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DEVICE FOR INDIVIDUAL HAND FINGER REHABILITATION

DISPOSITIVO PARA REABILITAÇÃO INDIVIDUAL DE DEDO DA MÃO

DISPOSITIVO PARA LA REHABILITACIÓN INDIVIDUAL DE LOS DEDOS DE LA MANO

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ABSTRACT

Hands are indispensable when carrying out various everyday tasks. Situations such as car, work or vascular accidents impair mobility and hand maneuverability, forcing individuals to seek rehabilitation methods. This study proposes a low-cost device for finger rehabilitation that facilitates flexion/extension movements while respecting the physiological limits of each joint. The model utilizes a system of linear actuators to move the phalanges of the index finger, mimicking natural flexion. The study leverages mathematical modeling to determine the index finger's trajectory during flexion, considering joint angles and phalanx dimensions. This modeling led to the development of a 3D prototype using free software, ensuring that the dimensions and movement of the mechanism respect the anatomical characteristics of the finger. The results demonstrate that the prototype achieves the working space limits of the index finger, performing controlled and precise flexion movements. The study also proves the feasibility of the device construction through 3D printing of parts and preliminary testing. Future steps include developing a mechanism control system, a patient safety system with an interface for programming movement repetitions and applied force, and expanding functionality to include other hand movements. This model shows promise as a finger rehabilitation tool, offering controlled and safe flexion movements.

RESUMO

Este estudo propõe um dispositivo de baixo custo para reabilitação dos dedos que facilita movimentos de flexão/extensão, respeitando os limites fisiológicos de cada articulação. O modelo utiliza um sistema de atuadores lineares para mover as falanges do dedo indicador, imitando a flexão natural. O estudo apresenta a modelagem para determinar a trajetória do dedo indicador durante a flexão, considerando ângulos das articulações e dimensões das falanges. Essa modelagem levou ao desenvolvimento de um protótipo 3D usando software livre, garantindo que as dimensões e o movimento do mecanismo respeitem as características anatômicas do dedo. Os resultados demonstram que o protótipo alcança os limites de espaço de trabalho do dedo indicador, realizando movimentos de flexão controlados e precisos. O estudo também comprova a viabilidade da construção do dispositivo por meio da impressão 3D e testes preliminares. Estudos futuros incluem o desenvolvimento de um sistema de controle do mecanismo, um sistema de segurança para o paciente com uma interface para programar repetições de movimento e força aplicada, e a expansão da funcionalidade para incluir outros movimentos, como adução/abdução da articulação metacarpofalangeana e movimentos do polegar. Este dispositivo se apresenta como ferramenta de reabilitação dos dedos, proporcionando movimentos de flexão controlados e seguros.

RESUMEN

Este estudio propone un dispositivo de bajo costo para la rehabilitación de los dedos que facilita movimientos de flexión/extensión, respetando los límites fisiológicos de cada articulación. El modelo utiliza un sistema de actuadores lineales para mover las falanges del dedo índice, imitando la flexión natural. El estudio presenta la modelación para determinar la trayectoria del dedo índice durante la flexión, considerando los ángulos de las articulaciones y las dimensiones de las falanges. Esta modelación condujo al desarrollo de un prototipo 3D utilizando software libre, asegurando que las dimensiones y el movimiento del mecanismo respeten las características anatómicas del dedo. Los resultados demuestran que el prototipo alcanza los límites de espacio de trabajo del dedo índice, realizando movimientos de flexión controlados y precisos. El estudio también comprueba la viabilidad de la construcción del dispositivo mediante la impresión 3D y pruebas preliminares. Estudios futuros incluyen el desarrollo de un sistema de control del mecanismo, un sistema de seguridad para el paciente con una interfaz para programar repeticiones de movimiento y fuerza aplicada, y la expansión de la funcionalidad para incluir otros movimientos. Este dispositivo se presenta como una herramienta de rehabilitación de los dedos, proporcionando movimientos de flexión controlados y seguros.

INTRODUCTION

Work carried out by humans in their daily routine is the object of study so as to optimize and reduce necessary effort. There are several tools that have been adapted to help do some tasks, which are compatible with the shape of the human hand, to provide user comfort (Moraes & Mont'Alvao, 2000).

For any activity performed, hands are responsible for the mechanics of the movement or task, making it difficult to perform a job without them. Grasping, pinching, pressure or precision movements are examples of these tasks (Couto, 1995). Thus, from the movements performed by the human body, the most accurate are performed by the hands, enabling faster and more accurate movements, resulting in human hand dexterity, allowing the execution of tasks or sending information through gestures. Fingers are so vital in developing tasks that an individual without fingers is considered 54% capable than a person with all limbs intact (Engelberg, 1990).

There is a considerable number of possible movement combinations that can be created by the biomechanical system of the hand. Among the various functions that the hand presents, the function of transmitting sensations, holding, leading and manipulating objects in different ways can be mentioned. Controlling finger movements and grasp are among the most precious activities of human movement. While performing these activities, the importance of coordination and finger movement pattern is evident (Levangie and Norkin, 2005).

Some pathologies can affect the normal functioning of upper limbs, selectively reaching approximately one or more functionalities of the hand (Freivalds, 2011; Netter, 2006). Muscle diseases start with a simple myalgia, common muscle pain, and can progress to muscle inflammation and lead to a more serious condition.

Hand injuries affect people in the productive age group, and any injury, however small, leads to a degree of disability that can limit individuals in carrying out work and daily activities (Gaspar, 2010). Accidents at work are identified as one of the main causes of removing workers from the productive field and are a major public health problem in Brazil (Santana et al., 2003). Therefore, reintegration to work is considered an important parameter when analyzing the impact of these accidents on workers' lives (Turner et al., 2000).

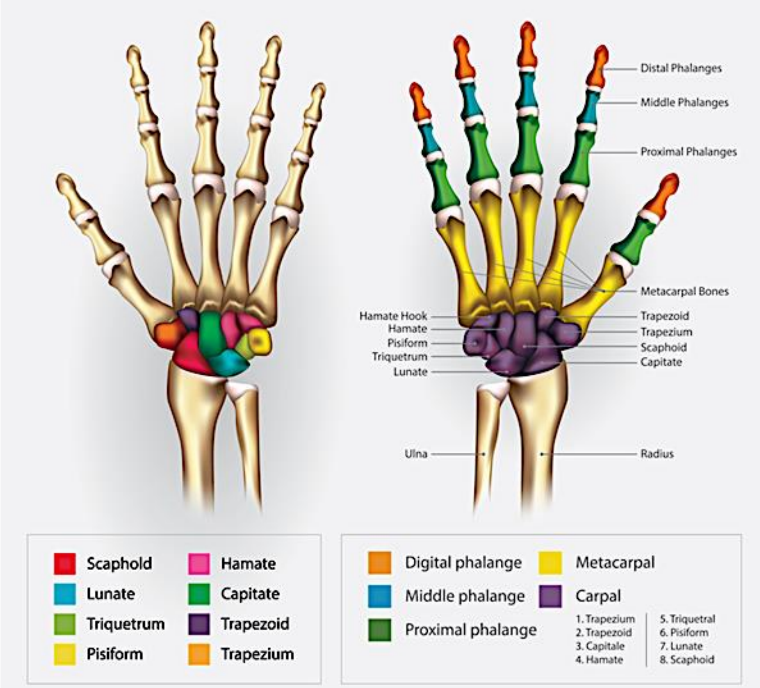
In the global context, rehabilitation had a great impulse and development in the 20th century, especially in the period after the great world wars, due to the injuries and sequelae caused (Dellon and Matsuoka, 2007). Rehabilitation is based on helping patients with the most effective, inexpensive treatment, with few side effects that allow them to return to their normal life and workplace.

This study aims to develop a mechanism that allows finger rehabilitation using low-cost technology, which can contribute to an efficient device, improved from existing models, ensuring user comfort and safety.

HAND ANATOMY

Hands are in the most distal part of the upper limbs (Hall, 2000) and can reach distant points in any position, within certain limits with any orientation, due to the mobility of all the arm joints, mainly the shoulder, which is the joint which has the greatest mobility of the whole body (Tubiana, 1981). Hand functionality, as well as its ability to change shape, adapting to different types of objects, is due to the fact that it has 23 degrees of freedom, 5 for the thumb, 4 for each one of the other fingers and 2 more for the palm (Polis, 2009).

Figure 1. Posterior and anterior view of the human right hand - bones and joints



Source: http://www.freepik.com, designed by pongpongching.

The literature on anatomy (Freivalds, 2011; Netter, 2006; Graaff, 1991; Sobotta, 2006) presents the nomenclature and division of the twenty-seven bones as three parts. They are divided into Carpus (Scaphoid, Semilunar, Pyramidal, Pisiform, Trapezius, Trapezoid, Capitate), Metacarpus (there are five and are numbered starting from the thumb) and Phalanges (Proximal, Medial and Distal, except for the thumb which does not have a phalanx medial) (Figure 1).

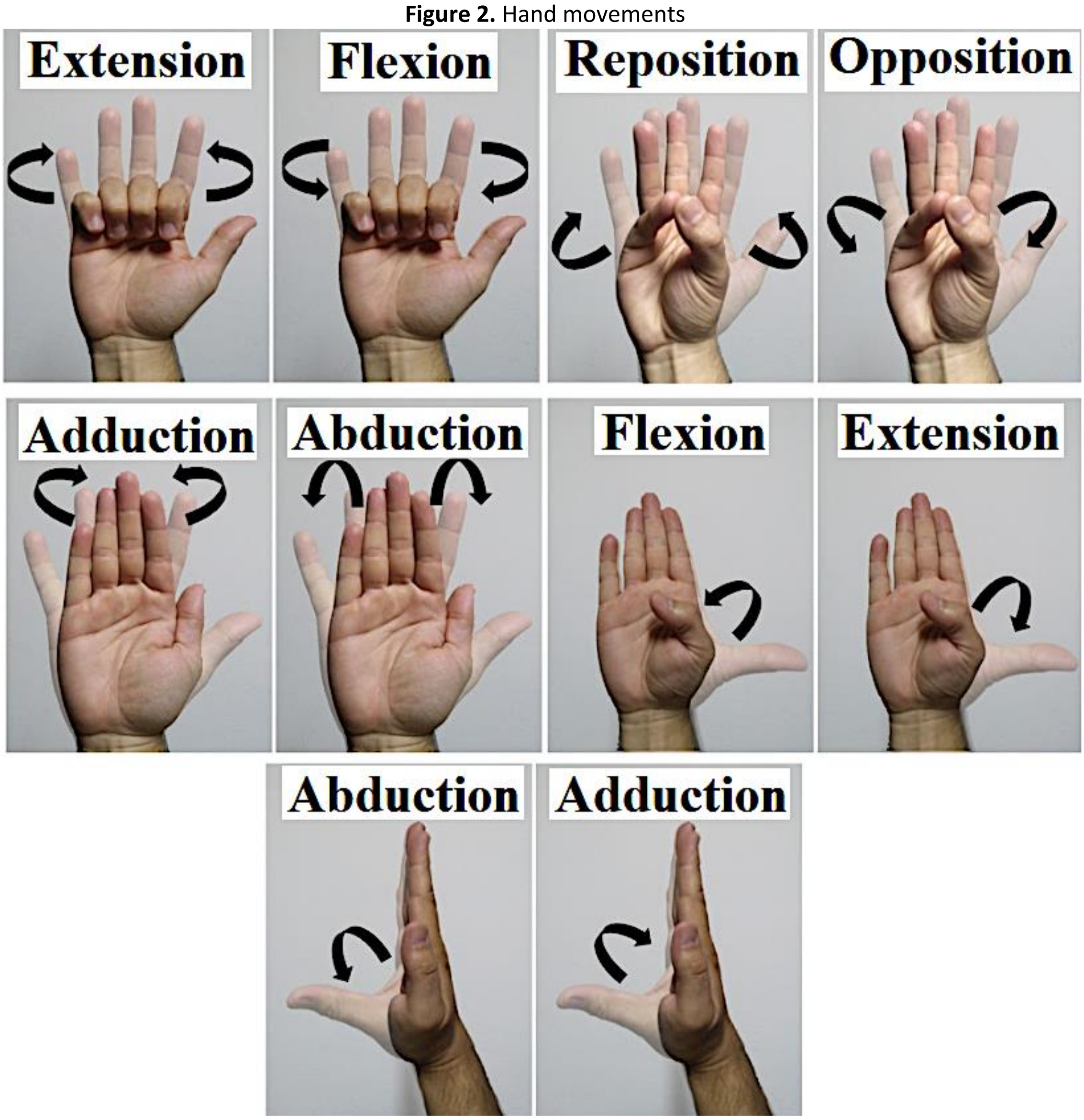
The joints between the bones are named according to their location, for example the Carpometacarpal (CMC) joint is situated between the bones of the distal row and the bones of the metacarpal. Between the metacarpal bones and the proximal phalanges is the Metacarpophalangeal (MCP) joint. The Proximal Interphalangeal (PIP) joint between the proximal and medial phalanges. Finally, the Distal Interphalangeal (DIP) joint between the medial and distal phalanges.

HAND MOVEMENTS

Movements originate in the joints between bones and cartilage, from the anatomical position of the hand, which is the position of the body standing, facing forward, arms at the sides of the body in which the palms and fingers face forward (Freivalds, 2011). The main movements performed by the hands are:

Flexion: angular variation in the closing direction of the hand.
Extension: angular variation in the opening direction of the hand. The movement of opening a limb beyond the anatomical position is called hyperextension.
Abduction: movement of the fingers away from the middle finger.
Adduction: re-approximation movement of the fingers in relation to the middle finger.
Opposition: movement where the pad of the thumb is brought closer to the pad of another finger.

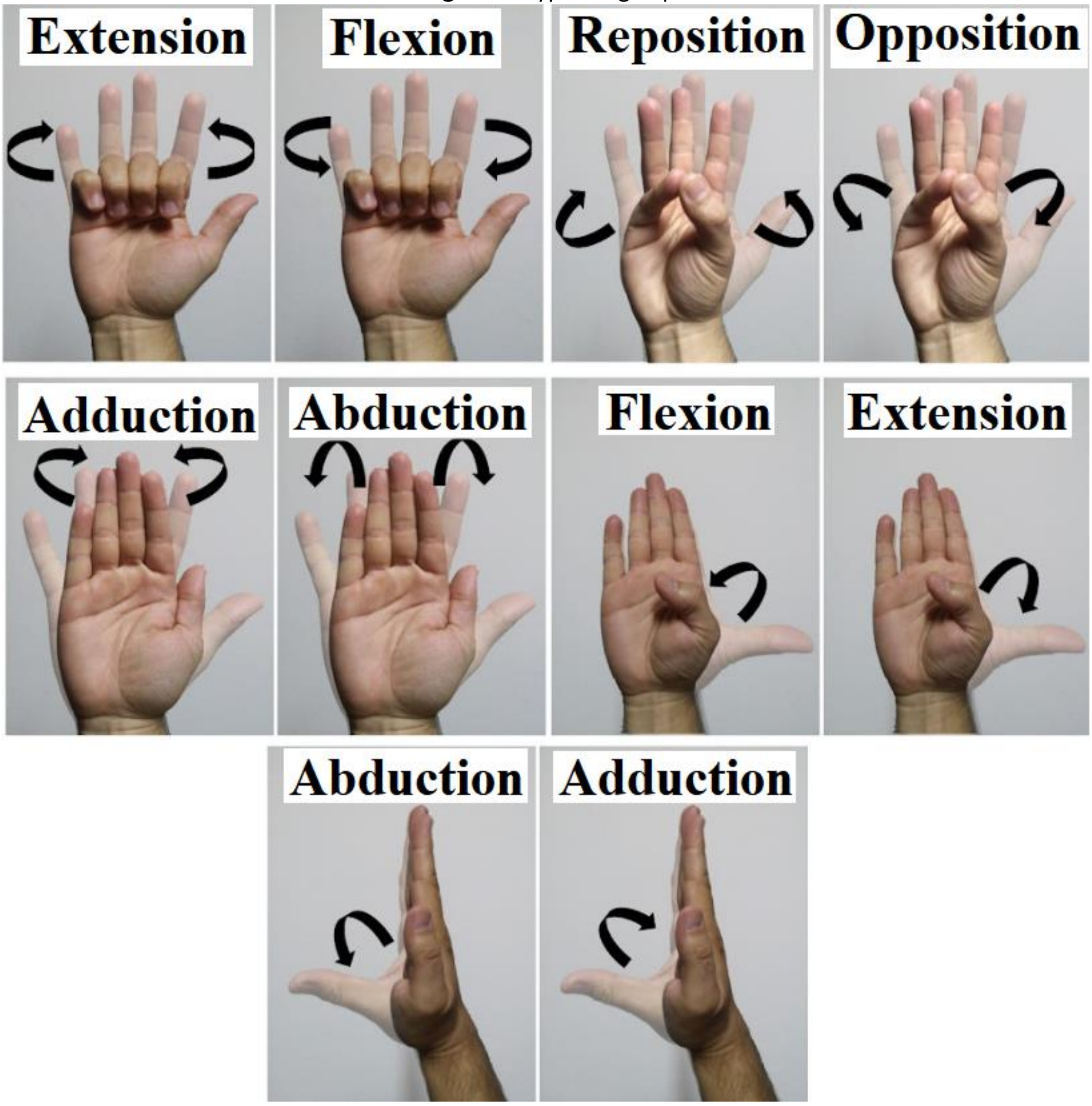
Figure 2. Hand movements



Source: Adapted from Dalley; Moore, 2007.

With the advent of anatomical and kinematic analysis of movements, two main types of movement were highlighted, receiving the nomenclature of force grasp and precision grasp (Napier, 1956). Factors such as compliance, connectivity, closing force, handling, slip resistance and stability are guidelines to define the analysis and description of each type of grasp. Other combinations of finger movements allow us to perform other tasks ranging from picking up a coin to holding a briefcase. In Figure 3, the following types of grasps can be seen: (A) Cylindrical, (B) Fingertip, (C) Hook, (D) Palmar, (E) Spherical and (F) Lateral (Cutkosky, 1989).

Figure 2. Types of grasp



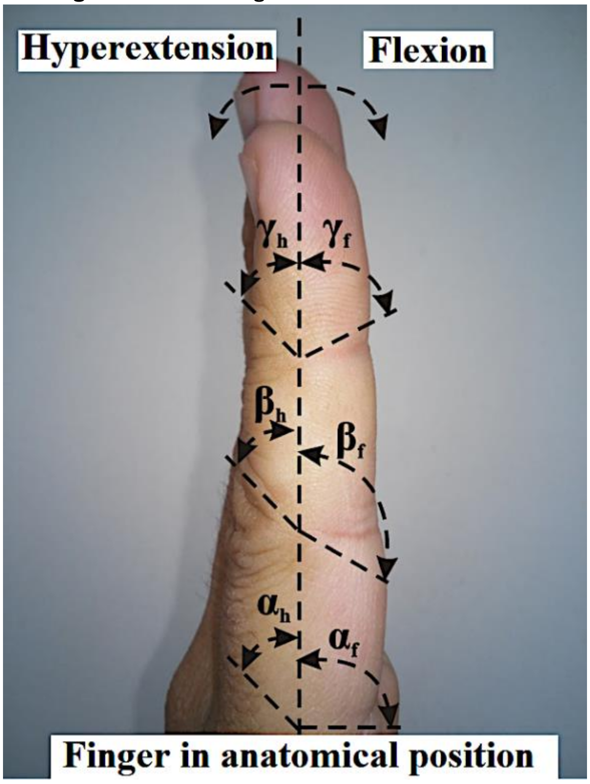
Source: Adapted from Cutkosky, 1989.

MATHEMATICAL MODEL

In situations where hand motor functions are lost, therapies are used to restore, or even develop, hand movement more quickly, so that an individual can return to doing normal activities (Gaspar, 2010). New technologies are being used to help this process, to add more possibilities to exercise the injured limb. One of the examples is assistive technology in rehabilitation methods, applying exoskeletons to perform flexion and extension movements. As it is an injured limb, the safety of the mechanism is an important factor, as a movement that exceeds the limits or exerts a force greater than the patient's clinical condition supports, would aggravate the patient's injury (Heo, 2012).

To represent the flexion and extension movement of the fingers, an analysis should be carried out of the angulation allowed for each joint. Except for the thumb, each finger has four degrees of freedom, two in the interphalangeal joints performing the flexion/extension movement, and two in the MCP joint referring to flexion/extension and abduction/adduction movements.

Figure 4. Index Finger in Anatomical Position



Source: Adapted from Kapandii, 2003.

Angles α, β and γ refer respectively to the movements of the MCP, PIP and DIP joints (Figure 4). When performing the opening movement of the hand, there is a possibility that the movement exceeds the anatomical position, defined by hyperextension. As the objective of the study is to perform the flexion/extension movement taken from the anatomical position of the finger, the angulation referring to hyperextension is not considered.

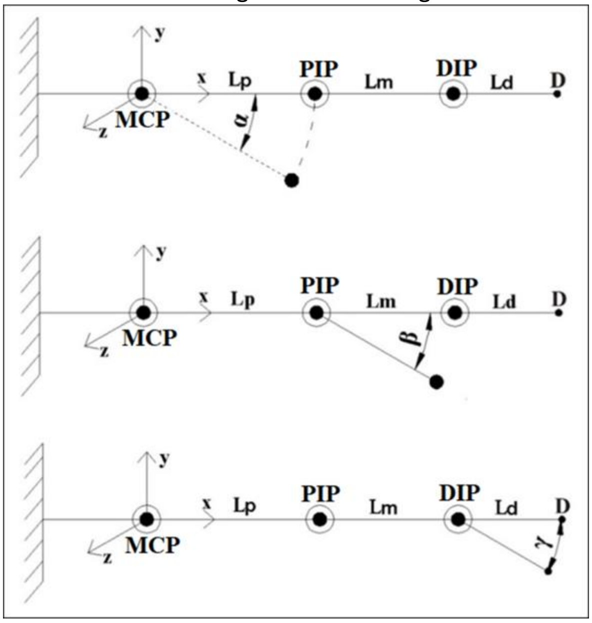
Flexion/extension is the result of an angular combination of joints, and can be represented by a serial robotic structure, in which the metacarpal is the base of the structure and the distal phalanx the terminal element. To determine the position of the terminal element, the fingertip (Point D), in addition to the angles of each joint, we have the lengths of the proximal, medial and distal phalanges as parameters, respectively represented by Lp, Lm and Ld (Figure 5).

Observing Figure 5 with reference to the three-dimensional Cartesian axis, it can be seen that the structure performs only the rotation movement in the joints on the Z axis, as the translation movement, which is the change of coordinates on a given axis, whether X, Y or Z, is not possible due to the dimensions of the phalanges being fixed. That is, the movement can be interpreted from a representation in two dimensions, that is, only in the X and Y axes. In this case, the abduction and abduction movements are disregarded.

Starting from the MCP joint, to obtain the x and y coordinates relative to Point D, the homogeneous transformation matrix of local rotation is used in each joint, analyzing the structure in parts (Figure 6), which can obtain the positions of each point in relation to the joint angulation.

After individually analyzing each structure, describing each local matrix, the rotation movement in the three joints must be considered simultaneously, generating a global homogeneous transformation matrix, where the displacement is related to the variation of the three angles. alpha, beta and gamma simultaneously, the final position of Point D is the x and y coordinates.

Figure 5. Schematic model for the angles of the homogeneous transformation matrix



Source: The Authors.

Following the reasoning developed by SILVA (2011), as it is a serial structure, the global transformation matrix is the product of the local matrices (TGlobal = TMCF.TIFP.TIFD.TD), and Equations 1 and 2 refer to coordinates x and y (Equations 1 and 2, respectively), of point D as a function of each angle (∝, β and γ) in the joints and the length of the phalanges (Lp, Lm and Ld) (Silva, 2011).

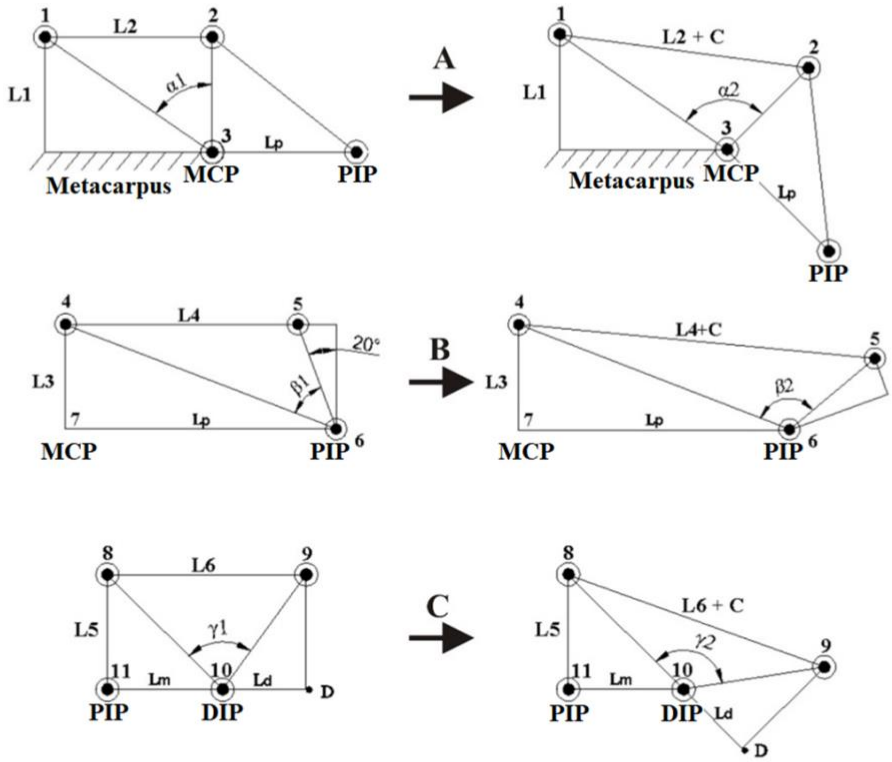
$$x = L_P \cos(\propto) + L_M \cos(\propto + \beta) + L_D \cos(\propto + \beta + \gamma) \qquad (1)$$

$$y = L_P \operatorname{sen}(\propto) + L_M \operatorname{sen}(\propto + \beta) + L_D \operatorname{sen}(\propto + \beta + \gamma) \qquad (2)$$

MECHANICAL STRUCTURE PROPOSAL

From the study of existing exoskeleton models, the need to search for a simple and efficient mechanism that ensures the full range of motion is clear, in addition to factors such as mobility and weight of the mechanism. Following the research line of the NENA Assistive Technology Center at Federal University of Catalão (UFCAT), which is based on searching for low-cost research, it was decided to use an electric linear servo actuator, with reduced dimensions of 47.5 x 21, 5 x 15mm, with a maximum stroke of 20mm and a mass of 15g, currently produced by the Canadian company called Firgelli Technologies. This actuator is manufactured to operate with a supply voltage of 6 or 12V and is compatible with the Arduino© open-source control board, making it possible to control the device in the future.

Figure 6. Geometric configuration of the coupling



Source: The Authors.

As the actuator movement is linear, a structure that converts linear displacement into rotary displacement (Rotation) had to be developed using a rack-and-pinion or connecting rod/crank couplings. To transmit this movement, a geometric model with three joint points was initially proposed (Figure 6-A).

Knowing that angle α (MCP Rotation) is a function of the linear advance of the actuator, by the Law of Cosines, the limits of movement and the relationship between the actuator stroke and the joint angulation are verified. The result is Equation 3, referring to the calculation of angle α as a function of the actuator stroke (C).

$$\cos \boldsymbol{\alpha} = \frac{2{L_1}^2+{L_2}^2-(L_2+C)^2}{2L_1\sqrt{{L_1}^2+{L_2}^2}} \qquad (3)$$

To rotate on the IFP, the structure is proposed (Figure 6-B), where the base of the structure is the proximal phalanx LP, the height of the structure is L3, and the right side is fixed at point 7 and rotates about point 4. In the rest position (C = 0), L4 has a size equal to Lp, resulting in angle β1.

As the actuator is fixed at points 4 and 5, with 100% of the feed, point 5 describes a circular path with a cent at point 6, which coincides with the PIP rotation center, resulting in β2. As it is a linear actuator, the maximum angulation that the structure allows without collision of parts of the mechanism is 90º, which does not satisfy the desired total angulation, requiring a change in the mechanism. In the altered model, an angulation of 20º was added, so that with the 100% advanced actuator, the fixed 20º is added to the 90º degrees made possible by the structure (Figure 6-B).

Using the Law of Cosines again, as in the first model, Equation 4 is obtained. As in the previous model, in addition to the angle over PIP, the length of the proximal phalanx Lp, the height of the L3 structure and the angle β are variables.

$$\cos\beta = \frac{{L_3}^2+{L_P}^2+\left(\frac{L_3}{\cos 20°}\right)-(L_P-L_3(\tan 20°)+C)^2}{2\left(\frac{L_3}{\cos 20°}\right)\sqrt{{L_3}^2+{L_P}^2}} \quad (4)$$

To perform the movement in the DIP joint, it is important to consider that, normally, the dimension of the Lm phalanx is not greater than the initial length of the linear actuator (42mm). Having this information, a model was developed whose joint point 10 corresponds to the DIP joint center (Figure 6-C). It can be observed that in the figure that the height of the structure is L5, the base of the structure is divided by phalanges Lm and Ld and dimension L6 is the length of the actuator in the rest position, equivalent to the sum of Lm and Ld, thus forming angle γ1. Equation 5 can be obtained using these values and the Law of Cosines.

$$\cos\gamma = \frac{2{L_5}^2+{L_M}^2+{L_D}^2-(L_M+L_D+C)^2}{2\sqrt{{L_5}^2+{L_M}^2}\sqrt{{L_5}^2+{L_D}^2}} \quad (5)$$

RESULTS

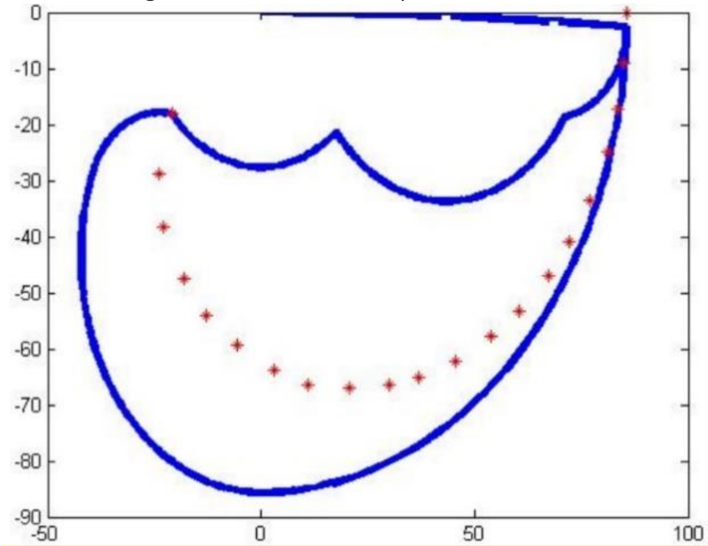
Based on Kapandji's studies, for the index finger to fully perform the flexion movement, alpha values range from 0 to 90º (MCP joint), beta values range from 0 to 110º (PIP joint) and gamma values range from 0 to 80º (DIP joint) (Kapandji, 2003). Adding to the length of the Lp, Lm and Ld phalanges, the working space of the index finger is obtained as shown in Figure 7.

With the equations of coordinates x and y at Point D (Equations 1 and 2), by the values of the phalanges and the angles (α, β and γ), which are a function of the advance stroke of the linear actuator, which varies from 0 to 20mm, the values of the fingertip x and y coordinates are obtained, in each millimeter of the advance of the actuator stroke. It should be noted that the coordinates shown in the graphs below are the result of advancing the three actuators simultaneously.

Having L1=17,72mm, L2=50mm, L3=12,9854mm, Lp=43,4mm, L5=23,0772mm, Lm=25,3mm, Ld=17mm, from Equations 3, 4 and 5, we obtain the angulation of each joint from the advancement of the actuator stroke, as shown in Table 1. To graphically analyze the results, it is necessary to visualize that the finger starts the movement in an anatomical position and the flexion movement is performed clockwise. As mentioned before, the rotation movement is performed counterclockwise on the Z axis of each joint, resulting in a 2D representation, having the Cartesian axis reference ((x,y)=(0,0)) in the MCF joint. Thus, explaining the values some negative values in x coordinates and all negative values in the y coordinates.

Figure 7 shows the trajectory of Point D, describing the working space of the index finger, comparing it with the red points, which are the coordinates of Point D for each millimeter of advance of the actuators simultaneously. It can be observed that Point D reaches the working space limit of the index finger trajectory, as the trajectory is the result of the increase in angles (α, β and γ) as a function of the actuator stroke.

Figure 7. Point D x Workspace coordinates

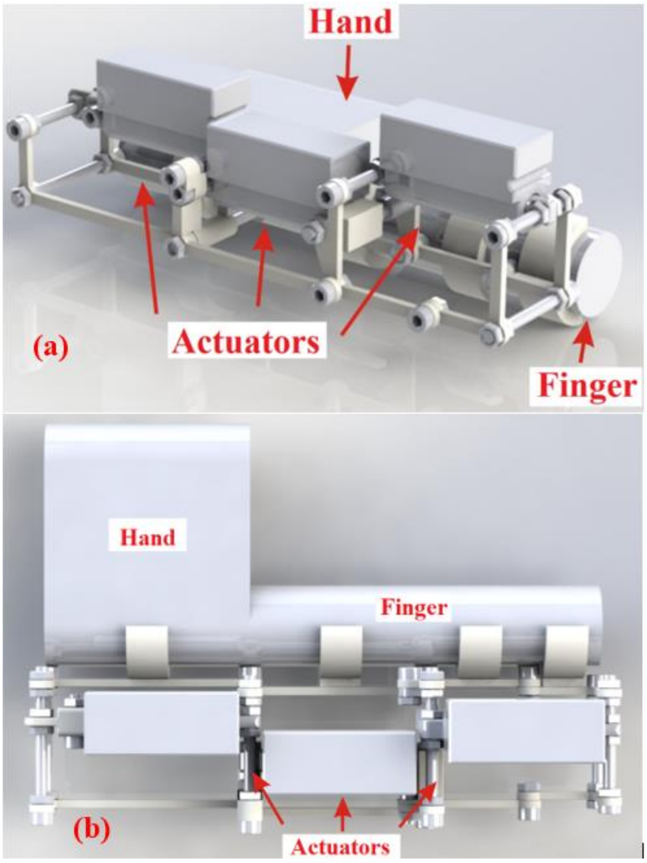


Source: The Authors.

MECHANISM

From the values obtained previously, FreeCAD (open source) software was used to develop the 3D model of the prototype. All dimensions must be obeyed and there can be no interference points such as collision of parts. Figure 8 shows the mechanism attached laterally to the finger in an anatomical position, on the medial line of the index finger, aligning the centers of rotation of each joint.

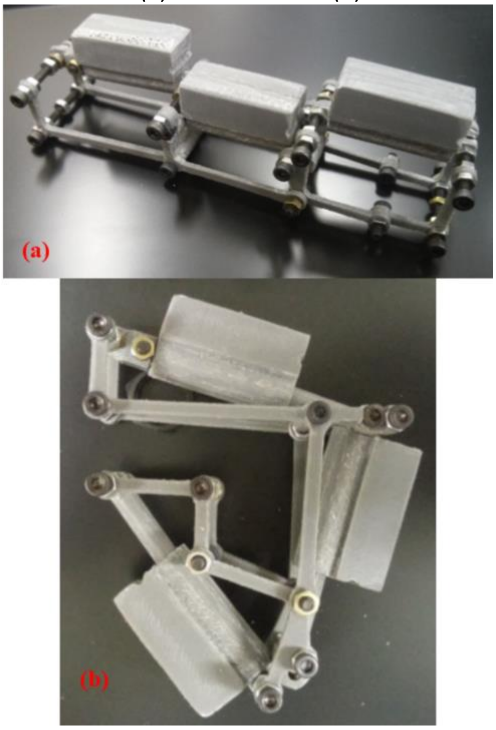
Figure 8. Isometric (a) and Top View (b) of the Mechanism



Source: The Authors.

In addition to the simultaneous advancement of the three actuators, it is possible to simulate what the coordinates would be from the dimensions determined by the mathematical model, impressions of the mechanism parts were made to verify and test some constructive characteristics. To physically evaluate the movement, parts were printed with the natural dimensions of the actuator. This made it possible to test the dimensions of the complete engine. Figure 9 shows the Isometric and Side views of the complete prototype with bends at the joints with the bends at each joint.

Figure 9. Isometric (a) and Side View (b) of the Mechanism



Source: The Authors.

CONCLUSIONS

With a two-dimensional modeling of the finger, the coordinates of the fingertip were calculated as a function of the advance of an actuator with the characteristics of the linear servo actuator used, in addition to the determination and definition of its working space, which served as a parameter for determining the functionality of the proposed model.

Although the mechanism performs the necessary movements, only with the entire structure assembled, the necessary adjustments can be made to carry out the real tests. For future work, the development of the mechanism control system is needed, as well as the development of a patient safety sensing system, including an interface for programming the number of repetitions of movements and maximum force applied to each joint, without causing injury to the patient's muscles.

The study of the adduction/abduction movement of the MCP joint would complete the movements performed by the fingers of the hand, as well as the analysis of the thumb movements would complete the study of the rehabilitation system of all the fingers of the hand. Following the evolution of the proposed model, the displacement of the mechanism's center of rotation should be considered so that it can be mounted on the top of the finger without harming the related movements, as the center of rotation of the medial line of the finger was considered.

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