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Mathematical Modeling of Orthosis for Hand Movement with Loss of Strength

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I certify that i have read this dissertation and that, in my opinion, is appropriate in content and form as a demonstrator of the developed work.

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Abstract

Several factors that can lead to a loss or decrease of an individual's motor and/or coordination abilities, such as spinal cord injury caused by an accident, a Cerebral Vascular Accident, Cerebral Palsy, and others alike. Since the hand is one of the members that most affect patient's independence and quality of life, this study focus on the development of a solution for the condition of lost of motor skills in the hands, specifically, in the realization of the pinch movement.

The solution proposed is the development a model of mechanical orthosis capable of assisting the basic movement of opposition between the index finger an the thumb (forceps), allowing the patient to perform daily actions that involve picking or lifting an object, as well as perform the writing movement, while keeping a low level of assembly complexity and cost of production.

The development of the model began by identifying the needs of the patients considered, the formulation of a methodology for obtaining the optimal geometry for the mechanism components, and realizing preliminary and functional tests to verify the proposed ideas.By the end, we have a functional model of mechanical orthosis, that validates the methodology elaborated.

Keywords: Orthotic Devices, Hand Debility, Mechanics, Mathematical Modeling

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Chapter 1

Introduction

1.1 Background

In the medical field, there are several factors that can lead to a loss or decrease of an individual's motor and/or coordination abilities, such as spinal cord injury caused by an accident. One of these lesions is hemiparesis, which would be the loss of mobility of only half of the body, most commonly generated by a stroke, as well as repetitive strain injuries or incorrect movement. According to Silva [1] , "80 to 85% of people suffering from stroke generate a partial loss of strength in the limbs of the opposite side of the brain injury", and "55-75% do not recover after 6 months of injury".

In the specific case of the hands, the motor limitations can be represented as loss of tonus muscular capacities, being caused by spinal injuries, stroke sequel or repetitive strain injuries, such as lateral epicondylitis (tennis elbow) and carpal tunnel syndrome [2], or of hyperflexion of the fingers as in some cases of hemiparesis [1].

To address such limitations and disabilities, current treatments have been focused on physiotherapeutic treatments, which seek to stimulate the affected region through repetitive movements of the affected member or in the parental member. However, when these not present satisfactory results, it is possible to opt for the surgical method, where is performed the transfusion or ligament of nerves from less affected places [1].

However, this type of surgical, besides being a intrusive alternative, only achieves success between 5 and 20% of the individuals, who completely recover their motor functions after 6 months of rehabilitation [3]. The movement of the limb is also less organic and comfortable. In this way, as a less invasive, mechanical and electromechanical orthoses have been used for the amplification of the movements and the involved forces applied to limbs with partial loss of force[4].

1.2 The Scope of the Thesis

Since the hand is one of the members that most affect patient's independence and quality of life, this study focus on the development of a mechanical solution for the amplification of motor skills in the hands. In this way, it will be developed a model of mechanical orthosis capable of assisting the basic movement of opposition between the index finger an the thumb (forceps), allowing the patient to perform daily actions that involve picking or lifting an object, as well as perform the writing movement.

Over the years, several models of hand orthoses have been developed, with only rehabilitation purposes, such as HandSOME [5] and HEXOSYS [6], or as support for hand movement, such as Martinez et al. [7], Hasegawa et al [8] and DIcicco et al. [9]. These orthotic models have variations both in their form of driving system and activation, however, these models generally have higher-value components, and are more complex in assembly, making it difficult to produce it in large-scale and be available for the general population.

1.3 Objectives

The main objective of the thesis is to develop a mechanical orthosis to aid in the accomplishment of the pincer movement between the index finger and the thumb, with the activation of the movement through the middle finger using a completely mechanical system.

Chapter 2

Models for Hands Orthosis

2.1 Medical Aspects of Hand Orthosis

In modern society, the number of people incapacitated due to medical issues and accidents is reaching worrying numbers. According to the World Health Organization, ”15 million people suffer stroke worldwide each year. Of these, 5 million dies and another 5 million are permanently disabled” [10] and ”between 250.00 and 500.000 become spinal injured every year” [11]. The increase of this numbers is generally related to the maintenance of unhealthy habits, like smoking, consumption of greasy foods and lack of exercises, and to the increase in the numbers of violence and car accidents.

Those problems not only have impact in the health quality and independence of the patients, but also have impact in the economy of each country, that loses capable labor force and has to bear the costs of treatment with these people, generating also a health care problem.

Of the sequels left by these problems, the one that most compromises the independence of those affected by it is the loss of tonus in the limbs, that can prevent the affected from walking, grasping objects or even eating by themselves, being the loss of tonus in the hands and upper limbs the worst of them.

The evaluation of the degree of commitment of the patient can be made using the Fugl-Meyer and the Motor Activity Log scales [12], that, through a series of standardized tests, classifies the patient over it's motor and reaction capabilities.

2.2 Modulation Process of the Fingers Movement

The first step in the project of any mechanical model is to define the desired movement to be realized by it. In the specific case of a hand orthosis, the objective is to reproduce the natural movement of the fingers and, in some cases, the wrist. To achieve the objective, the first step is to to analyze the movement the finger in an anatomic way [3], [4], [9], [13]–[15], which means to convert the human finger into a set of three bones (phalanges) and three joints, whose rotational movement is generated through the extension and contraction movement of the muscles linked at each bone/joint junction, like shown in the Figure 2.1, and then converting it to the movement of three bars with determined length linked with three rotational joint.

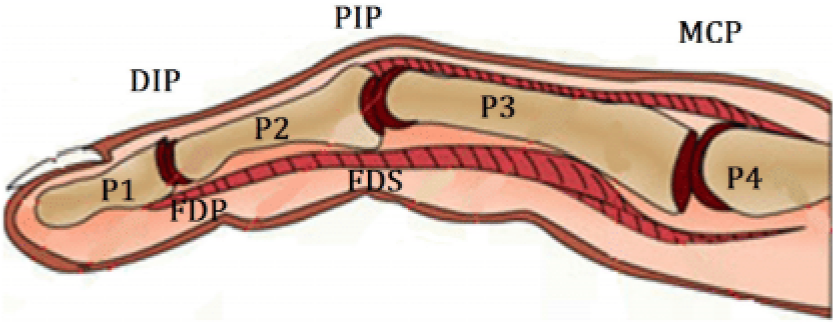


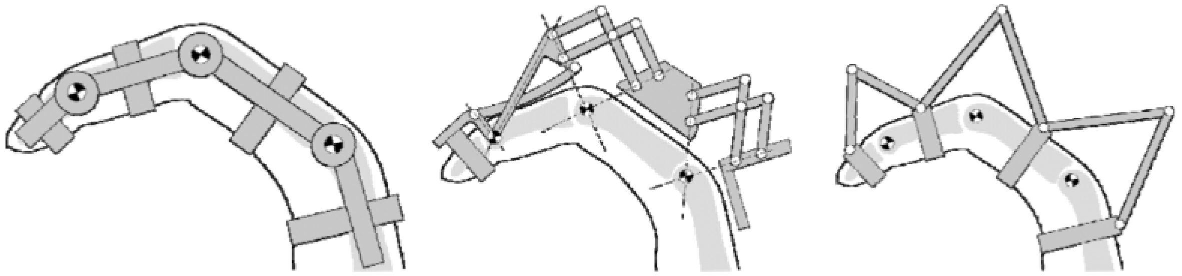
Figure 2.1: Human finger model [13]

Being that settled, the next step is to evaluate the movement of the finger by the variation of the angles of each bar. This can be made using anthropometric data [14], [15] or photos and pictures taken from a real person [4]. With this information, it is possible to come up with a mechanism that will realize the wanted movements.

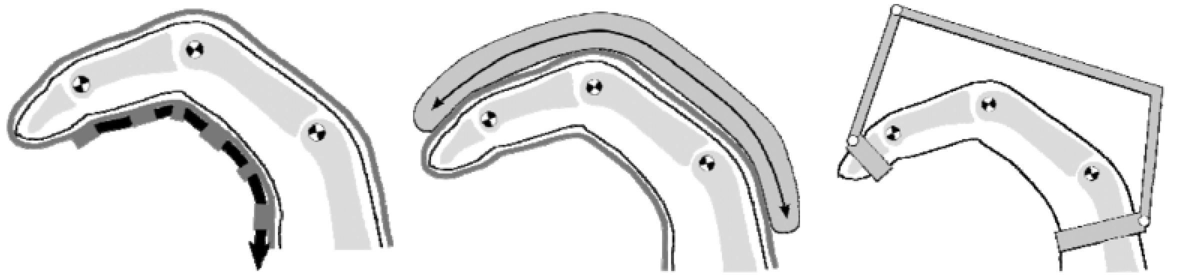
With the mechanism established, it is necessary to determine the forces involved in the movement, which can be estimated through anthropometric values [16], then determine how this forces are going to be exerted by the mechanism, analyzing the tensions in each component of it or closed groups of them [14]. The tension variation model can be made using differential equations based on the mechanism movement [14] or with the variation of the finger movements depending of time [4].

2.3 Existing Models for Hand Orthosis

Nowadays, the orthotic models that seek to solve the proposed problem are mostly using electromechanic solutions, where the mechanisms associated with the commonly used solutions replicate the mobility of the human limb in the positions of bones and tendons, mostly with an electric motor system, as shown below.



(a) Direct matching of joint centers[22] (b) Linkage for remote center of rotation[23] (c) Redundant linkage structure[24]



(d) Tendon-driven mechanism[25] (e) Bending actuator attached to the joint[26] (f) Serial linkage attached to distal segment[27]

Figure 2.2: Examples of configuration in mechanisms utilized in hand orthosis [3]

The models presented in figure 2.2 have as main objective to promote the articulation of the finger based on the natural bio-mechanical finger joints, elaborating several systems of mechanisms with one degree of freedom as a closed kinematic chain, that is, a single output for a single input of the driving system. In these cases, the driving system is made using electric motors or pneumatic actuators, promoting the unidirectional movement of the mechanism (extend or fold only) or bidirectional (allows the extension and folding of the finger).

The mechanisms differ in their type of activation: strings, springs or pneumatic actuators, and in the type of movement obtained, that can be just the rotation of the finger over the MCP joint, or to produce the "hook" position. Some examples of this configurations are shown below.

- **HandSOME**

  Brokaw et al.[5] propose the HandSOME device. This device was elaborated focusing on patients that are experiencing excessive contraction of the muscles of the hand due to a stroke, which is called hypertonia [5]. Based on that, the mechanism was elaborated to keep the fingers in the extended position, allowing the grasping movement.

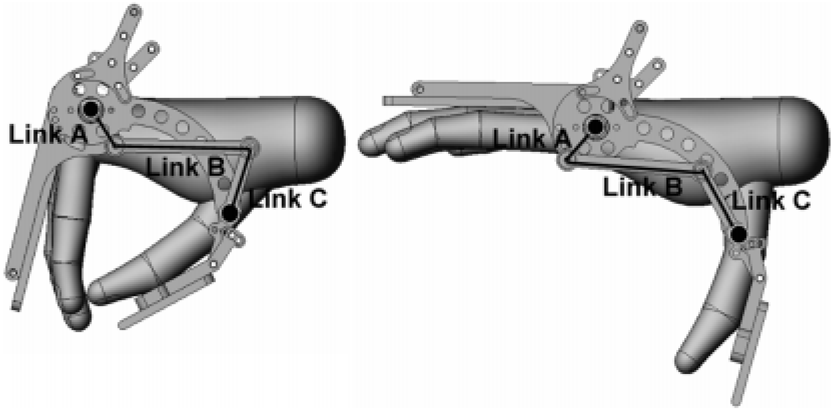


Figure 2.3: Scheme of the model HandSOME [5]

The HandSOME [5] model is considered a passive mechanism, because it's driving system is basically composed by an adjustable spring that keeps the fingers in an extension position, allowing the patient to close it's hand only when intended.

Being a passive mechanism, this model can not be used in the case of patients with loss of tonus or mobility in the hands.

- **HANDEXOS**

  The HANDEXOS model was developed by Chiri et al [17], with the objective of restore the capabilities of realizing the Activities of Dailing Living (ADL) for stroke patients. With that in mind, the authors came up with an idea of an light-weight mechanism with an cable driving to mimic the human fingers movement and compensate the hypertonia, as shown below.

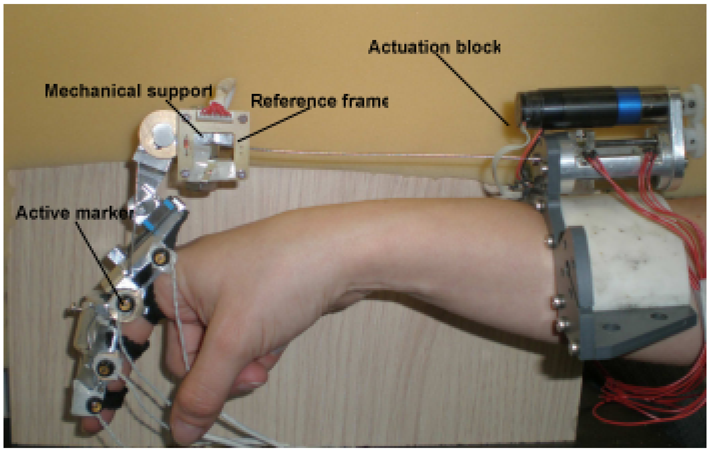


Figure 2.4: HandEXOS complete montage [17]

The HandEXOS[17] prototype uses the mechanism configuration (a) from Figure 2.2, being driven by a electric motor that tightens the filament connected to the pulleys positioned at the positions of the joints, extending the fingers. The tension force exerted on the wire is controlled by three sensors positioned along the three phalanges of the fingers.

Like the HandSOME model, this mechanism is not meant to be used in patients with loss of mobility.

- **Dicicco device**

  This model was developed by Dicicco et al [9] with the idea of giving back the patients with paralyzed limbs the capacity of realizing the pinch movement through a mechanical system, “controlled by the user’s residual electromyography (EMG) signals” [9].

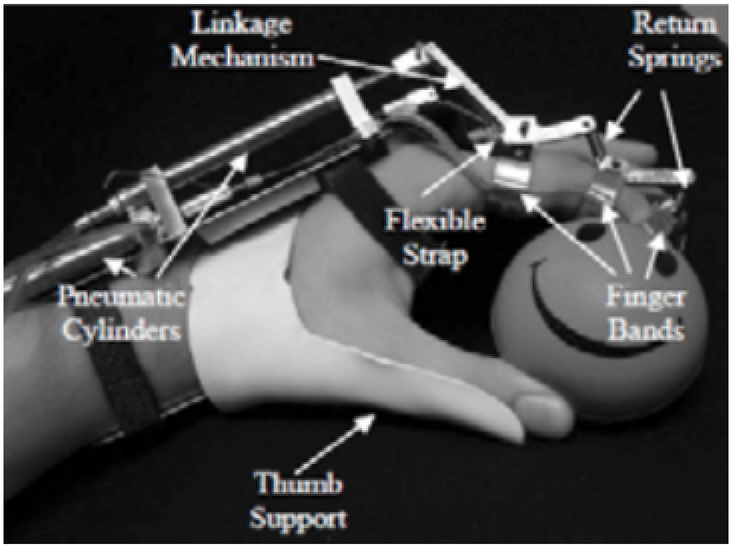


Figure 2.5: Dicicco model [9]

This prototype uses the mechanism configuration (c) from Figure 2.2, using a pneumatic wrist-coupled trigger to promote the extension and abduction movement of the index finger, coupled with some return springs to give smoothness to the movement. The air accumulation system is positioned on the patient’s waist, whose control is made, as mentioned, by a system who reads residual EMG signals and then, through a developed algorithm, makes the proportional activation of the pneumatic system.

However, the EMG system increases significantly the value of the device, and the air accumulation system can be considered uncomfortable by the patient.

- **Hasegawa device**

  The model elaborated by Hasegawa et al [8] have the objective of assisting the grasping movement of the hand, so the mechanism includes all the fingers, leaving the thumb locked and controlling the movement of the index finger alone, and the middle, ring and minimum fingers in conjunction.

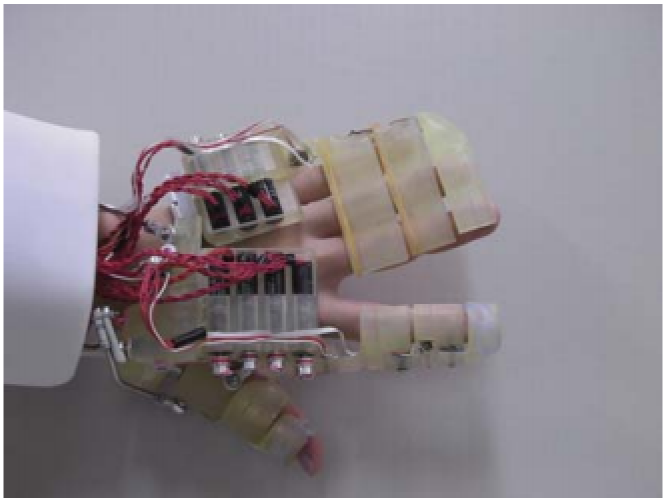


Figure 2.6: Hasegawa prototype [8]

  The mechanism utilized uses the configuration (a) from Figure 2.2, where each joint is driven separately by cables tensioned using electric motors. The motors are driven through electrodes positioned above the lumbrical muscles, which capture bioelectric potential produced, that is used to calculate the desired movement and the force that should be exerted by the system.

  Despite of it's portable design an good functionally, the bioelectric capture system increases the value and complexity of the device, which narrow it's use world wide.

- **Shields et al device**

  One of the oldest models, was developed by Shields et al, that were NASA engineers, to help the astronauts realize the grasping movement while wearing their pressurized gloves, preventing hand fatigue and allowing the realization of precision and strength based action.

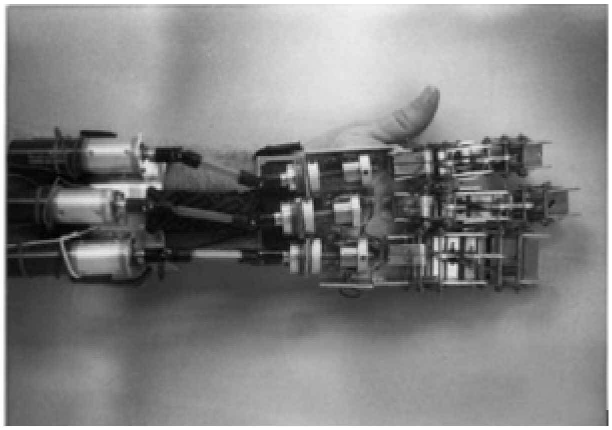
  

  Figure 2.7: Shields model [18]

  The mechanism utilized uses the configuration (b) from Figure 2.2, being driven by three electric motors that tensions cables connected to a set of cams that move the central module of articulation, generating the contraction of the index, middle and/ or annular/minimum fingers, while the extension of the fingers would be generated passively by the own pressurized glove. The three motors are controlled using "a state-of-the-art programmable microcontroller using pressure sensor input" [18].

  Despite of it's good integration between electrical and mechanical system, it's use is not valid for usual patients without the astronauts apparel.

- **Tadano et al device**

  The Model proposed by Tadano et al [19] focus on amplify the grip strenght of an individual, being that on a medical or on a labor situation.

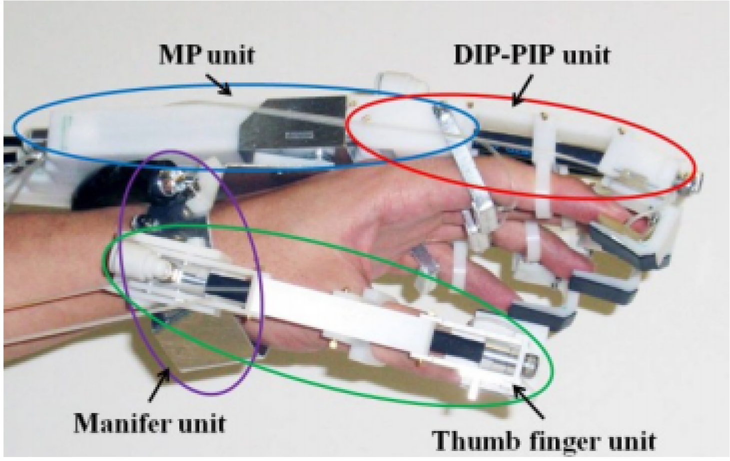


Figure 2.8: Tadano model [19]

  The mechanism uses a system of artificial rubber muscles, connected to a configuration of type (f) from Figure 2.2. The drive control is done through a balloon sensor positioned at the proximal and distal parts of the fingers, that measures the pressure applied by the user and amplifies it's value through a programmed algorithm.

  Being the device that most aligns with the objectives of this paper, it's limitations are similar to the Hasegawa device: the rubber muscles system increases the cost and complexity of the mechanism, limiting it's reach.

Chapter 3

Proposed model: M.O.H.

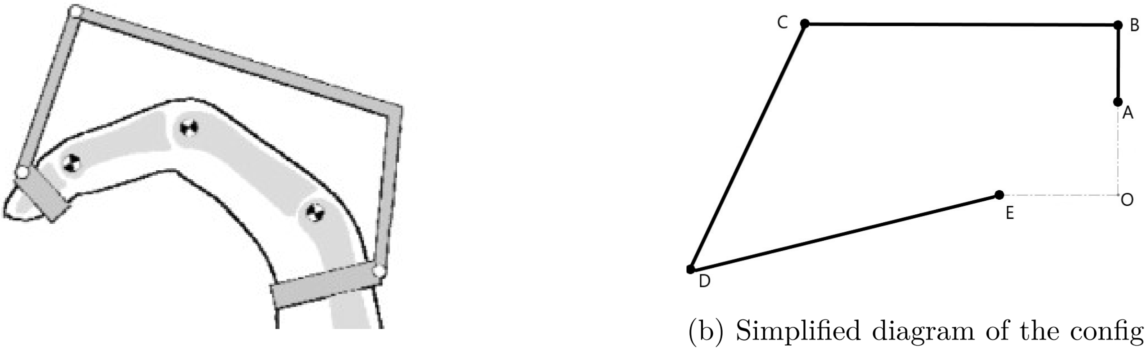
The model proposed in this work consist in a mechanical system capable of amplifying the strength of the index finger, in order to realize the pinch movement.

The input and control of the movement induced in the index finger will be done through the movement of the middle finger. The objective is to produce a model with a simple mechanical system, adaptable to the needs of each patient, whose components may be produced with a low cost method, such as 3D printing.

To accomplish this objective, the development of the model was divided into two elements: the Fingers Mechanism, where is developed the structures responsible for transmitting the movement for the index finger and from the middle finger, and the Transmission Mechanism, which, as the name suggest, is responsible for making the transmission of the movement from the middle finger to the index finger.

3.1 Fingers Mechanism

The mechanism configuration used in both fingers, index and middle, is a variation of the configuration (f) from the Figure 2.2. To study the best form of adapting this configuration to the model necessities, it was developed a simplified diagram, as shown in Figure 3.1



(a) Configuration (f) of Figure 2.2

(b) Simplified diagram of the configuration used

Figure 3.1: Original configuration and simplified diagram used during development

The main objective of the Fingers Mechanism study is to calculate the optimized length of each component of the mechanism, based in the length of each finger and the natural movement done by patient. The optimized length of each component would be the ones that, for the index finger mechanism, produces a maximum oscillation of the finger with minimum oscillation of the input member; and for the middle finger, produces a maximum oscillation of the output member with minimum oscillation of the finger. For the accomplishment of this task, it was chosen the software Ansys workbench, due to it's geometrical support, rapidity and facility to set up and analyse the input data and the obtained results [20] .

- **Geometric optimization**

The optimization process using the software Ansys began with the creation of a three-dimensional model of the diagram shown in the Figure 3.1, using the geometry software Ansys Design Modeler, for both the index and middle finger. The Figure 3.2 presents the proposed model created.

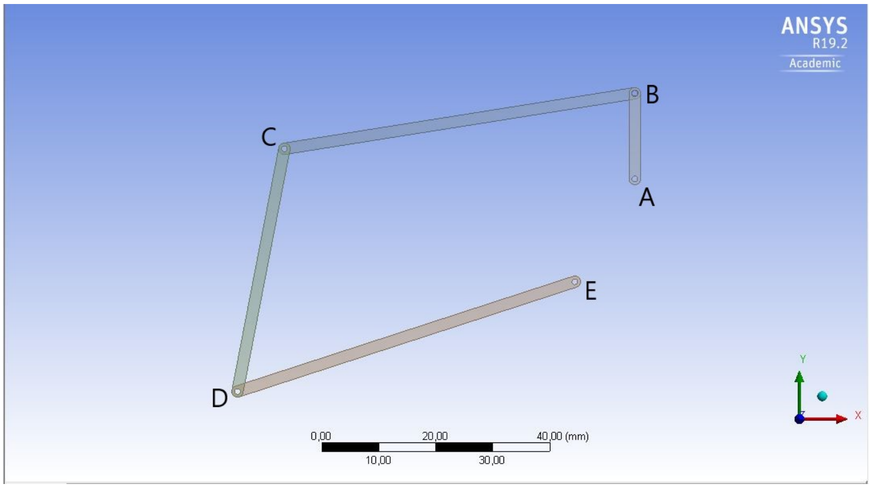


Figure 3.2: Ansys model

For the procedure of the optimization process, it was necessary to choose dimensions to serve as variable parameters and fixed parameters for the simulations.

The system is composed by a set of parameters, named: the lengths L1 (length $\overline{AB}$), L2 (length $\overline{BC}$) and the angles for the initial position θ_1 (angle between member L1 and the axis X) and β (angle between member L2 and L3), while were set as fixed parameters the length L4 (finger length) (length $\overline{DE}$) and it's initial angle θ_4 (angle between member L4 and the axis X). By this definition, the length L3 (length $\overline{CD}$) became then derived from those other parameters.

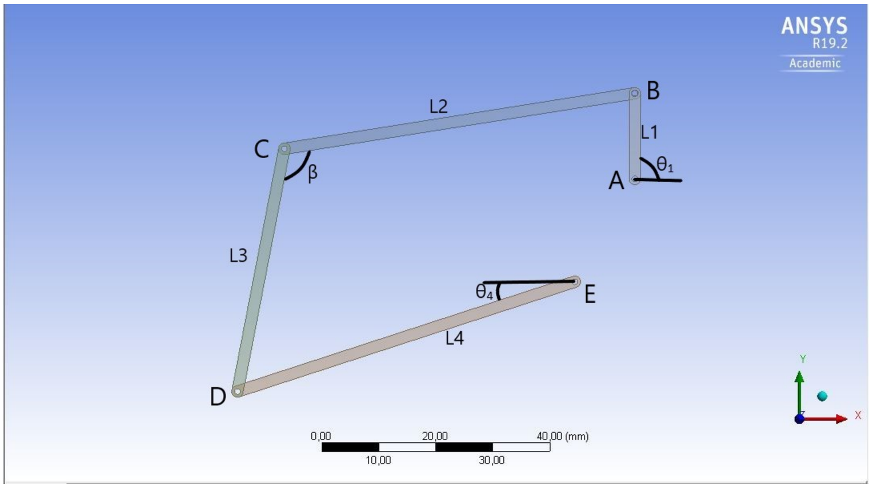


Figure 3.3: Optimization parameters

In the index model system, the joint between the members L1 and L2 is fixed, while in the middle model system, the joint between the members L2 and L3 is considered fixed. This difference on the configurations came from an empirical observation of better results for each finger in each case. The mentioned parameters are shown identified in figure 3.3.

Both models were submitted to a rigid dynamics simulation, where the input movement was a angular velocity of one degree per second imposed to the member L4, and the results obtained were the position of the most distant point of the members L4 and L1, as shown in the Figure 3.4. This results were also set as parameters values.

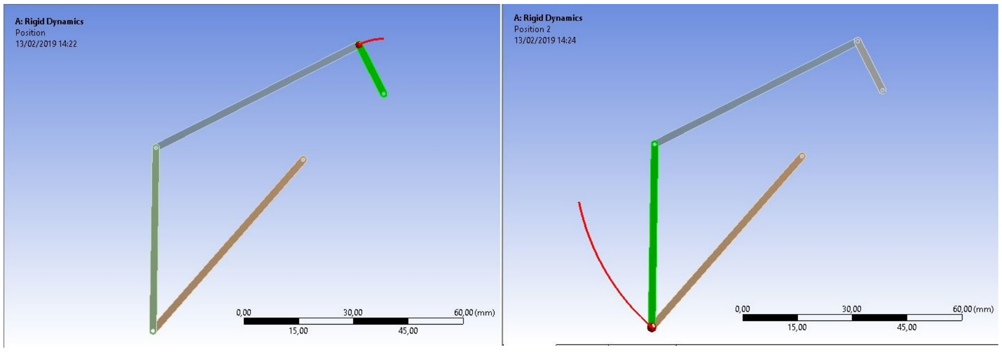


Figure 3.4: Rigid Dynamics simulation results

Concluded the basis simulation, the optimization process was made using the tool Response Surface Optimization [21], where were created 25 design points, utilizing the “Optimal Space-Filling Design” method to generate aleatory values for each of the input parameters, within the boundary limitations imposed to each one of them. Each design point is them submitted to the same rigid dynamics simulation, to analyse the influence of varying each one of the four values in the results obtained. This study is used as basis to determine the optimized value of each parameter seeking to achieve the intended goal, in this case, maximize the oscillation of the member L1 for the index finger study and maximize the oscillation of the member L1 in the middle finger study. Ansys returns the values of most promising five candidate points, from which is chosen the one with most satisfying results.

As a preliminary test, there was first made simulation using standard values for the lengths of the index (62.22mm) and middle (67,84mm) fingers for man. The candidate points obtained for the index finger mechanism system are presented in Table 3.1.

Candidate Points	L1(mm)	L2(mm)	θ_1(degree)	β(degree)
1	12.002	69.444	240.09	112.88
2	12.000	67.942	240.04	105.99
3	12.001	66.942	240.00	110.25
4	12.017	66.942	240.00	107.89
5	12.015	66.863	240.00	108.26

Table 3.1: Candidate Points for the index finger mechanism system

The candidate points obtained for the middle finger mechanism system are presented in Table 3.2.

Candidate Points	L1(mm)	L2(mm)	θ_1(degree)	β(degree)
1	19.999	74.505	119.96	158.09
2	19.997	74.173	119.98	148.90
3	19.998	74.499	119.96	138.68
4	19.999	70.073	120.00	153.83
5	19.994	71.066	119.99	156.95

Table 3.2: Candidate Points for the middle finger mechanism system

Based on the results presented by the verified analysis of each candidate point, it were chosen as the best options for study the Candidate Point 2 for the index finger and the Candidate Point 1 for the middle finger.

- **Force analysis of fingers mechanism system**

  With the lengths of each parameter of the mechanism geometrically established, it is necessary to analyze the forces needed to activate the mechanism and realize the intended task. This analysis was made by first creating a mathematical model for the movement of the mechanism, using the systematic method of kinematic analysis applied to the diagram shown in Figure 3.5.

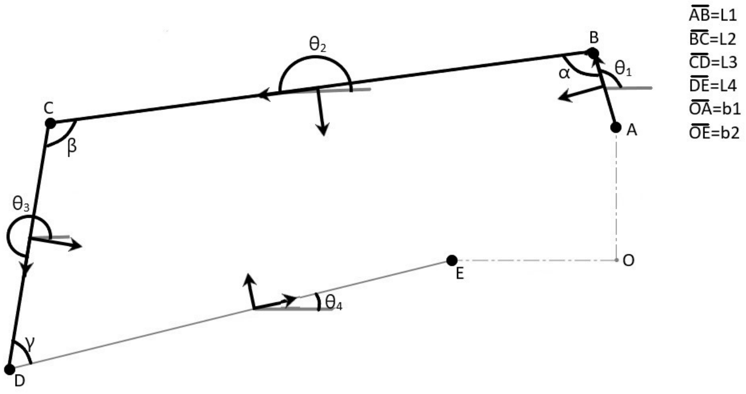


Figure 3.5: Diagram of the proposed model in MatLab

Based on this diagram, it was elaborated the system of physical and mechanical constraints, shown below. Φ_D^K, defined at (1), represents the kinematic and driving constrains system of the nonlinear equations system which control the movement of the index finger mechanical system, while Ω_D^K, defined at (2), represents the kinematic and driving constrains system of the nonlinear equations system which control the movement of the middle finger mechanical system.

$$\Phi_D^K = \begin{bmatrix} x_1 - \frac{L_1}{2}\cos(\theta_1) \\ y_1 - \frac{L_1}{2}\sin(\theta_1) \\ \theta_2 - \theta_1 - \alpha \\ x_1 + \frac{L_1}{2}\cos(\theta_1) - x_2 + \frac{L_2}{2}\cos(\theta_2) \\ y_1 + \frac{L_1}{2}\sin(\theta_1) - y_2 + \frac{L_2}{2}\sin(\theta_2) \\ x_2 + \frac{L_2}{2}\cos(\theta_2) - x_3 + \frac{L_3}{2}\cos(\theta_3) \\ y_2 + \frac{L_2}{2}\sin(\theta_2) - y_3 + \frac{L_3}{2}\sin(\theta_3) \\ x_3 + \frac{L_3}{2}\cos(\theta_3) - x_4 + \frac{L_4}{2}\cos(\theta_4) \\ y_3 + \frac{L_3}{2}\sin(\theta_3) - y_4 + \frac{L_4}{2}\sin(\theta_4) \\ x_4 + \frac{L_4}{2}\cos(\theta_4) + b1 \\ y_4 + \frac{L_4}{2}\sin(\theta_4) \\ \theta_4 - (0.1\pi + \omega t) \end{bmatrix} = 0 \qquad (1)$$

$$
\Omega_D^K = \begin{bmatrix}
x_1 - L1/2\cos(\theta_1) \\
y_1 - \frac{L_1}{2}\sin(\theta_1) \\
\pi - \theta_3 + \theta_2 + \beta \\
x_1 + \frac{L_1}{2}\cos(\theta_1) - x_2 + \frac{L_2}{2}\cos(\theta_2) \\
y_1 + \frac{L_1}{2}\sin(\theta_1) - y_2 + \frac{L_2}{2}\sin(\theta_2) \\
x_2 + \frac{L_2}{2}\cos(\theta_2) - x_3 + \frac{L_3}{2}\cos(\theta_3) \\
y_2 + \frac{L_2}{2}\sin(\theta_2) - y_3 + \frac{L_3}{2}\sin(\theta_3) \\
x_3 + \frac{L_3}{2}\cos(\theta_3) - x_4 + \frac{L_4}{2}\cos(\theta_4) \\
y_3 + \frac{L_3}{2}\sin(\theta_3) - y_4 + \frac{L_4}{2}\sin(\theta_4) \\
x_4 + \frac{L_4}{2}\cos(\theta_4) + b1 \\
y_4 + \frac{L_4}{2}\sin(\theta_4) \\
\theta_4 - (0.1\pi + \omega t)
\end{bmatrix} = 0 \qquad (2)
$$

Solving this nonlinear equations system, it is possible to calculate the values for each group of variables, based on informed values for the initial position, through all the movement realized by each finger.

With the nonlinear system set up, it was created a simulation setting the initial conditions for the system and the angular velocity of one degree per second.

To obtain the simulation behavior, the software must solve the nonlinear system, using for that the MatLab *fsolve* command, that makes the solution of the equation system by the Trust-Region Dogleg Method [22], obtaining in the end the coordinates of each point at each second, during thirty seven seconds, that would be a complete movement realized by each finger. With this information, it was possible to calculate the variation of each one of the angles between the members, and the position of each one during the complete movement.

The forces analysis was made using the method of calculation for loads in beams, which consists of considering each joint individually, and them applying the force equilibrium law at each one to discover the values of the forces applied by each member connected in the joint. The expect load at the point of the finger was applied at the joint point D, perpendicular to the member $\overline{ED}$ (force P),and them it was obtained the reaction force generated in the joint point B, perpendicular to the member $\overline{AB}$ (force F).Theses two forces are shown in Figure 3.6, and the equation who represents this process is shown below.

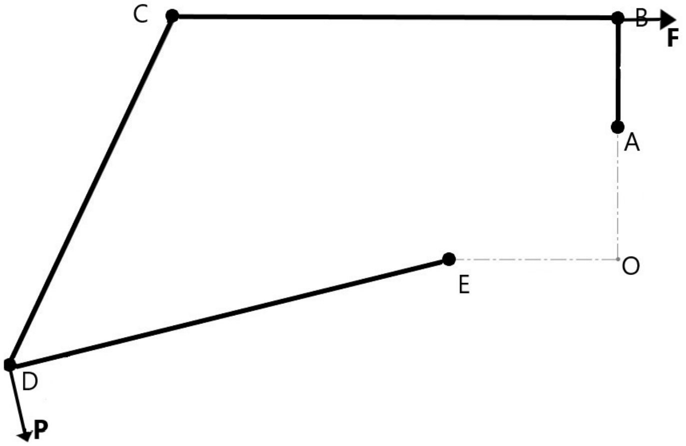


Figure 3.6: Diagram of forces

$$F = -P\frac{\cos(\theta_3 - \theta_2)}{\sin(\theta_3 - \theta_4)}$$

The standard values of force used for this calculation are shown in Table 3.3. To obtain the values of force between the 40mm and 1mm pinch, it was used a linear approximation.

	Index Healthy		Middle Healthy	
	male	female	male	female
40mm pinch	21.77	17.60	11.67	7.94
1mm pinch	19.07	15.59	7.55	6.18

Table 3.3: Standard values for pinch force in the index and middle fingers

3.2 Transmission mechanism of the model

The transmission mechanism idealized for the model is based, first, by a lever mechanism, that would make the multiplying of the forces from the middle finger, and a spring connected to a piston configuration, that would apply the force multiplied to the index finger, allowing a gradual apply of strength along the movement. The sketch of the mechanism is shown in the Figure 3.7.

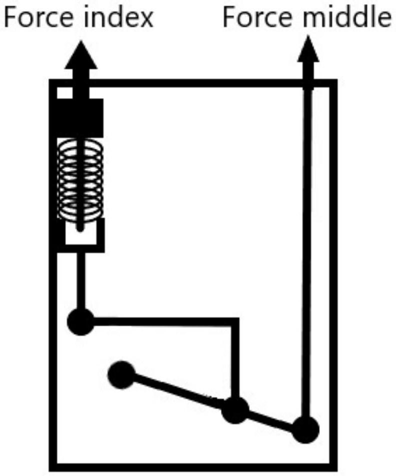


Figure 3.7: Transmission mechanism sketch

The selection of the multiplying factor used in the lever mechanism would be made dividing the highest value obtained for the input forces in the index finger by the lowest value obtained for the output forces in the middle finger.

The selection of the spring is made by calculating the spring constant, dividing the maximum value for the input force necessary in the index finger by the available length of the piston in the moment.

The geometry of the piston system was determined such as the application of force in the joint B (Figure 3.5) would made in the most efficient way, which means applying the force in the most perpendicular way to member $\overline{AB}$, during most of the movement realized.

3.3 Model Prototype

In order to ascertain of validation, it was elaborated a prototype of the model, to see how much mechanical factors, like friction, weight, and the ergonomic factors would affect the mechanism. The first step was select four healthy volunteer from the IPB community, two men and two women, with the standard height of the Portuguese community, to take measures of the elements of their hands, such as their index and middle fingers phalanx, and also the angulation of them when performing the pinch movement.

- **Data acquisition**

  The measurements of the volunteers proximal phalanx (P3 from Figure 2.1) and medial phalanx (P2 from Figure 2.1) were made using a plastic rule with milimetrical precision at the calculations center, and the values observed are shown in the table 3.4. The angulation of the fingers during the realization of the pinch movement was measured by taking a picture of the voluntary hand during the act, and realizing the measurement over it using the software Kinovea[4]. This measurements can be seen in Figures 3.8 to 3.11.

	Man 1	Man 2	Woman 1	Woman 2
index P.P.(mm)	45	44	40	44
index M.P.(mm)	21	20	18	21
middle P.P.(mm)	52	49	44	50
middle M.P.(mm)	25	25	24	26

Table 3.4: Lengths of the proximal and medial phalanx in each volunteer

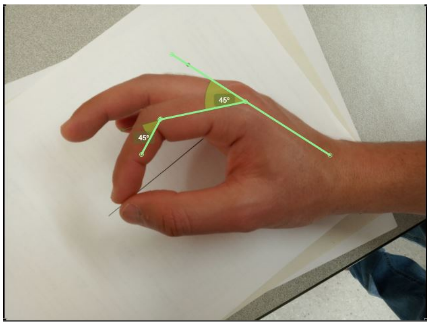


Figure 3.8: Angles Man 1

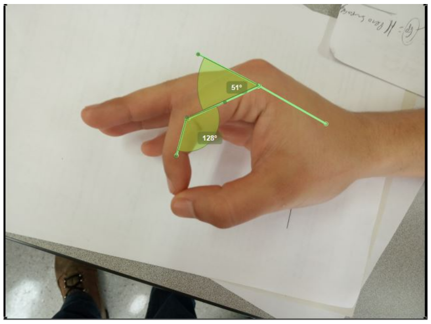


Figure 3.9: Angles Man 2

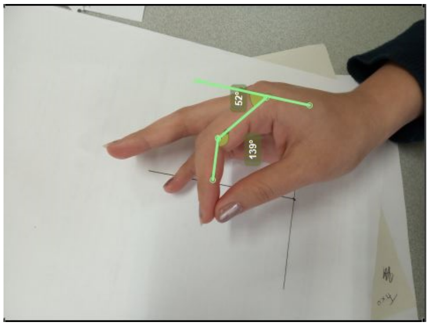


Figure 3.10: Angles Woman 1

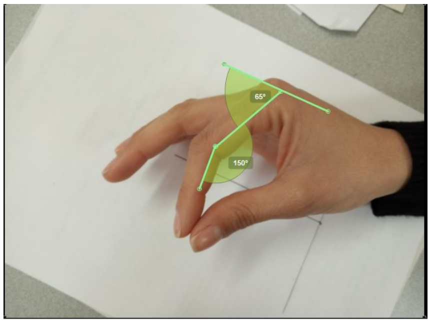


Figure 3.11: Angles Woman 2

The length L4 used in the simulation process is obtained by the sum of the vectors linked to phalanx of each finger, when angled in the pinch position. The calculated values are shown in table 3.5.

	Index Finger	Middle Finger
Man 1	64.30	75.00
Man 2	62.37	72.67
Average Man	63.34	73.84
Woman 1	57.77	67.71
Woman 2	63.65	74.38
Average Woman	60.71	71.05

Table 3.5: Calculated L4 for each volunteer and average values in mm

- **Prototype design**

  With the information acquired, showed in Table 3.4, it was developed a virtual model for the male and female hand, using the CAD software SolidWorks, and based on this initial model, it was created the geometry to the fingers members and the transmission mechanisms, shown in the Figures 3.12 e 3.13, following the lengths and angles obtained in the first step. The geometry of the components was defined so that it would reduce the printing time necessary, while retaining the precision degree that the machine could offer. Because of that, most of components were designed as bars with a 5mm square cross-section and rounded ends.

  The pieces were produced using a 3D printer Ultimaker 3[23] and PLA (polylactic acid) as material, which having a tensile modulus of 49.5 MPa[23], should provide the necessary resistance for the pieces. The initial concept was to make the model build over a cotton glove, that would be worn by the volunteers, which is shown in Figure 3.14. However, this configuration has shown some mobility problems, due to the inflexibility generated in the glove by the mechanism and the dismantle of some components during the process of putting and taking off the gloves, due to it's natural contraction behavior.

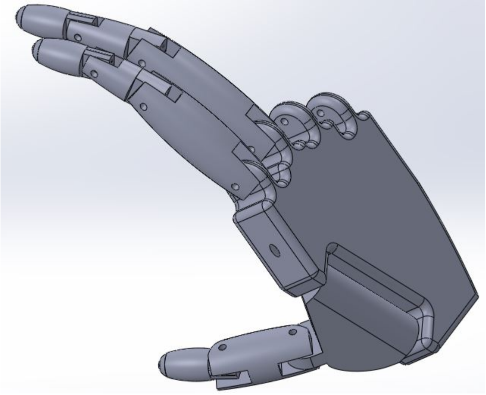


Figure 3.12: Human hand model

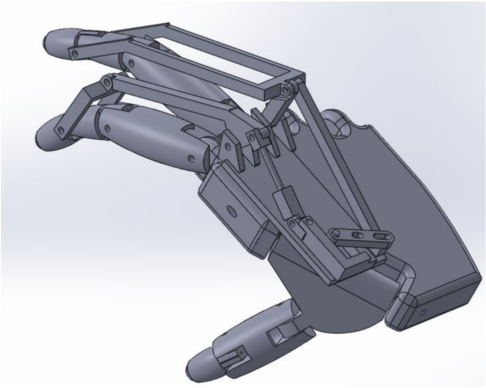


Figure 3.13: First prototype assemble

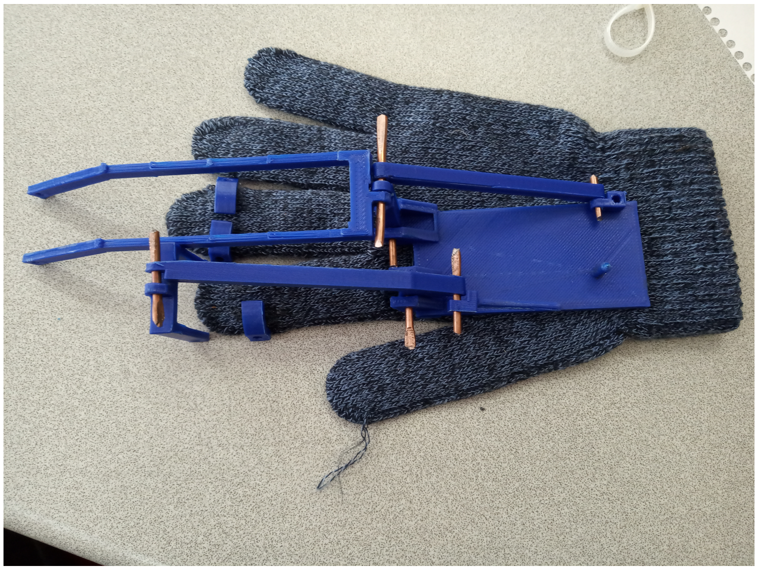


Figure 3.14: Prototype configuration I

Because of that, it was elaborated a new geometry for the fingers prototype, where the prototype elements would be coupled in the fingers using plastic strips, and be fixed in the hand using a leather strip with a adjustable lock. The new configuration is shown in Figure 3.15.

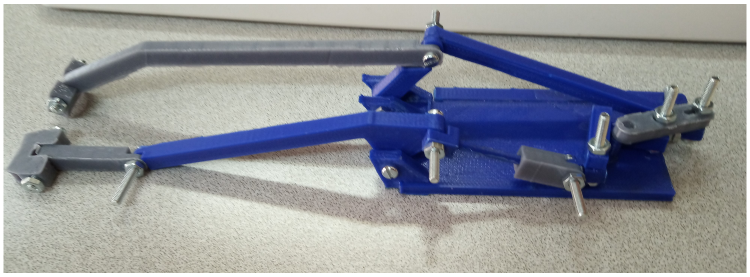


Figure 3.15: Prototype configuration II

Following the feedback given by the volunteers, there were made adjust and some additions to the model, seeking to improve it's performance, like lateral paths to secure the linear movement of the components. The model installation during the tests, and it's final configuration are shown in Figures 3.16 and 3.17.

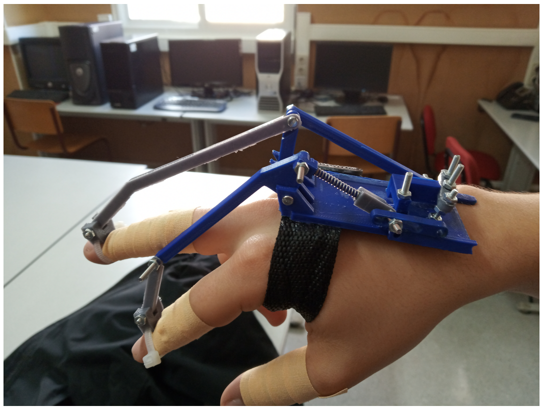


Figure 3.16: prototype during test

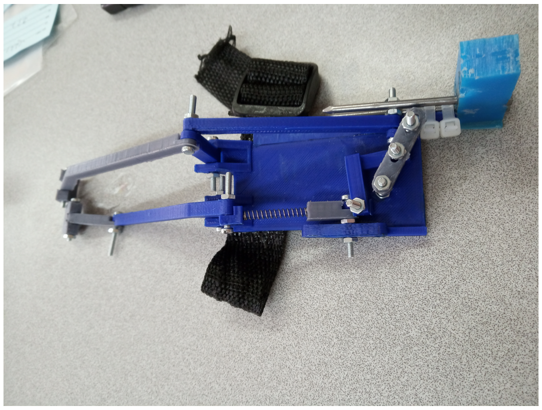


Figure 3.17: Prototype configuration IV

By the end of the tests, the prototype achieved it's purpose, allowing the volunteers to grab a bottle of water with approximately 150 ml and to writing some words with a pen, using only the movement of the middle finger and with minimum application of force by the index finger.

In conclusion, it can be affirmed that, to obtain the ideal performance of the model, it is necessary to collect the anatomic of the patient, and develop one personalized model of study for each one, realizing first the geometric analysis to define the finger mechanism for the index and middle fingers, second the forces analysis to define the transmission mechanism of the model, and at the end produce the pieces of the model, seeking to ensure that the real model works as close as possible from the theoretical model.

Chapter 4

Tests with Patients

4.1 Characterization of patients

Based on the good results obtained by the prototype model tests, it was set to advance to the tests with volunteers with real debilitation. For that, it was contacted the occupational-therapist Telmo Teles, who introduced me to two patients that he thought would present a good study case scenario: a elderly woman, who suffered from an stroke and had a complication due to a fall, that will be called Patient A, and a girl who suffer of Cerebral Palsy since birth, that will be Patient B.

Both patients present debility on the right side of the body. during a conversation with the physiotherapist, it was defined that Patient A has a degree of debility of sixty percent and Patient B has a degree of debility of thirty percent.

- **Data collection**

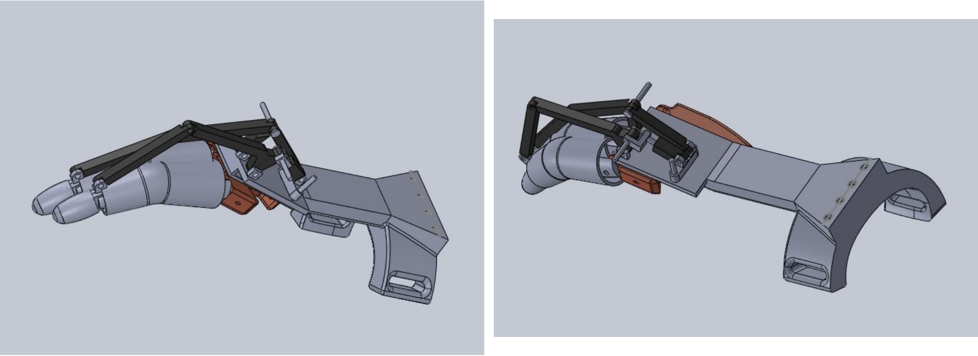
  During a conversation with the therapist, he emphasized the need of the addition of a wrist support in the model, otherwise it would be difficult for the patients to keep their hands stable for realizing the pinch movement. For that reason, in addition to the fingers measures, it was also taken measures of the hand and the wrist of the patients. These measurements are shown in Table 4.1,

  The changes made in the model design to accommodate the wrist support, and also

	Patient A	Patient B
Index P.P.(mm)	35.00	28.00
Index M.P.(mm)	24.00	23.00
Calculated L4(mm)	57.65	51.77
Middle P.P.(mm)	38.00	33.00
Middle M.P.(mm)	26.00	24.00
Calculated L4(mm)	62.53	55.68
Wrist width(mm)	54.00	35.00

Table 4.1: Data collected from the patients

ensure the correct linear movement of the members of the transmission mechanism, are shown in Figure 4.1.



(a)

(b)

Figure 4.1: New model design

4.2 Fingers Mechanism

- **Patient A**

Using the length L4 previously calculated, shown in Table 4.1, the Candidate Points obtained in the Ansys simulation for both fingers are shown in Tables 4.2 and 4.3.

Candidate Points	L1(mm)	L2(mm)	θ_1(degree)	β(degree)
1	12.000	50.001	240.01	105.01
2	12.001	50.232	240.01	107.25
3	12.000	50.436	240.00	110.48
4	12.001	50.573	240.03	105.06
5	12.002	50.23	240.03	105.19

Table 4.2: Candidate Points for the index finger mechanism system

Candidate Points	L1(mm)	L2(mm)	θ_1(degree)	β(degree)
1	19.995	50.500	119.93	158.44
2	19.993	51.023	119.97	152.58
3	19.994	50.888	119.98	144.84
4	19.982	51.234	119.91	154.73
5	19.985	51.101	119.78	156.19

Table 4.3: Candidate Points for the middle finger mechanism system

Analysing the candidate points obtained for each finger, the lengths chosen for each member of the mechanism are shown in table 4.4.

	Index	Middle
L1 (mm)	12.000	20.000
L2 (mm)	50.436	50.5.000
L3 (mm)	48.980	53.288

Table 4.4: Length of the members for each finger mechanism

- **Patient B**

Using the length L4 previously calculated, shown in Table 4.1, the Candidate Points obtained in the Ansys simulation for both fingers are shown in Tables 4.5 and 4.6.

Candidate Points	L1(mm)	L2(mm)	θ_1(degree)	β(degree)
1	12.000	50.003	240.00	105.05
2	12.001	50.286	240.00	106.31
3	12.001	50.294	240.00	107.76
4	12.008	50.296	240.05	105.47
5	12.008	50.296	240.05	105.47

Table 4.5: Candidate Points for the index finger mechanism system

Candidate Points	L1(mm)	L2(mm)	θ_1(degree)	β(degree)
1	19.998	41.364	119.99	107.41
2	19.997	40.096	119.98	148.70
3	20.000	41.142	119.98	155.54
4	19.998	40.580	119.95	110.28
5	19.995	41.009	119.96	107.46

Table 4.6: Candidate Points for the middle finger mechanism system

Analysing the candidate points obtained for each finger, the lengths chosen for each member of the mechanism are shown in table 4.7.

	Index	Middle
L1 (mm)	12.000	20.000
L2 (mm)	50.003	41.142
L3 (mm)	45.661	56.195

Table 4.7: Length of the members for each finger mechanism

4.3 Transmission Mechanism

Considering a degree of debility of sixty percent for the Patient A and thirty percent for the Patient B, the results for the force exerted by the middle finger when flexed, and the input force necessary for the compensation of the debility on the index finger are shown in the table 4.8. The table shows each value of force obtained at each second during the movement of each finger, considering a velocity of one degree per second of the member $\overline{ED}$, a total time of 37 seconds, and a multiplying factor of 1.25 during the application of force in the index finger, due to an geometric characteristic of the piece that comprises the length L1. The table also shows the compensation ratio, which represents the minimum necessary multiplying factor that needs to be applied by transmission mechanism to the force exerted by the middle finger, to matches the necessary input force to be applied at the index finger.

	Patient A			Patient B		
Time(s)	Index	Middle	Compensation ratio	Index	Middle	Compensation ratio
1	2.40	3.70	0.65	1.13	6.86	0.16
2	2.42	3.83	0.63	1.14	7.07	0.16
3	2.44	3.94	0.62	1.16	7.26	0.16
4	2.46	4.05	0.61	1.17	7.43	0.16
5	2.48	4.14	0.60	1.18	7.58	0.16
6	2.50	4.23	0.59	1.19	7.73	0.15
7	2.52	4.31	0.58	1.20	7.87	0.15
8	2.54	4.39	0.58	1.21	8.00	0.15
9	2.55	4.46	0.57	1.21	8.13	0.15
10	2.57	4.53	0.57	1.22	8.25	0.15
11	2.58	4.60	0.56	1.23	8.36	0.15
12	2.60	4.66	0.56	1.24	8.48	0.15
13	2.61	4.72	0.55	1.24	8.59	0.14
14	2.62	4.78	0.55	1.25	8.70	0.14
15	2.63	4.84	0.54	1.25	8.80	0.14
16	2.64	4.89	0.54	1.26	8.91	0.14
17	2.65	4.95	0.54	1.26	9.01	0.14
18	2.65	5.00	0.53	1.27	9.11	0.14
19	2.66	5.05	0.53	1.27	9.21	0.14
20	2.67	5.10	0.52	1.27	9.31	0.14
21	2.67	5.14	0.52	1.27	9.41	0.14
22	2.67	5.19	0.51	1.27	9.52	0.13
23	2.67	5.24	0.51	1.27	9.62	0.13
24	2.67	5.28	0.51	1.27	9.72	0.13
25	2.67	5.33	0.50	1.27	9.83	0.13
26	2.67	5.37	0.50	1.27	9.94	0.13
27	2.67	5.42	0.49	1.27	10.05	0.13
28	2.66	5.46	0.49	1.27	10.16	0.12
29	2.66	5.51	0.48	1.26	10.28	0.12
30	2.65	5.55	0.48	1.26	10.40	0.12
31	2.64	5.59	0.47	1.25	10.52	0.12
32	2.63	5.64	0.47	1.25	10.65	0.12
33	2.62	5.68	0.46	1.24	10.79	0.11
34	2.61	5.72	0.46	1.23	10.94	0.11
35	2.60	5.77	0.45	1.23	11.09	0.11
36	2.59	5.81	0.45	1.22	11.26	0.11
37	2.57	5.85	0.44	1.21	11.43	0.11

Table 4.8: Values of output and input force for the transmission mechanism

As can be observed in the table, the compensation ratio necessary for the transmission mechanism must be, at least, of 0.65 for the Patient A and of 0.16 for the Patient B. However, due to construction limitations connected to the minimum distance necessary to be covered by the piston to realize the full movement of the mechanism and exert the force necessary through the spring, the compensation ratio used in both cases was equal to 1.8. The information used in the selection of the spring that composes the transmission mechanism of each orthosis are shown in Table 4.8.

	Patient A	Patient B
Middle total length covered (mm)	10.00	9.71
Index total length covered (mm)	5.55	5.39
Index length needed (mm)	4.69	4.91
Minimum length for contraction of the spring (mm)	0.86	0.48

Table 4.9: Measures used in the choice of the spring

Dividing the input force necessary in the last position for the calculated minimum length available, we have a value for the elastic constant of 2.99 N/mm for Patient A and 2.52 N/mm for the Patient, but, for commercial reasons, it was used a spring model with constant equal to 3N/mm for Patient A and 2.6 for Patient B.

4.4 Final Tests

Using the measures obtained through the Ansys and MatLAb simulations, the pieces of both models were 3D-printed using PLA as material in a printer model Builder V3.02 Big, and mounted together using hexagon screws as joints, where the screws were sawed right after the bolt and the point was covered with a layer of silicon, to prevent the loosening of the bolt due to the movement. The fixation of the orthosis on the arm and hand of the patient was made using cloth strips that were stitched with Velcro, while for the Patient A, it was also developed a glove with a hardened leather surface between the thumb and the index finger, to help keep the thumb stable, helping in the realization of the movement. A picture of the models is shown in Figure 4.1.


(a) (b)

Figure 4.2: Final model orthosis

The connection with the finger was first idealized to be made through a full 3D-printed piece, that would cover all the surface of the finger, shown in Figure 4.2, keeping it stable and giving support to the movement. However, in a a first encounter with the patients, they pointed that the smooth surface of the piece was not practical to use, since it sometimes was slipping off from the fingers after repeating the movement for some period, and the smooth surface on the outside did not allow them to have a good grip of the objects. Based on that, it was developed a new connection, that consisted on a 3D-printed ring, that was fixed on a hollow half cone piece made of leather, that had a strip of Velcro stitched on the surface that would correspond to the inner part of the finger. This new piece is also shown in Figure 4.2.

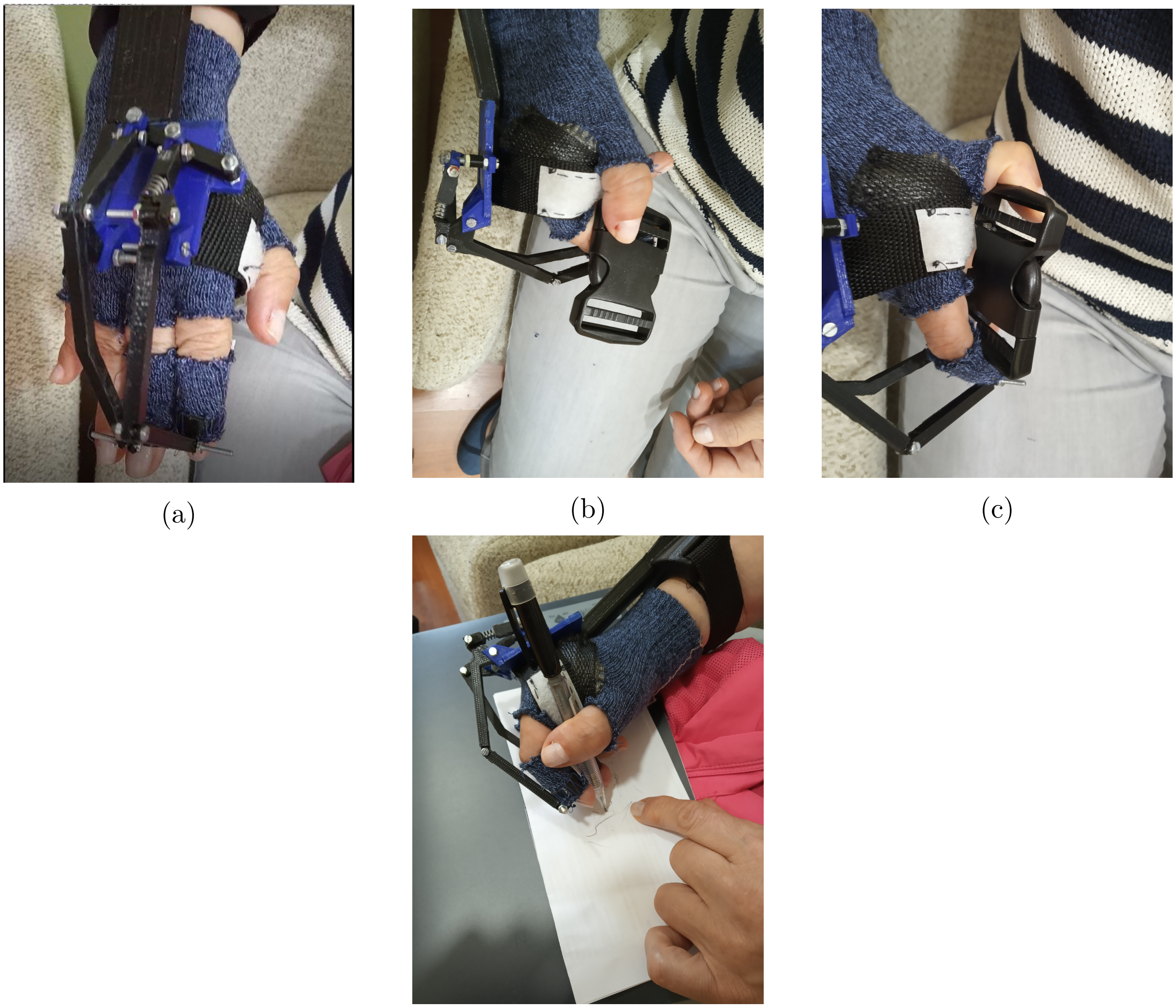

(a) first design (b) final design

Figure 4.3: Designs of the finger connection

Solved the question of the finger connection, it was time to advance to the functionality tests.

- **Patient A**

  During the tests, the patient was able to realize the full movement with the fingers, hold firmly piece a plastic, in it's wide and thin positions, a piece of paper and a pen. However, due to the degree of debility present in the whole arm, she was only able to make short lines on the paper, and make small movements with the pieces in hold. The images of the test are shown in Figure 4.4.



(a) (b) (c)

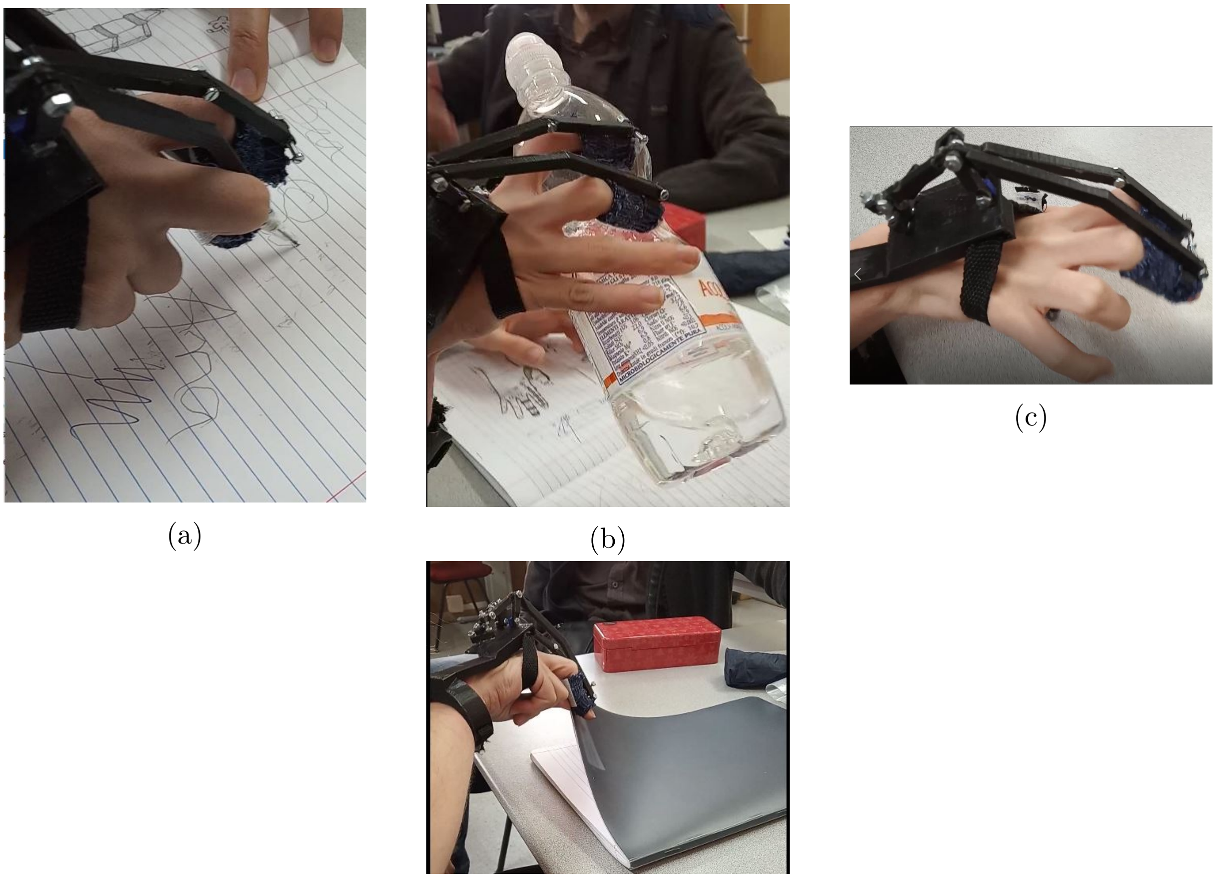
(d)

Figure 4.4: Test Patient A

By the end of the tests, the patient affirmed that the orthosis gave good support for the wrist and the thumb, increased the range of movement for the fingers, and she felt more safe to hold the objects.

- **Patient B**

  During the tests, the patient was able to realize the full movement of the fingers, open a notebook, and hold firmly a cellphone, a bottle of water and a pen, being able to draw curving lines and write down some words, even in cursive letters. The images of the test are shown in Figure 4.5.



(a) (b) (c) (d)

Figure 4.5: Test Patient B

By the end of the test, the patient affirmed that she felt her wrist more stable, an improvement in the range of movement of the fingers, an that it was easier to hold things, specially during writing. However, holding heavier things, like the bottle, was still weary.

Chapter 5

Conclusion and Future Work

In the medical field, there are several factors that can lead to a loss or decrease of an individual's motor and/or coordination abilities, such as spinal cord injury caused by an accident, a Cerebral Vascular Accident, Cerebral Palsy, and others alike. These medical conditions can affect the whole body, or just part of it, affecting directly the capacity of the patient for realizing daily activities and lead an independent life.

Since the hand is one of the members that most affect patient's independence and quality of life, this study focused on the development of a solution for the condition of lost of motor skills in the hands, specifically, in the realization of the pinch movement.In this way, it was be developed a model of mechanical orthosis capable of assisting the basic movement of opposition between the index finger an the thumb (forceps), allowing the patient to perform daily actions that involve picking or lifting an object, as well as perform the writing movement.

Over the years, several models of hand orthoses have been developed, with only rehabilitation purposes, or as support for hand movement. These orthotic models, despite presenting many variations in their shapes, form of driving system and activation, generally have higher-value components, and are more complex in assembly, making it difficult to produce it in large-scale and be available for the general population.

Having that in mind, and through the use a of CAE optimization process and numerical simulations, there were elaborated a model of mechanical dynamic orthosis, that, through the transmission of forces between the middle and index fingers, and using a lever mechanism to compensate the lack of strength caused by the debility, would allow the patient to realize the pinch movement and, with that, perform daily activities, such as eat by themselves, write, or hold/move objects in general.

As can be observed by the results obtained in the final tests, the functionality of the proposed model for a mechanical orthosis for hand debility has been proven, as long as the methodology developed for the definition of the members that compose it. The patients in the tests were able to write and hold objects with different shapes

However, It was also clear that the model, by itself, does not present much practical efficiency in cases with great degree of debility presented by the patients, in cases where the arm is also affected, since in this situations, even having the movement of pinch restored, the incapacity of moving or articulating the arm does not allow the patient to make a good use of it.

The next step would be the development of a model that, following the basic principles in which this work was based, could also help restore the mobility and muscular capabilities of the patient's arm, working together with the hand model.

The model shown in this work has been submitted to preliminary tests with voluntaries from the IPB community and real patients, and have been approved for presentation at the VI EIJE (International Meeting for Young Entrepreneurs) and the DD 2019 (The Double Diploma Summer School & Symposium 2019).

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