COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-0570
A NOVEL DESIGN OF ROBOTIC HAND WITH LINEAR MOTORS

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Abstract. *The hand is considered one of the most complex organs of the human body. It has in total 27 degrees of freedom in addition to an extremely high precision of each movement, and such high levels of dexterity make it also one of the hardest organs of the human body to artificially reproduce with all its movements. A lot of research has been already put into the development of robotic hands, and their applications have only grown as well, with their use in medical fields as a prime example: upper-limb prostheses represent an excellent solution to many amputees who wouldn't be able to perform daily tasks without them. However, due to practicality and availability, the vast majority of robotic hands are developed with the use of a small number of rotary motors, whose torque is often transmitted to the moving parts through cables, which tends to result in under-actuated mechanisms with a lack of precision in the final control due to backlash, in addition to a limited dexterity of movement due to the few actuators. Thereby, the main objective of this research is to explore the viability of developing more dexterous and precision-based upper-limb robotic hands with the use of alternative mechanisms, in order to further study the applications of control theories while also mitigating the common mechanical issues cited before. For this purpose, it was proposed the project of a hand able to perform an extended range of movements, with the use of 13 linear motors. Given the same dimension restrictions for the complete mechanism, linear motors generally provide a higher torque output, and their applications and behaviour haven't been as explored as the ones of rotary actuators. The actuators are placed inside the hand, transmitting motion directly through its structure, of aluminum, and thus minimizing the backlash. The hand is capable of performing extension, flexion and abduction movements of the fingers, as well as the opposition of the thumb. Unfortunately, due to the recent pandemic, it was not possible to manufacture the project, and therefore it was only developed virtually through the use of CAD and simulation softwares.*

Keywords: *Robotic hand, Linear motor, Biomimetic, Biomechanic*

1. INTRODUCTION

In 2018, over 59 thousand amputations of lower and upper limbs were performed in Brazil (de Souza *et al.*, 2019). An amputation of the limb may cause both physical and psychological challenges to the patient. To solve these problems, several groups have been researching ways to improve the adaptation of these patients to this new reality. A largely explored option is the development of prostheses.

Prostheses are artificial devices designed with the goal to replace a lost limb. Prostheses for upper and lower limbs are used for aesthetic reasons, as well as to substitute the functionality of the lost limb. These prostheses can be driven by the movements of the own body or through the use of external power sources (Ottobock, 2020), (Semasinghe *et al.*, 2019), (Sreedhar *et al.*, 2019).

One of the examples is the Galileo Hand, an anthropomorphic hand developed by researchers from the University Galileo, in Guatemala, and the University of Campinas, in Brazil. The prosthesis, as shown in Fig. 1a, is a device with 15 degrees of freedom (DoF). It has a total of 6 DC rotary motors as actuator. Five of them are responsible for the flexion of the five fingers, with the use of nylon cables as a transmission system; The extension of these fingers are achieved by the use of elastic materials. The sixth motor and its gear system is responsible for the additional movements of the thumb (Fajardo *et al.*, 2017), (Farjardo *et al.*, 2020), (Fajardo *et al.*, 2016).

Galileo hand cannot reproduce completely the movements of the human hand, which has a total of 27 DoF (Semasinghe *et al.*, 2019). Besides, the use of cables as transmission system has its limitations.

In general, upper limb prosthesis use a combination of DC rotary motors and cables as the actuation system (Semasinghe *et al.*, 2019). These systems are often under-actuated, which means more DoF than the number of actuators, in order to achieve a lighter prosthesis and lower power consumption (Sreedhar *et al.*, 2019). However, cables also restrict the possible movement of the joints through which they pass, as well as generate additional factors that need to be considered for modeling and control of the mechanisms, compromising the precision of the movements of the prosthesis.

The movements of the hand normally used are commonly divided in 2 main categories: precision handling and power grip. Precision handling is defined by the focus on the control of movements, at the expense of the applied force, and generally involves contact between the object and the distal phalanges of the fingers, while the power grip is characterized by the applied force, and the contact is defined by the object itself (Landsmeer, 1962).

Among the precision movements, there is also the subdivision based on the contact points between the fingers and the object: holding by the tips of the fingers grants greater control, but involves a smaller applied force to the grip than holding by the ventral surface of the fingers. The abduction and adduction of the thumb also play a large role in the hand grip, allowing the movement of pinch or the lateral grip with the index finger (Landsmeer, 1962).

On the other hand, power grip present less precision over how the movements are performed. Besides, the initial position of the fingers is also important to the type of grip executed, being able to do a *hook grip*, when the thumb and palm of the hand are not involved, *cylindric grip*, when the whole hand covers the object while the thumb is adducted, or *esferic grip*, when the thumb is adducted (Landsmeer, 1962).

Movements related to more delicate manipulations, such as holding a pencil or a sheet of paper, together with the power grip used for cylindrical objects, make up 85 % of every day's tasks (Semasinghe *et al.*, 2019).

Nevertheless, in a recent work (Kate *et al.*, 2017), data was collected from 58 prosthesis made by additive manufacturing, and it was shown that only 24 of them were able to perform some sort of precision handling, and less than a fourth performed successfully in any variety of the movements categories. For the majority of the cases, the prosthesis presented independent actuation on each finger, functioning with a power source external to the prosthesis.

(a) (b)

Figure 1. A picture of (a) the Galileo Hand and (b) the Shadow Dexterous Hand.

An example of humanoid device with great emphasis on precision of movements is the Shadow Dexterous Hand, presented in Fig. 1b. It is a robotic hand developed by the Shadow Robot Company, United Kingdom, which presents 20 DoF and a total of 24 movements, as well as 129 sensors implemented for a better control of the movements (Andrychowicz *et al.*, 2020), (Shadow Robot Company, 2020), (Song *et al.*, 2018).

The Shadow Hand is widely used as basis for researches about control theories (Andrychowicz *et al.*, 2020), (Eguiluz *et al.*, 2017), (Li *et al.*, 2019), (Song *et al.*, 2018), due to the dexterity delivered by the precision of the mechanisms and due to the amount of sensors used for feedback. However, the complexity and the mass of the hand, 5 kg, are limiting factors for its application as prosthesis. This is because hand and forearm, together, make up barely over 2 % of the total mass of the human body, (Plangehoeff *et al.*, 1983).

The main objective of this work is the development of a robotic hand for further use in researches with control theories, focusing on the precision and the dexterity needed to perform precision handling movements, while also preserving the needed output torque of its mechanisms in order to execute a variety of power grips. Thereby, the hand is supposed to be able to perform the majority of the daily tasks. For this purpose, the use of linear motors was proposed, as an alternative to the transmission of the motion through cables.

2. MATERIALS AND METHODS

In this paper, we are going to focus on the modeling and the design of a robotic hand driven by linear motors, to improve the controllability and to minimize the backlash. First, we are going to analyze all the DoF in a human hand to decide which one should be controlled and which one can be passively driven. Later, suitable linear actuators will be chosen for each DoF and, finally, mechanisms will be designed for each movement.

2.1 Degrees of freedom

A human hand presents a total of 14 phalanges: two for the thumb, namely proximal and distal phalanges, and three for each of the other four fingers, namely proximal, middle and distal phalanges. Each phalanx is connected to other parts of the body through joints, where the movements of flexion and extension occur. These joints are called metacarpophalangeal joint (MCP), located between the metacarpal bones and proximal phalanges; proximal interphalangeal joint (PIP), located between the proximal and middle phalanges; and distal interphalangeal joint (DIP), located between the middle and distal phalanges. Because of the absence of middle phalanx in the thumb, the joint between the proximal and distal phalanges is called interphalangeal joint (IP).

Although there is a total of 14 independent movements of flexion and extension for human hand, not all of them is essential to perform daily tasks. For example, there is no reason why we need to perform only the flexion of the distal phalanx of the index finger. Therefore, all the distal phalanges in this work is underactuated, with its motion dependent on the actuation of the previous phalanx. Distal phalanges on every finger except the thumb move alongside the middle phalanges. In thumb, the distal phalanx moves alongside the proximal phalanx.

As for the abduction and the adduction of the fingers, the same line of thought was considered. The middle finger does not present these movements, since it is rarely used in a routinely activities. The abduction and the adduction of the ring and little fingers is made through one single actuator, because of the minor importance of independence between these 2 movements. Lastly, the abduction and the adduction of the index finger and the thumb are both made independently, with the use of one actuator for each.

The final movement considered in this work is also one of great importance: the opposition and reposition of the thumb. Although this movement in the human hand is made by a combination of others, it was decided to simplify it by applying a rotary motion between the metacarpal bone and the palm.

Thereby, our design presents a total of 13 actuators: 9 for the flexion and the extension of all 5 fingers, 3 for the abduction and the adduction of 4 of the fingers, and 1 for the opposition and the reposition of the thumb. Our design has, therefore, 13 DoF, and is capable of performing 19 different movements.

2.2 Actuators

The torque values considered ideal for each movement of the hand were based on previous works, such as the hand proposed by Krausz, (Krausz *et al.*, 2016), which presents 5 actuators used for the flexion and the extension, and an actuator for the opposition and the reposition of the thumb. However, commercially available rotary motors, alongside with their gearboxes, were not able to provide at the same time an acceptable output torque, the appropriate dimensions to fit a larger number of motors and a reduced mass in order to minimize inertia effects. Therefore, in this work, we decided to use linear motors, which can generally provide great output forces even in smaller size.

The proposed minimum torque value for extension and flexion of the fingers was 0.2 N.m, which was considered enough to perform most of the daily tasks. In turn, the torques for the movements of abduction/adduction and opposition/reposition were not as definitive to the choice of the actuators, since the prehension force applied by these motions in the human hand present lower magnitudes.

Among the linear motors commercially available, the model PQ12-P with a 100:1 reduction ratio, from Actuonix, Canada, showed itself adequate to the project, since it has a reasonable output force, limited dimensions and it is generally lighter than motors with similar outputs. At its peak efficiency point, the motor provides 20 N of force through a stroke of 20 mm, while weighing only 20 g. In order to simplify further controlling implementation of the project, the motor was assigned to every actuator of the hand.

Since linear motors produce an output of linear force instead of torque, the obtained torques for the movements are completely dependent on the transmission systems considered, which are the main focus of this work.

2.3 Flexion and extension of the fingers

For the motion of flexion and extension of the fingers, it was considered a range of operation of 90° for each joint, with the exception of the MCP joint of the thumb, with a range of 45°. It was not possible to use other published values for these definitions, since the values differ depending on the population considered. Nevertheless, the ranges of motion chosen are among the values published in literature for the execution of the main movements of the hand, aside from simplifying the development of the transmission mechanisms.

The developed mechanisms were divided between directly actuated joints, the MCPs and PIPs, and underactuated joints, the IP and DIPs.

2.3.1 MCP and PIP joints

The transmission mechanism proposed for the directly actuated joints, as shown in Fig. 2a, has the function of transforming the linear applied force and displacement of the motor into a torque and angular motion.

The working principle of the mechanism consists in preserving the vertical distance between the stroke of the motor and the center of rotation of the mechanism, and therefore keeping the generated torque constant throughout the movement in its entirety. For this purpose, the connection between the stroke and the transmission part is made through a slot, with the tip of the stroke sliding along it as it performs a linear motion.

In order to implement the mechanism, it was first made an optimization of the main parameters, based on the representation made by the diagram shown in Fig. 2b: the total length used of the stroke, C, which corresponds to the final value of ${}^{0}AO_y$ with its initial value considered as 0; the vertical distance between the stroke and the center of rotation,

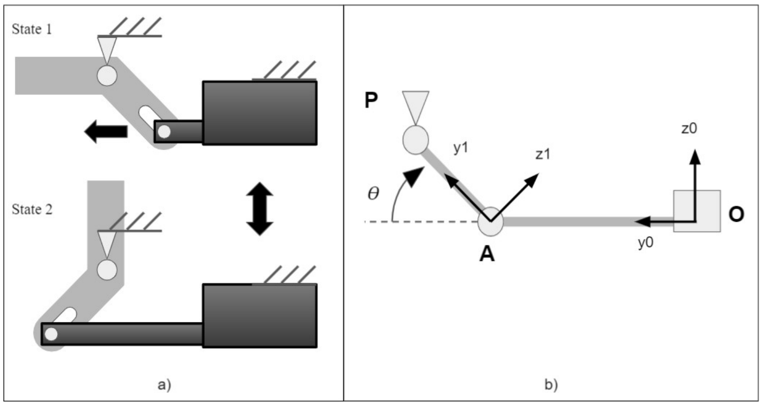


Figure 2. An illustration of (a) the linear to rotary conversion mechanism and (b) its corresponding diagram.

represented by the constant ${}^{0}PO_z$; and the initial angle of the transmission part of the mechanism, α, which corresponds to the initial value of θ when ${}^{0}AO_y$ = 0.

Since the angular movement of the mechanism has a range of 90° and the singularity points where the stroke of the motor and the transmission part align must be avoided, it was considered that $0 < \alpha < 90°$. The value of the total used stroke should also be at maximum of 20 mm, since it's the maximum provided by the motor. Lastly, since the minimum considered torque for the movement is of 0.2 N.m and the output force of the motor is of 20 N, the value of ${}^{0}PO_z$ should be at minimum of 10 mm. Combining these conditions with the geometric relation found between the parameters,

$$C = {}^{0}PO_z \cdot (\cot\alpha + \tan\alpha), \qquad (1)$$

one single solution was found at α = 45°, C = 20 mm and ${}^{0}PO_z$ = 10 mm. These parameters were utilized in every mechanism of the MCP and PIP joints. At the MCP joint of the thumb, however, only half of the stroke was used by its motor, since the range of motion was defined as only 45°. This mechanism served as the basis to the development of the rest of the hand, since the principle of transformation of linear force to torque was utilized on every motion generated.

2.3.2 IP and DIP joints

In contrast to the mechanism presented before, the mechanism over the DIP and the IP has the function of transmitting the rotary motion from the previous actuated joints to the next. Although this is most commonly made through the use of gears or pulleys, these elements require angular fixations in order to properly work, which often cause backlash. Therefore, an alternative mechanism was proposed, inspired by the one previously developed, as shown in Fig. 3.

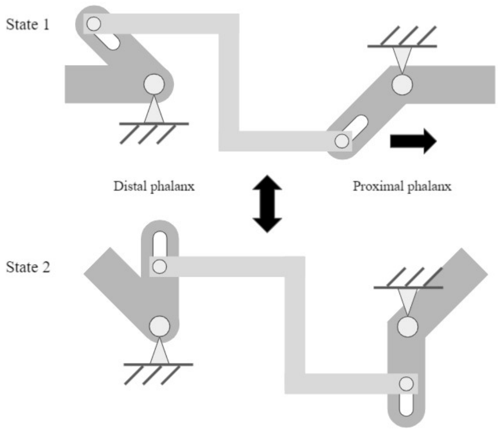


Figure 3. An illustration of the rotary transmission to the distal phalanx mechanism.

The working principle is analogous to the one of the previous mechanism. The rotary motion generated by the previous joint is converted into linear motion by a transmission part similar to the one used before. The linear transmission is made through a part encased by the phalanx located between the two joints. Finally, the linear motion is converted once again into rotary motion, through the same way as described before.

The nature of the mechanism grants the torque conservation throughout the movement in its entirety, while also providing greater precision than gear or pulley systems. Although the parameters of the mechanism are the same as the ones previously discussed, they do not alter the resulting torque over the DIP or IP joints, which will be the same as the one seen over the MCP and PIP joints as long as the transmitting parts are designed with the same dimensions. Therefore, in order to simplify the design, the parameters previously defined were reused in this mechanism. The dimensions of the linear moving part were restricted by dimensions of the phalanges, which were aimed to keep a proportion similar to the one seen in a human hand.

2.4 Abduction and adduction of fingers

The mechanism developed for the abduction and the adduction of the thumb presented a divergent design to the one made for the remaining fingers, and therefore it is discussed separately.

As cited before, it was decided to not include the abduction and the adduction of the middle finger, and the actuation of this movement over the ring and little finger is bounded. Thus, a mechanism was designed solely to actuate these two fingers, while another was made for the index finger. An illustration of the mechanism made for the ring and little finger is presented in Fig. 4.

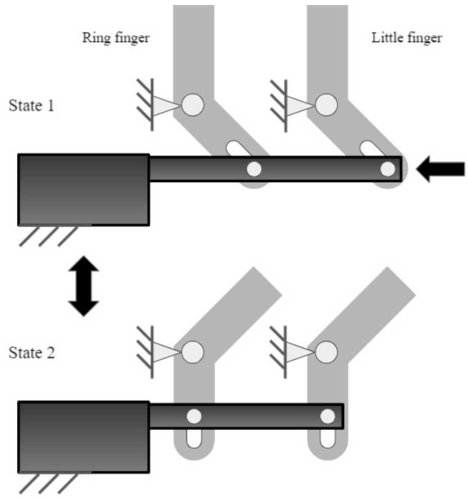


Figure 4. An illustration of the abduction and adduction mechanism.

The working principle of the mechanism is identical to the one utilized for flexion and extension. The main difference is the actuation of the motor over two transmitting parts instead of one: as the stroke performs linear motion, the ring and little finger rotate over the end of their metacarpals, simulating their abduction and adduction.

The definition of parameters, however, was not as similar as the one described before. The required output torque over the movements was not determinant to the dimensions of the mechanism, since it was considered satisfactory for it to be enough to rotate the fingers. The major restrictions over the dimensions of the mechanism were the maximum reached angles in abduction by each finger in relation to their position when fully adducted. In order to maintain the angles between the middle and ring finger and between the ring and little finger proportionate to the rotations, the reached angles in abduction for the ring and little fingers were respectively defined around 10° and 20°.

In order to facilitate further manufacturing of the parts, these angles were defined by the distances between the center of rotation of fingers and the motor stroke, as well as by the total stroke length utilized. Due to the lack of physical space to accommodate the mechanism in the palm, only 5 mm of the motor stroke were used in the mechanism in order to provide the needed ranges of motion, spoiling therefore some of the precision of the movement controlling when compared to the ones of flexion and extension.

In regards to the abduction and adduction of the index finger, the mechanism designed was the same, but rotating the finger in the opposite direction to perform the abduction. Through a similar manner as the other fingers, the range of motion was defined around 20°. Because of the same issues cited before, the used stroke of the motor was only 5 mm.

2.5 Opposition and reposition of the thumb

The movement of opposition and reposition of the thumb was simplified into an actuation through a single motor, rotating the thumb towards or away from the palm. In order to also include the abduction and adduction, the thumb was placed over a platform, which rotates with it. The mechanism, shown in Fig. 5, is identical to the one used for extension and flexion of the fingers.

Since the mechanism, as discussed before, can perform a maximum rotation of 90° when the torque of the movement is maximized to 0.2 N.m, the platform in which the thumb stands has an initial angle in relation to the palm in order to ensure that the thumb opposes the hand after its complete rotation. This initial angle was defined as 45°, in order to both

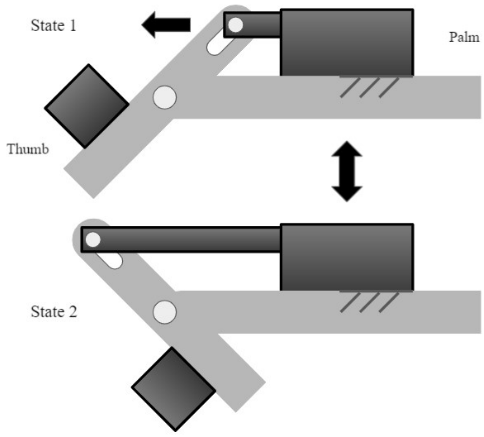


Figure 5. An illustration of the opposition and reposition mechanism.

simplify the design and ensure the contact between the thumb and every other finger.

2.6 Abduction and adduction of the thumb

The last designed mechanism was the one responsible for the abduction and adduction of the thumb. Due to lack of space on the platform that supports all the mechanism of the thumb, the motor responsible for the movement actuation had to be fixed on the palm. This disposition created the challenge to ensure the operation of the mechanism for any position of the thumb in regards to its opposition and reposition. The proposed design is presented in Fig. 6. The platform and the palm in the figure are not on the same plane.

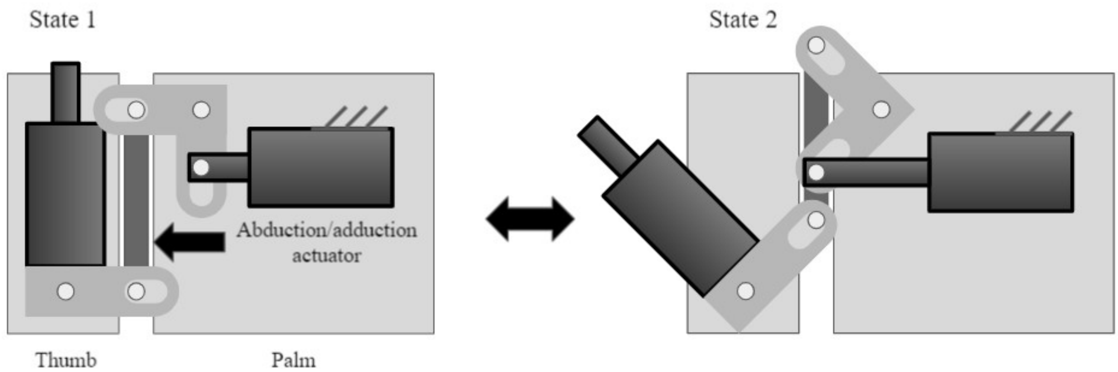


Figure 6. An illustration of the abduction/repositon mechanism over the thumb.

In order to transmit the movement from the actuator to the platform independently, it was proposed to do so by connecting the transmission elements on the palm and on the platform through the axis of rotation of the opposition and the reposition movement. The linear movement of the motor has its direction and position changed through a rotating part, which transmits the movement to a linear moving part aligned with the rotation axis of opposition/reposition. Due to this alignment, the linear movement is received by the platform regardless of its relative rotation to the palm. The linear movement is then converted into rotational through the use of the same mechanism cited before, rotating the thumb and performing the abduction and adduction.

Although the mechanism has a larger number of elements, the parameters are the same as the ones presented before. Once again, the main restrictions of the dimensions were the available space and the range of the movement, not the torque provided to the finger. In order to guarantee the contact between every finger as well as to simplify the mechanism, the range of the movement was defined as 45°. Since the parameters from flexion and extension were reused, the motor stroke availed was of 10 mm.

3. RESULTS AND DISCUSSIONS

The hand model was designed by using the CAD software (SolidWorks, Dassault Systèmes SolidWorks Corporation, USA). The structure was based on the mechanisms described, and was designed in order to facilitate future manufacturing.

It was decided to use the aluminum alloy 7075 for the entire project, since it is a light material with great machinability, as well as good structural properties. Since the final result presented a large number of small dimension parts, and in order to assure uniformity, only M2 and M3 screws will be used for fixation. Figure 7 illustrates the designed hand.

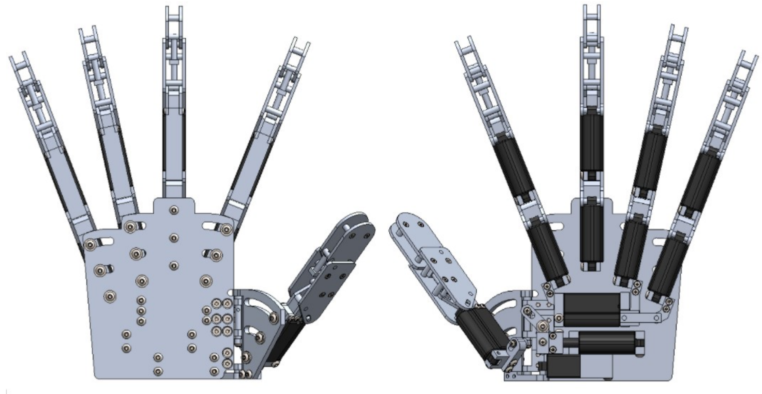


Figure 7. The designed hand in CAD with the fingers fully extended from (a) a ventral view and (b) dorsal view.

In Fig. 7b it is also shown the disposition of the motors on the hand. The motors responsible for the extension and the flexion of the proximal phalanges are located at the metacarpal of each finger; the motors responsible for the flexion and the extension of the middle and distal phalanges are located at each proximal phalanx. In the thumb, the motor at the metacarpal actuates both the proximal and distal phalanges. The remaining 4 motors are all fixated on the palm: three responsible for the abduction and adduction of the index finger, the ring and little fingers and the thumb, and the remaining performing the opposition and the reposition of the thumb.

3.1 Numerical results

The final structure is estimated to have 652 g of mass, which was considered acceptable when in comparison with a human hand and it is appropriate to be used in control studies targeted to biomimetic systems. However, the main dimensions obtained, which are presented in Tab. 1, were considered generally larger than the ones seen in a human hand. The major reason for this discrepancy was the size of the motor used. Although it presents high force output for its dimensions, they were still an obstacle to its proper fixation on the hand, resulting in larger parts than theoretically needed for the mechanisms to operate. Yet, an effort was made to ensure the proportion between the dimensions, considering the similarity to a real hand. The total width of the hand was measured by the maximum distance between the tip of the thumb and the little finger, which was 246 mm. Moreover, the total length was measured by the distance between the tip of the middle finger and the bottom of the palm, which was 242 mm.

Table 1. Length of each phalanx in the hand, measured by the distance between joints and noted in millimeters.

Phalanx	Thumb	Other fingers
Proximal	38	58.5
Middle	-	33
Distal	37.25	25

The torques and ranges of motion, on the other hand, were very similar to those found in the literature. Since the mechanisms were developed based on these values, the results were expected and already discussed previously. Table 2 presents the values of torque and ranges performed by each joint in flexion and extension, as well as the abduction/adduction and opposition/reposition movements. Although the resulting torques of abduction and adduction were greater than others, the availed motor stroke in these mechanisms was also considerably lower due to space limitation on the palm.

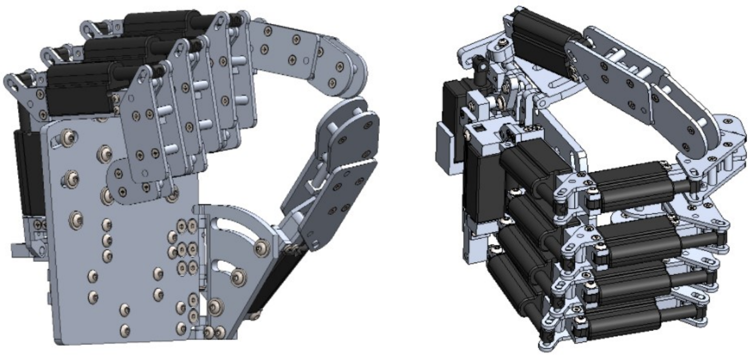
3.2 Performed movements

Due to the major focus on dexterity in this work, the hand was able to perform a variety of movements. The actuation of fingers in terms of flexion and extension allowed them to move independently, with 9 DoF. The opposition and reposition of the thumb was fundamental to ensure the effectiveness of prehension movements. Finally, the presence of abduction and adduction movements in the fingers allowed the execution of more complex actions, such as precision handling movements (Fig. 8), but also provided more refined power grip movements (Fig. 9). The high number of actuators on the hand were considered appropriate to perform most of the movements related to daily tasks, such as holding a pencil,

Table 2. Ranges of motion and torques on each movement. Ranges are noted in degrees and torques in N.m.

Movement	Range of motion	Torque
Fl/Ex of IP joint	90	0.1
Fl/Ex of MCP joint of thumb	45	0.2
Fl/Ex of other joints	90	0.2
Ab/Ad of thumb	45	0.2
Ab/Ad of index	21.8	0.25
Ab/Ad of ring and little finger	12.26 and 21.04	0.46 and 0.26
Op/Re of thumb	90	0.2

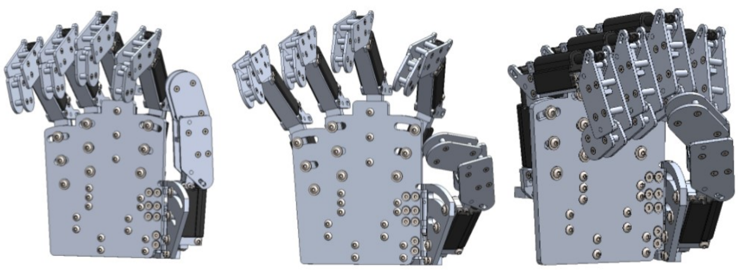
a piece of paper or any object with dimensions comparable to the hand.



a) b)

Figure 8. The hand performing (a) a pinch prehension and (b) lateral prehension.

Although it could not be completely validated, the final precision of the hand was also valued to be substantially high, since it has no angular fixations in its structure due to the absence of radial transmissions such as gears and pulleys, therefore minimizing the final backlash of the mechanisms, in addition to not relying on cables for the transmission of movements. This was mainly possible due to the use of linear motors as actuators on the hand, which not only eliminated the need for angular fixations, but also provided more direct options to transmit its force, even where the necessity of converting its linear motion to angular is considered.



a) b) c)

Figure 9. The hand performing (a) a *hook grip*, (b) a *esferic grip* and (c) a *cylindric grip*.

With a total of 13 DoF and 19 movements, the hand was able to execute a considerable range of actions with high precision. It presents significantly lower mass as well, when compared to other projects with a similar number of actuators, and the simplicity of the design of its mechanisms makes it viable for manufacture. With the integration of an appropriate electronic system, the hand is considered a valid option for the use as an instrumented device in control studies.

4. CONCLUSION AND FUTURE WORKS

The main objective of this work was to develop a robotic hand aimed to be utilized in control studies. A new design of biomimetic hand, with the use of linear actuators, was proposed. With the main focus on designing both precise and simplified mechanisms, it was possible to reproduce several of the human hand movements through the actuation made by 13 motors. The independent flexion and extension of each of the 5 fingers, alongside the reposition and opposition of the thumb and the implemented adduction and abduction of the fingers allowed the designed hand to reach high dexterity while also minimizing the backlash, resulting in a precise model with 13 actuators and 19 movements.

However, the dimensions of the actuators used were a significant obstacle to the design of mechanisms, resulting in systems larger and more complex than they could have been while also reducing some of the availed stroke of the motors as well. The final size of the model was therefore evaluated as outside of the range of a human hand, but its proportions were still considered valid to be compared to one.

Since this project focused mainly on the mechanical structure of the hand, it is within the scope of future works the definition of sensors to be implemented to the hand, such as touch and current sensors, as well as their quantities and fixating positions in the structure. Once the adaptations have been made, it is also considered for future works the complete manufacturing of the hand, in order to validate both its mechanisms and integrated systems, therefore effectively evaluating the precision and dexterity of the movements performed.

5. REFERENCES

Andrychowicz, M., Baker, B., Chociej, M., Józefowicz, R., McGrew, B., Pachoki, J., Petron, A., Plappert, M., Powell, G., Ray, A., Schneider, J., Sidor, S., Tobin, J., Welinder, P., Weng, L. and Zaremba, W., 2020. "Learning dexterous in-hand manipulation". *International Journal of Robotics Research*, Vol. 39, No. 1, pp. 3–20.

de Souza, Y.P., Oliveira, A.C. and de Albuquerque, L.C., 2019. "Characterization of amputees at a large hospital in Recife (in Portuguese)". *Jornal Vascular Brasileiro*, Vol. 18, pp. 1–8.

Eguiluz, A.G., Rano, I., Coleman, S.A. and MgGinnity, T.M., 2017. "Reliable object handover through tactile force sensing and effort control in the shadow robot hand". In *Proceedings - IEEE International Conference on Robotics and Automation*. pp. 372–377.

Fajardo, J., Ferman, V., Lemus, A. and Rohmer, E., 2017. "An affordable open-source multifunctional upper-limb prosthesis with intrinsic actuation". In *Proceedings of IEEE Workshop on Advanced Robotics and its Social Impacts, ARSO*. pp. 1–6.

Fajardo, J., Lemus, A. and Rohmer, E., 2016. "Galileo bionic hand: Semg activated approaches for a multifunction upper-limb prosthetic". In *Proceedings of the 2015 IEEE 35th Central American and Panama Convention, CONCAPAN 2015*. pp. 1–6.

Farjardo, J., Ferman, V., Carona, D., Maldonado, G., Lesmus, A. and Rohmer, E., 2020. "Galileo hand: An anthropomorphic and affordable upper-limb prosthesis". *IEEE Access*, Vol. 8, pp. 81365–81377.

Kate, J.T., Smit, G. and Breedveld, P., 2017. "3d-printed upper limb prostheses: a review". *Disability and Rehabilitation: Assistive Technology*, Vol. 12, No. 3, pp. 300–314.

Krausz, N.E., Rorrer, R.A.L. and Weir, R.F.F., 2016. "Design and fabrication of a six degree-of-freedom open source hand". *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 24, No. 5, p. 562–572.

Landsmeer, J.M., 1962. "Power grip and precision handling". *Annals of the rheumatic diseases*, Vol. 21, pp. 164–170.

Li, S., Ma, X., andM Gorner, H.L., Ruppel, P., Fang, B., Sun, F. and Zhang, J., 2019. "Vision-based teleoperation of shadow dexterous hand using end-to-end deep neural network". In *Proceedings - IEEE International Conference on Robotics and Automation*. pp. 416–422.

Ottobock, 2020. "Upper limb prosthesis". Ottobock Co, Duderstadt, Germany, ottobockus.com/prosthetics/upper-limb-prosthetics. Accessed 27 September 2020.

Plangehoeff, S., Evans, F.G. and Abdelnour, T., 1983. "Anatomical data for analyzing human motion". *Research Quarterly for Exercise and Sport*, Vol. 54, No. 2, pp. 169–178.

Semasinghe, C.L., Madusanka, D.G.K., Ranaweera, R.K.P.S. and Gopura, R.A.R.C., 2019. "Transradial prostheses: Trends in development of hardware and control systems". *International Journal of Medical Robotics and Computer Assisted Surgery*, Vol. 15, No. 1, pp. 1–10.

Shadow Robot Company, 2020. "Dexterous hand series: The world's most dexterous humanoid robot hands". Shadow Robot Co, London, UK, shadowrobot.com/dexterous-hand-series. Accessed 10 September 2020.

Song, F., Zhao, Z., Ge, W., Shang, W. and Cong, S., 2018. "Learning optimal grasping posture of multi-fingered dexterous hands for unknown objects". In *2018 IEEE International Conference on Robotics and Biomimetics, ROBIO 2018*. p. 2310–2315.

Sreedhar, M., Shekar, S.S.M., Vardhan, K.A. and Krishina, S.V., 2019. "A review on bionic arm". *International Journal of Trend in Scientific Research and Development*, Vol. 3, No. 3, pp. 1032–1038.

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