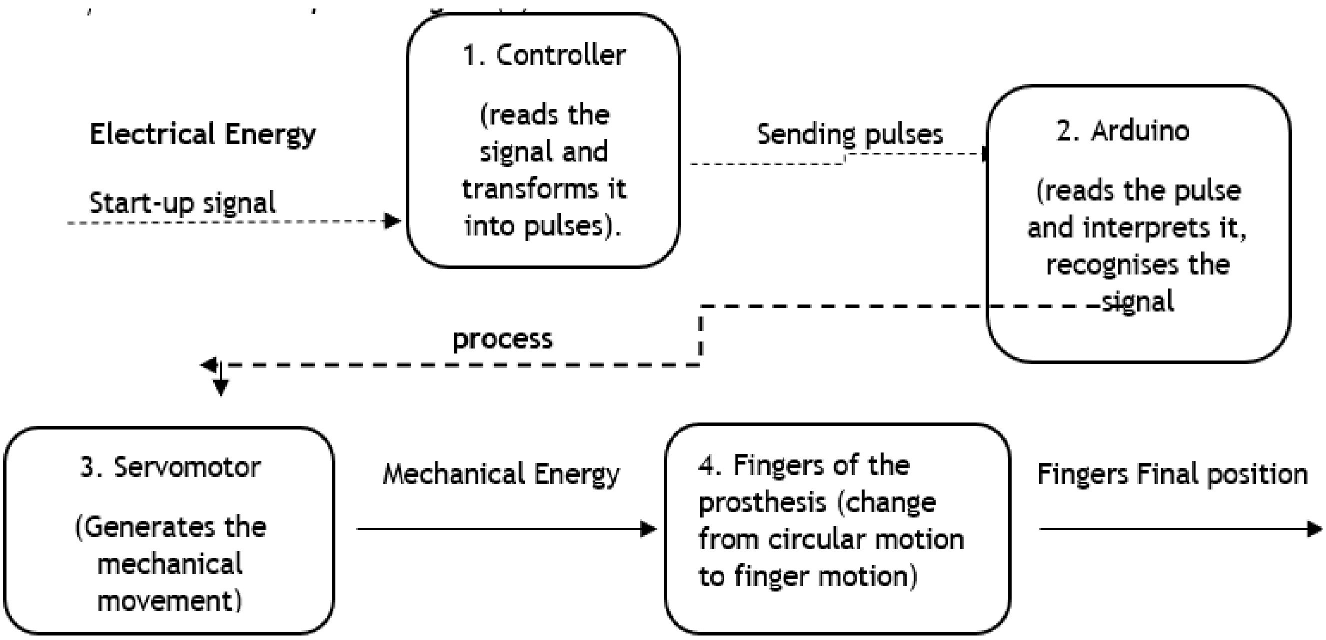
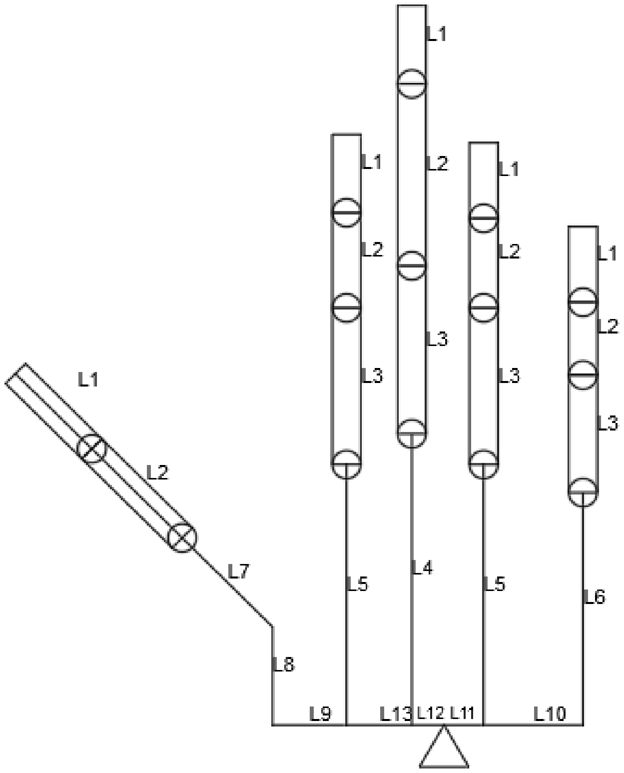


Figure 3. Functional Description Diagram

DEVELOPMENT
Modular structure
Mechanical design

A mechanism with 20 to 26 degrees of freedom was developed, and a rotational joint with 1 degree of freedom was considered.[7]

It is determined that the best angle of inclination of the thumb's CMC (carpometacarpal) joint is forty-five degrees.[8] In addition to the fact that the metacarpals will have no movement, it will be sought to achieve adequate material for the fingertips, giving an improved for finger traction.



Source: design and construction of a power grip prosthetic hand[8]
Figure 4. Hand mechanism

Mechanism of motion transmission

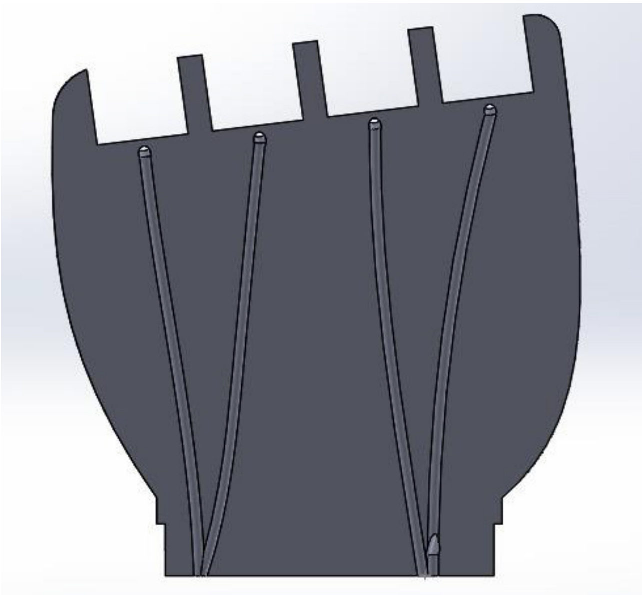


Figure 5. Representation of the front view of the palm

In the hand's functioning, the fingers' mobility and extension are controlled by the muscles of the forearm, transmitting movement through tendons.[9]

Linear motion transmission using rods is precise and economical, allowing speed control at the entry point. However, the structure of the mechanism is complicated, and torque is reduced at the endpoint. In addition, the length can affect the structural strength of the links. Linear motion transfer via static pulleys: These systems employ a single actuator, decreasing cost, weight, and complexity. Additionally, it increases the torque of the end element relative to the initial one. These systems are equally simple to operate. However, they have drawbacks such as a decrease in range of motion, an increased danger of transmission system breakdown, and lower accuracy.[9]

Considering the proposed prosthesis's utility and cost, the pulley drive method was chosen. This approach avoids excessive complexity in the design, reduces unnecessary costs, and facilitates control by voice command.

CAD design of the prosthesis

A first idea for the CAD model is defined, where the previously acquired dimensions are considered. As it is a first model, only the general dimensions are considered, and the aesthetic part is not considered.

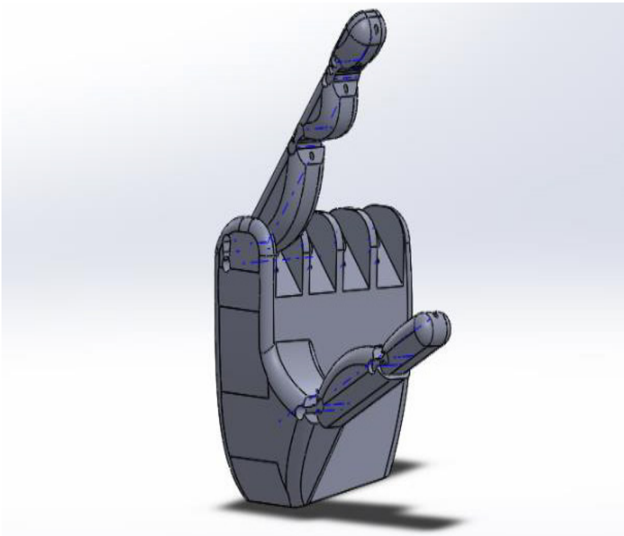


Figure 6. First Transradial Prosthetic Hand Prototype

RESULTS

Simulation of the model of each finger

Using the model generated in SolidWorks, a structural analysis was designed in ANSYS for each finger to verify deformations, Von-Mises equivalent stresses.

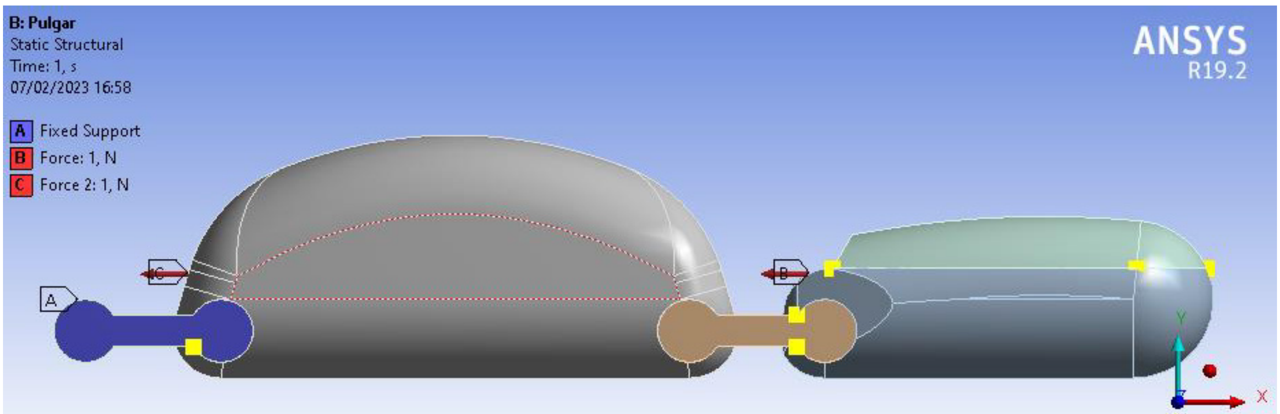


Figure 7. Finger model

Working parameters of the hand

To reproduce the natural movement of opening and closing the hand, the following data obtained in the ANSYS program were taken into account, giving results for each position of the simulated hand and the complementary working angles for the correct functioning of the prosthesis.[10]

Table 4. Working angles

Position	Angle	Position	Angle
Open hand position	85°	Gripping position sphere	35°
Closed hand position	5°	Bucket grip position	6°
Gripping position cup	50°		

Commands

In order for the prosthesis to function properly, the required instructions to be used for voice actuation are specified in the following table:

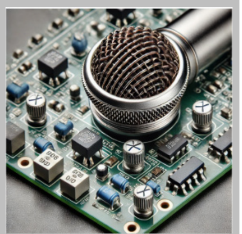
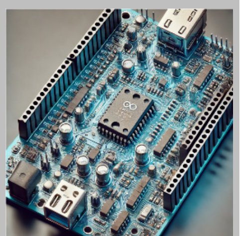
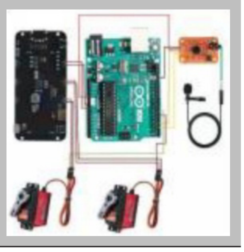
Table 5. Drive commands

Entrance	Action
Tumbler	the hand closes at 50°.
Pencil	the hand closes at 35°.
Spoon	the hand closes at 6°.
Open	the hand opens to the initial position at 85°.
Close	the hand is closed to the maximum
Greeting	the hand closes
Grip	the hand closes at a 45° angle to the hook

Components of the prosthesis

The electronic system consists of the most fundamental parts for the correct operation of the prosthesis.(10,11)

Table 6. Electronic components used for the prosthesis

Electronic System	
1. Controller (reads the signal and transforms it into pulses)	
2. Arduino (reads the pulse and interprets it, recognises the signal	
3. Servomotor (Generates the mechanical movement)	
4. Electronic circuit diagram	

Prosthesis drive system

Figure 8. Finger model

Characteristics of the prosthesis

The transradial prosthesis elaborated using 3D printing and analyzed in the ANSYS system presents the following general characteristics: Length: 290,04 mm, Width: 90,45mm, giving a maximum load capacity of 150 gr. The material selected for the construction is polylactic acid (PLA), and for the electrical system, the servomotor used is 20kg. After finishing the prosthesis assembly, we obtained a total weight of 315 gr.

Figure 9. Assembled Prosthesis

DISCUSSION

Transradial prostheses focus primarily on the technological evolution that has improved the functionality, comfort, and adaptability of these prostheses, as well as addressing the challenges and opportunities in their development. Several studies and authors have explored different aspects of transradial prostheses, from control systems to advances in materials and design.[12] Myoelectric control technology allows users of transradial prostheses to control prosthetic movements using electromyographic (EMG) signals generated by the contraction of residual muscles. This type of control has significantly improved the functionality of prostheses, allowing complex movements such as hand opening and closing or wrist rotation to be performed with greater precision. However,[13] some authors caution that, despite advances, the reliability of myoelectric systems is still limited by factors such as muscle fatigue and signal interference, which can affect the accuracy and speed of prosthetic response.

Actuator and motor design have been another crucial aspect in improving trans-radial prostheses.[14] Using smaller, more efficient motors has allowed for lighter and more comfortable prostheses, improving user acceptance and long-term use. In addition, these advances have enabled the creation of prostheses with greater dexterity, increasing users' independence in everyday tasks. However, one of the biggest challenges remains sensory feedback. Adequate tactile feedback is essential for the user to feel contact with objects and make precise adjustments to the grip.

In the kinematic analysis performed, it was observed that the velocity of the fingers varies depending on the type of movement, with the thumb reaching a maximum velocity of 0,057 mm/s while the other fingers reaching 0,62 mm/s. Acceleration also showed differences, with the thumb showing the highest acceleration (1,179 mm/s^2) compared to the other fingers (0,35 mm/s^2). The experimental tests showed that although the prosthesis could lift objects weighing up to 220 grams with difficulty, the ideal weight for optimal performance is between 100 and 120 grams. It was also observed that the prosthesis had difficulty lifting small, flat objects, such as coins, due to their shape, while round objects or objects with large surfaces were lifted more easily.

CONCLUSIONS

The development of transradial prostheses has seen significant advances in functionality, comfort, and adaptability, most notably the use of myoelectric control systems, which have improved the accuracy of movements. However, key challenges remain related to the reliability of these systems, mainly due to factors such as muscle fatigue and signal interference, which limit prostheses' accuracy and response speed. The design of smaller and more efficient actuators has created lighter and more comfortable devices, leading to greater user acceptance. Despite these advances, sensory feedback remains a critical area for improvement, as the lack of adequate tactile feedback hinders precision in object manipulation and fine grasping. Furthermore, the kinematic results indicate that, although the prosthesis can execute precise movements, its optimal performance is only achieved with objects of specific characteristics, such as a given weight and shape. These findings underline that, despite remarkable progress in trans-radial prosthesis technology, there is still a need to continue developing solutions that improve adaptability, reliability, and sensory feedback, which is essential to increase users' functionality and quality of life.

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None.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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