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Scale anthropomorphic hand based on human anatomy with linear actuators as the basis for motion

Mano antropomorfa a escala basada en anatomía humana con actuadores lineales como base para movimiento

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This article presents the development of an anthropomorphic hand, based on human anatomy. This prototype has a total of 20 degrees of freedom, four for each finger. The design took into account the anatomical features of the human hand such as tendons and joints for different movements. The movements are generated with servomotors and controlled directly from a computer with the help of an Arduino Mega. The parts were designed in Autodesk Inventor and printed on a 3D printer.

Keywords: Fingers, joint, linear actuators, mechanical design, prototype, robotic hand

Éste artículo presenta el desarrollo de una mano antropomorfa, basada en la anatomía humana. Este prototipo tiene un total de 20 grados de libertad, cuatro por cada dedo. El diseño tuvo en cuenta características anatómicas de la mano humana como tendones y articulaciones para los diferentes movimientos. Los movimientos son generados con servomotores y controlados directamente desde una computadora con la ayuda de un Arduino Mega. Las piezas se diseñaron en Autodesk Inventor y se imprimieron en una impresora 3D.

Palabras clave: Actuadores lineales, articulación, dedos, diseño mecánico, mano robótica, prototipo

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Introduction

The man currently lives in a box, built according to our characteristics, both psychological and physiological being his way of walking, his posture, and his hands, the three main features that are sought to imitate in anthropomorphic robotics (Martínez, Martínez, & Jacinto, 2014). In order for the technological world to continue advancing, technological creations must be truly efficient and must adapt to our daily lives. The creations need to look more and more like us.

The idea of creating mechanical anthropomorphic limbs was originally intended for prosthetics, but this concept now extends to modern robotics, which is at the height of development. With more and more humanized robot designs, it is hard to believe that these artificial systems are limited to the medical field. We live in a world by man and for man, the logical thing is that technology evolves in the direction of ourselves, either to imitate us or to adapt to us.

For example, each time a new model of cell phone or computer comes out, its ergonomic design stands out, being these our hands, the fundamental pillar in the technological development and means for the creation of infinity of possibilities because there is not being alive on the planet that can carry out tasks with its hands as the human does, and it is a fact that our evolution has been based on them. Human evolution has been based on its creativity. At first to survive and now to adapt the environment to us. Hands were the means to develop our creativity, to be able to create from lances in antiquity, to rifles today.

At the beginning of the Christian era, the hands were already replaced by different artificers. The first artificial hand, attached to the forearm, was found in an Egyptian mummy 2000 years before Christ (Dorador, Ríos, Flores, & Juárez, 2004). At the beginning of the Christian era, the hands were already replaced by different artificers. The first artificial hand, attached to the forearm, was found in an Egyptian mummy 2000 years before Christ. In the second Punic war (218-201 BC) the Roman general Marcus Sergius lost his right hand and ordered to build a metal one (Zuo & Olson, 2014).

In 1501, Gotz Von Berlichingen ordered an articulated iron hand to be built to hold his sword. However, the sword was very heavy and had to be attached to the armor. The fingers and wrist of this hand could be flexed and extended passively (Orr, James, & Bahrani, 1982).

The first mobile, but passively, an elbow-level artificial arm was built by a locksmith on behalf of the French military doctor Ambroise Paré. The fingers of the prosthesis could be opened or closed by pressing or traction. It was also Ambroise Paré who built the first aesthetic leather hand (Thurston, 2007).

In 1917, F. F. Simpson founded the *American Limb Makers Association*, in which all the manufacturers of the sector existing at that time in the United States joined. The materials used in the construction of the prosthesis began from then on to be lighter, ductile and appeared among others the aluminum alloys, the synthetic fibers, and the plastics. After the First World War, all the countries united in a common effort aimed at the best rehabilitation of the invalid. The hands designed then were interchangeable according to the different occupations (Zuo & Olson, 2014)

In the designs studied we can notice how they emphasize the grip of the objects rather than the shape of the grip. As a result, bi-directional opening and closing movements (forward and return) are obtained, in addition to using a greater force than should be used for the grip.

For several years there have been studies of the hands, we have tried to replicate many of their characteristics. For example, in (Wang, Fan, & Liu, 2012), the study is carried out analyzing the anatomy of the thumb, since it is the part of the hand that presents the greatest degree of freedom. This project proposes that in order to design the target of the hand it is necessary to start from the thumb since its rotations are complex.

The movements of the hand are too complex to design and implement in robotics, making their movements very tense (Tan, Zhang, Chen, & Du, 2009), which shows that each movement has a great effort and to verify this, there is a series of graphs where tests are made both flexibility and effort that has to obtain a grip on objects, it can be noticed the rigidity it has when making the different movements.

The term Robot, which comes from the Czech word robotic meaning *forced labor*, was first introduced by the Czech dramatist and author Karel Capek in his 1921 theatre play R.U.R (Rossum Universal Robots) (Christoforou & Muller, 2016).

Both prostheses and robotic hands have tried to achieve a more functional hand, focusing on the most common movements, however, despite all the advances of today most designs are still characterized by rigid movements and do not include the full range of possible combinations of a real hand, and those prototypes that approach real hands tend to be expensive, and therefore of limited access for people. As a result of this a less robust prototype was made, focused on performing as many movements as possible integrating the abduction and adduction movements, in addition to taking into account anatomical characteristics of the human hand and being developed with easily accessible materials.

In order to achieve the objective, it was necessary to design three previous prototypes, each with a different approach. The first one was based on a double articulation system which offered greater flexibility, but the pieces were thin and fragile as it consequently obstructs the path of the tendon inside the piece. The second prototype is similar to the first, but since its fineness of movement was not the one we wanted to obtain, it was a null design. The third prototype was designed with articulations in the shape of a sphere achieving greater movement, but for the assembly, it required additional safety pieces, because they were very small.

The development was made throughout 11 months, considering research, designs, selection of elements, consultation of suitable materials for the assembly, tests, and delays among others. The project had a cost of $1'600.000 Colombian pesos M/Cte, in this value is reflected only the materials used, it does not consider labor. The approximate cost for manufacturing the prototype is $750,000 Colombian pesos M/Cte (materials only).

Problem formulation

We want the hand to be seen as a means, not as an end, for this, we thought of innovative design, an effective prototype, economical, expendable and that can be adapted to the purposes and utilities of many people (Martínez, Acero, & Castiblanco, 2014).

To carry out this project, an anthropomorphic robotic hand prototype was designed and implemented with improvement in design and performance to previous prototypes of the ARMOS research group, adding the abduction and adduction movements. It was designed as a research and development platform for different hand movements, although it is only a prototype to improve with time, to give it practical use in the future and greater versatility, either as a control platform, prosthesis or as part of an advanced robot (Fig. 1).

Figure 1. Electrically active hand prosthesis in the form of a clamp or hook.

The purpose of the research project is the development of a robotic hand, whose design will focus on the reproduction of most of its movements. In order to do this, we looked directly at the source, that is to say, we tried to imitate the anatomy of the human hand or at least its motor part. Since the designs of robotic hands seen in articles and conferences consulted are focused to fulfill specific tasks, from their idea to their conception, in other words, they are focused to an end, it was decided to develop a prototype with the capacity to adapt to different circumstances. Many designs do not have the form of a hand, they are limited to put a glove with the form of one, but below this, they are a clamp, in addition, several designs are based on a system of three fingers.

Guided by the anatomy of the human hand, it is evident that many of the movements we can make with our hands are omitted, because their usability is underestimated. This is the case of the adductor and abductor movements, which are evidently omitted in the designs consulted, being these movements those that allow us to accommodate our hands for more efficient use.

Methodology and design

After defining the main characteristics that the design of the prototype of the anthropomorphic hand will have, a series of consultations begins, both in human anatomy and in articles and designs of prototypes already developed, as well as making a slight documentation on mechanical behavior, materials and software handling (Martínez, Rendón, & Guevara, 2016).

Anatomy

Hand anatomy research focused on the locomotor system, skeleton or bones, muscles, tendons, and joints (Staff, 1988).

Bones. The bones are light but very strong and hard, have very varied forms that depend on the function they perform in the body, some of these functions are:

- The protection of soft or vital organs such as the brain and the entire thoracic cavity (Staff, 1988).
- Supports most organs (Staff, 1988).
- Allow movement thanks to the synchronized contractions of tendons that are attached to the bones (Staff, 1988).

Although bones have other functions apart from those mentioned above, these tasks are more metabolic and therefore do not fall within our competence for the development of this project.

The bones of the hand are divided into three groups (Staff, 1988): Carpus, metacarpus, and fingers. The bones of the carpus are eight arranged in two rows of four bones. They constitute the skeleton of the wrist.

- Trapezium.
- Trapezoid.
- Hamate.
- Capitate.
- Pisiform.
- Triquetrum.
- Lunate.
- Scaphoid

The bones of the metacarpus are five, and they are arranged in a fan. They constitute the skeleton of the palm of the hand (Staff, 1988).

The bones of the fingers are called phalanx, they are organized in a number of three for each finger, except in the thumb that has only two (distal and proximal) (Staff, 1988).

- Distal phalanges.
- Middle phalanges.
- Proximal phalanges (Fig. 2).

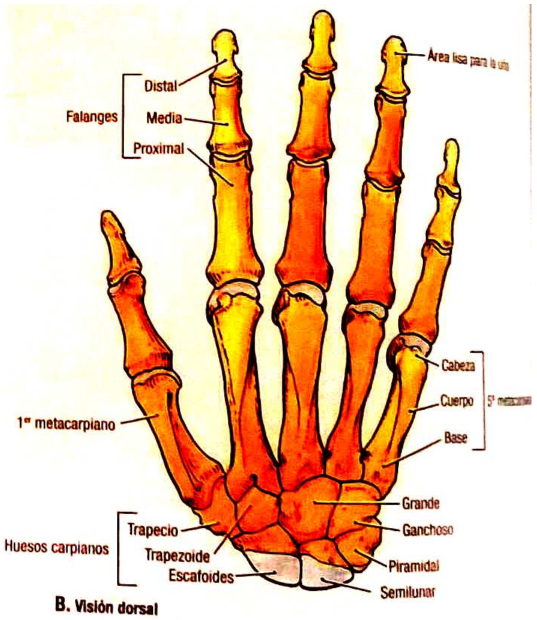

Figure 2. Bone structure of the hand (Staff, 1988).

Bone is a firm, hard and resistant tissue, it is composed of hard and soft tissues. The main hard tissue is bone tissue, a specialized type of connective tissue made up of cells called osteocytes and calcified extracellular components. Bones have a superficial covering of fibrous connective tissue called periosteum and their articular surfaces are covered by cartilaginous connective tissue. The soft components include the myeloid connective tissues hematopoietic and adipose tissue in a few words fat to the bone marrow. The bone also has vessels and nerves that respectively irrigate and innervate its structure (Fratzl & Varga, 2017).

The ligaments are masses of connective tissue in which the collagen fibers are very reinforced extends from bone to bone, these give stability to the hand.

Tendons. The bundles of muscle fibers continue with the tendon fiber, which, at the other end, penetrates into the interior of the periosteum. They are the unions of the muscles to the bones, which are not made directly, but through bands of connective tissue that constitute the tendons.

The bones are linked by the joints (Fratzl & Varga, 2017), which are classified as follows:

- Synarthrosis (immobile): When there is intimate contact between the bones, there is no joint cavity and movement is impossible.
- Amphiarthrosis (semi-mobile): Allows very limited movements, that of the vertebrae, for example, the union is made by cartilage fiber.
- Diarthrosis (mobile): The bones are separated by a joint cavity, a series of ligaments prevent them from deviating from their relationship positions. The joint cavity is covered by the synovial membrane and a liquid fills the cavity and lubricates the surfaces in contact.

Joints. The types of joints we can find are:

- Saddle joint, such as the thumb, allows movement in two directions (Fig. 4).
- Hinge joint, allows movement in one direction, such as the elbow (Fig. 5).
- Spheroidal joint, very flexible, it makes possible rotations and lateral inclinations (Fig. 6).
- Rigid joints are limited to their movement by ligaments but can support loads ().

Outline. Colombia is at the height of development in terms of prosthetics and anthropomorphic robotics, however, until some time ago there was very little research and development (Quinayas, 2010). After the arrival of the 3D printer, there was this sudden interest in designing anthropomorphic prostheses, so it is less expensive, more practical and simple to design. After carrying out complete research with respect to the anatomy, such as its movements and degrees of freedom, especially of the thumb due to its complexity of movements, it goes on to talk about different materials, structures and designs of biomechanical hands, all this in search of a natural robotic hand.

Some interesting thumb designs assume that the movement is developed by the horizontal movement of the base of the thumb, with an additional design similar to the other fingers (Mahmoud, Ueno, & Tatsumi, 2011). In these cases, there is a mechanism in which in the most important joints are located the actuators, in a mechanical system which causes the circular movement to be converted to linear by means of a mechanical coupling similar to the rack pinion. With this type of design many movements are lost and clearly in certain tasks shows a behavior less suitable for certain applications, such as typing on a keyboard or holding things.

The aim of the design is that its movements will be natural. One option to make them lighter is the use of pneumatic valves, with which a strong grip is achieved (Gaiser et al., 2008). This gives two key aspects, such as the strength and speed of the piece, but still omits many natural movements. With the pneumatic actuators, it is achieved that their movements are not so rigid, in spite of this it is achieved that it makes two movements: opening and closing, since to implement it in the design would be necessary a too robust design and would not make circular or curved movements in a natural way, this would make it deviate from the main objective, which is quantity and quality of movements.

There are also designs in which the actuators are not located in the joints, nor inside the hand, but the system of actuators are located in a separate section and from there the hand moves by means of threads and gears

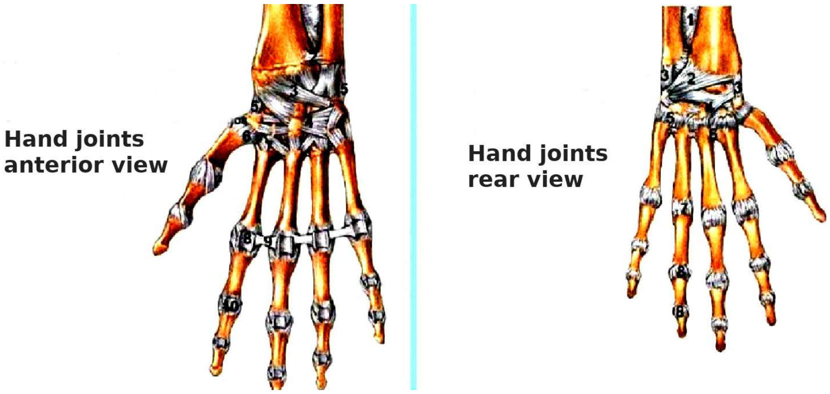

Figure 3. View of bone articulation of the hand in its two positions (Fratzl & Varga, 2017).

Figure 4. Saddle joint giving movement in two directions (Fratzl & Varga, 2017).

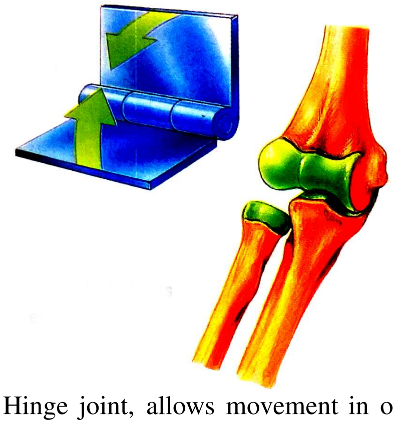

Figure 5. Hinge joint, allows movement in one direction (Fratzl & Varga, 2017).

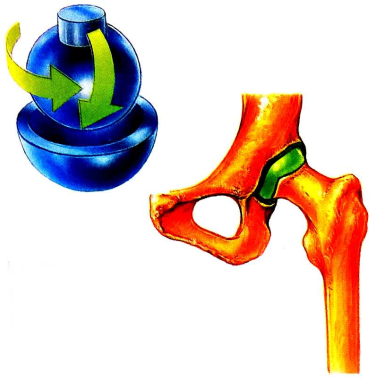

Figure 6. Spheroidal joint or rotation and lateral inclination (Fratzl & Varga, 2017).

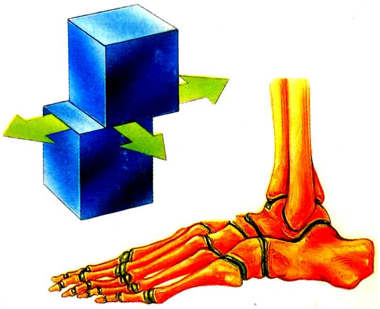

Figure 7. Rigid joint to support loads (Fratzl & Varga, 2017).

(Niola, Rossi, Savino, & Troncone, 2014). This design shows an advantage in comparison with the previous ones because the actuators are out of the hand, it will have less weight.

As part of the sensor system, it is necessary to have a system that allows the collection of information on objects in the hand during the gripping processes (Dang, Weisz, & Allen, 2011; Zhang, Fan, Zhao, Jiang, & Liu, 2014).

Design

What is offered with this project is a change of perspective, it is not wanted an end as in previous cases, it is wanted a means. A prototype that is not designed for something in particular, but that adapts to the infinite possibilities, being our best reference our own hands and considering us mainly the movements of abduction and adduction that are evidently omitted. Being these movements, those that give us agility, flexibility and a better grip.

These capabilities can be seen in:

- To write quickly on the keyboard of the computer, since we do not have the necessity to move the whole hand, but we only move the fingers, which gives us a greater speed.
- In the case of gripping or holding objects, thanks to these movements are achieved to adopt the shape of the hand obtaining a greater firmness and variety with which it is possible to hold objects that are much larger.

Today there are many machines that make great efforts and carry out tasks that are physically impossible for a person, but there is no machine that is designed to carry out everyday tasks in a natural way. We do not propose that the prototype presented below will do all the tasks mentioned above, but this prototype shows a window into these ignored possibilities.

Hand pieces. The designed hand has 17 fundamental pieces and four additional pieces that will serve as a base. In addition, if the arm is to be implemented in the future, there will be no need to modify the hand directly, but an adjustment of the base pieces will suffice.

The parts were designed to come in under pressure because they wanted to have the least number of parts needed. Consequently, it was necessary to make certain finishes in order for the pieces to fit without the risk of fracture.

Each finger has three pieces with the exception of the thumb which has four to reach the palm, in addition to this, it is worth mentioning that the hand was designed so that it could be both right and left (Figs. 8, 9, 10, 11 and 12).

The tips of the fingers make the times of distal phalanges, this one has two holes by which the threads of hemp will go, besides that to the height of the nails the entrance to a rectangular cavity was left to annex a piece of thread-rubber that helps with the retrocession of the piece, avoiding that this one decouples. The piece in the lower part has two circular holes on the sides, these will vary their dimensions depending on the finger and will be the ones that will be coupled with the next piece and allow movement (Figs. 13 and 14).

The piece that makes the times of the middle phalanx, like the previous ones have two holes to let pass the tendons that go in the tip of the fingers, since this one serves as means for the route of the tendon, because on the one hand few people have the facility to move the tips of the fingers without moving the middle phalanx and on the other side the reduction of costs. Like the previous pieces, a protuberance was left with a rectangular cavity to annex the rubber thread, this piece has two protuberances to the sides of circular shape that fit with the holes of the pieces (Figs. 15, 16 and 17).

The pieces that will be explained next will act as proximal phalanx, these in the upper part will be coupled to the middle phalanges and therefore have two holes on the sides to make the hinge movement, in the lower part these pieces have the shape of a toroid with an opening to be coupled with the rings of the palm or in the case of the thumb with the ring that connects the finger with the palm.

These pieces have six holes, two destined to be the conductor of the tendons of the tip, two will be destined to the movements adductor - abductor and two will be to move the knuckles; according to how these pieces are coupled to the palm the hand can be both right and left.

These parameters apply to all fingers, except for the thumb, in which case the thumb moves the base of the finger up and down (Figs. 18, 19, 20 and 21).

Before reaching the palm we will talk about the piece that joins the thumb to the palm. This has a toroid shape and on one side has a cylinder with a hole, allowing the union to the palm. This piece allows the horizontal movement of the thumb and in conjunction with the adjacent piece can achieve rotary movements. It is worth mentioning that it is the only piece that does not have any type of adjustment with rubber thread and as this piece is coupled to the palm the thumb will take the form of left or right hand (Figs. 22, 23 and 24).

The palm has a toroid for each finger except the thumb in order to achieve the saddle joint, this will serve as the carpus and metacarpus except the metacarpus of the thumb.

Although the hand functions as a left hand because we wanted to keep the dimensions of a real hand we had to leave some paths that favor more the movement of the right hand.

As mentioned before, the types of bones such as carpal bones, are focused not on movement but to withstand impacts and give a little more flexibility to the hand, so that it does not suffer damage. Originally we looked for a design more similar morphologically to the human hand to achieve a better coupling to the objects, but for this, it was necessary to make the ducts smaller or the palm larger. The manufacturing capacity limited the final size of the hand (Figs. 25 and 26).

Actuator parts. For most of the movements, we use servomotors with propellers. These did not need a large displacement, with a displacement of two to three centimeters was enough to achieve the change of circular motion for a linear one. In spite of this, there are some movements that need a greater range than the propellers can offer us.

With this in mind, we designed the linear actuators, which consist of six parts: the actuator box, three conical pinions, and two racks. For the correct functioning of the actuators it was necessary to truncate the servomotors, that is to say, to achieve a 360-degree rotation instead of their normal rotation capacity of 180 degrees.

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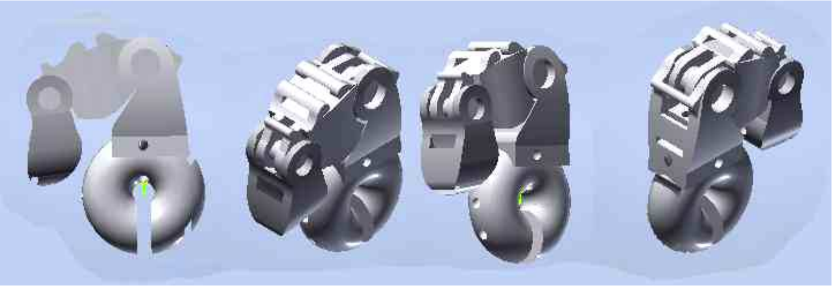

Figure 8. Middle finger, closed, seen from different planes.

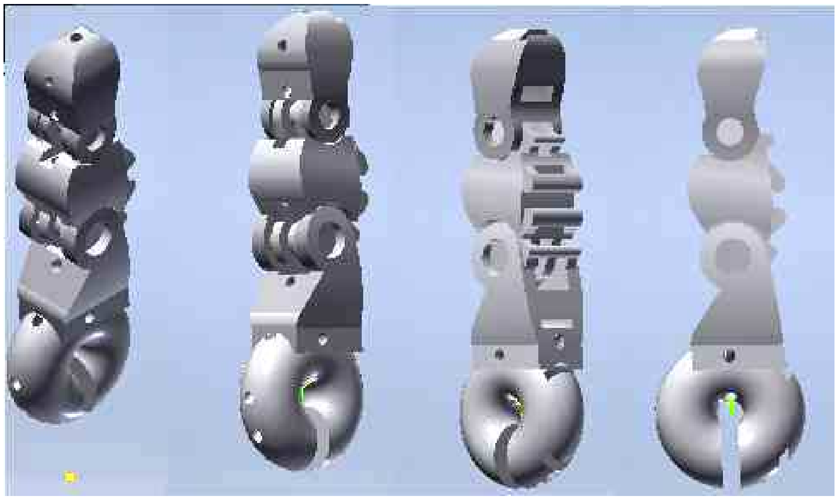

Figure 9. Middle finger, open, seen from different planes.

Figure 10. Thumb conformed in four pieces.

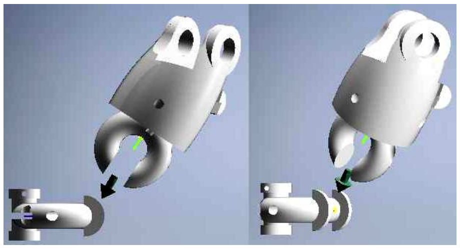

Figure 11. Union toroid and palm.

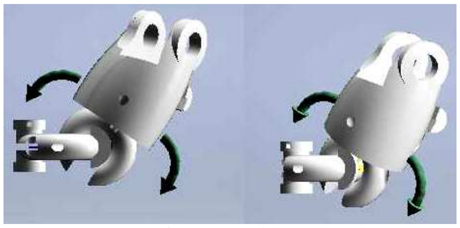

Figure 12. Movement of the toroid and palm.

The box containing all actuator parts has three sides. In the front face, there is a circular hole of approximately two centimeters in diameter that forms the pinion of the servomotor. This will be in charge of transmitting the movement to the other two pinions. To the sides we have another circular hole in each face of half a centimeter in diameter, this is used to pass a screw that is the axis of the pinions, because if they do not fit they would also come out.

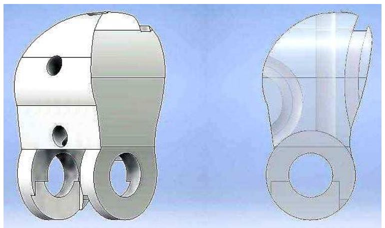

Figure 13. Fingertip and its joints.

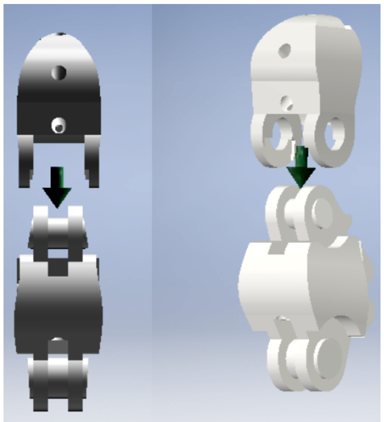

Figure 14. Connection between the distal phalanx and the middle phalanx.

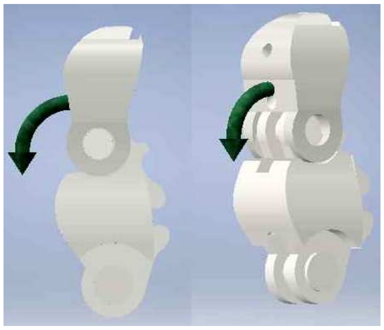

Figure 15. Movement of the joint of the phalanges.

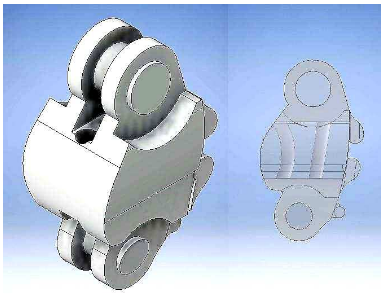

Figure 16. Middle piece or middle phalanx of the finger with its joint.

It has two vertical cavities on the sides that act as rails for the zippers (Figs. 27, 28, 29 and 30).

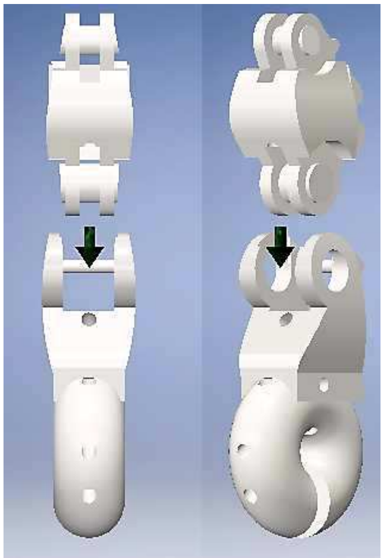

Figure 17. Connection between the middle and proximal phalanx.

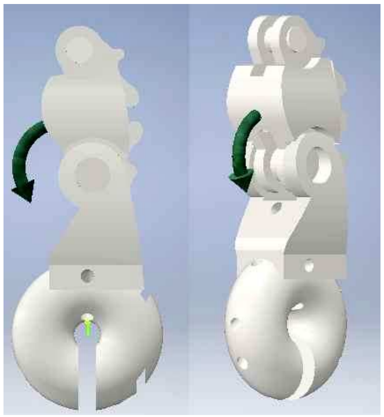

Figure 18. Movement of the joint of the middle and proximal phalanges.

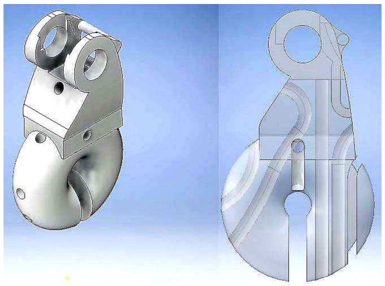

Figure 19. Union of the base of the finger to the palm with its articulation.

The first pinion will connect through the gearbox to the servo motor. This will have on each side a pinion with a circular toothed base that will be located at 90 degrees with respect to the mentioned pinion and will go in the internal

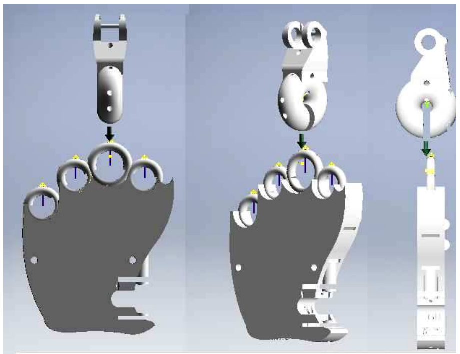

Figure 20. Phalanx union proximal to the palm.

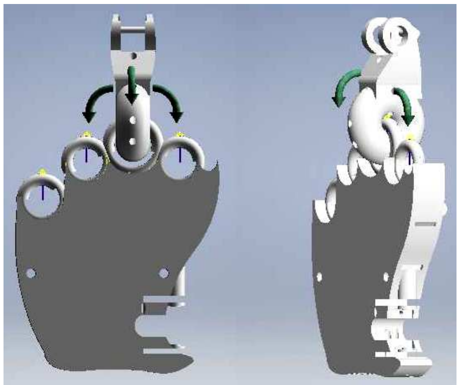

Figure 21. Movements of the proximal phalanx and palm.

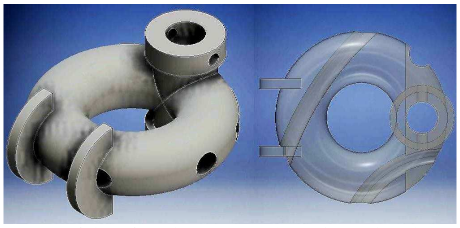

Figure 22. Toroid union between thumb and palm.

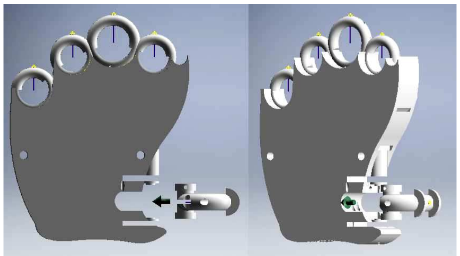

Figure 23. Toroid union between thumb and palm.

part of each face, managing to displace the zippers each one in different directions (Figs. 31, 32 and 33).

With the previous assembly, it can be seen how the movement of the motor is transmitted in two directions, exerted in the pinions on the sides, fitted to the racks that are railed in the box. In the box this set will form the actuator, in addition, these racks must coincide with the teeth of the base of the pinions achieving a linear movement. While on one side the rack goes down, on the other it goes up and vice versa (Figs. 34 and 35).

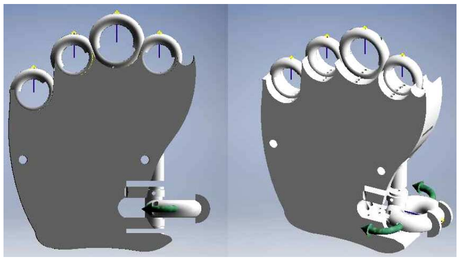

Figure 24. Movement between the toroid and the palm.

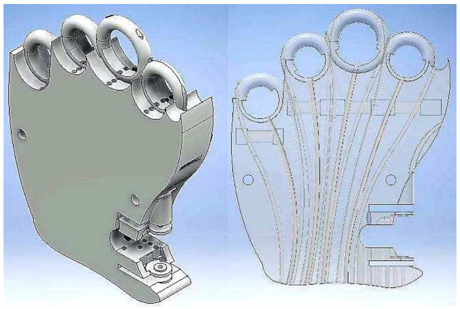

Figure 25. Palm with its joints and ring joints.

The base of the prototype is not exactly an arm as such, it was made with characteristics similar to those of a human arm. In spite of this, not much importance was given to appearance, but the functional part of the arm was given priority over the hand, in other words in the relationship that the arm shares with the hand.

This base was made in order to give firmness and stability to the hand since it generates the movements and control. As in the anatomy of the hand, most muscles are connected to the arm, similarly the motors and actuators, which work from this position achieving each of the different movements. Otherwise, the hands would be much larger, and for the prototype, the hand would become larger and heavier. On the other side, the base or arm is also in charge of protecting the actuators and propellers from external agents that would damage their behavior (Figs. 36 and 37).

The base was made of wood for two reasons. The first, that the focus was centered on the anthropomorphic prototype of the hand, not the arm. The second, that due to its size by the actuators was impossible to print, and it was more practical to make it this way. The holes of the servo motors were made in such a way that the displacement that makes the hemp thread after leaving the printed pieces until the actuators or propellers of the servo motor should not have an angle greater than 30 degrees, because being a diagonal tension, the force is divided in two, one vertical and another horizontal. The exploitable force is the vertical

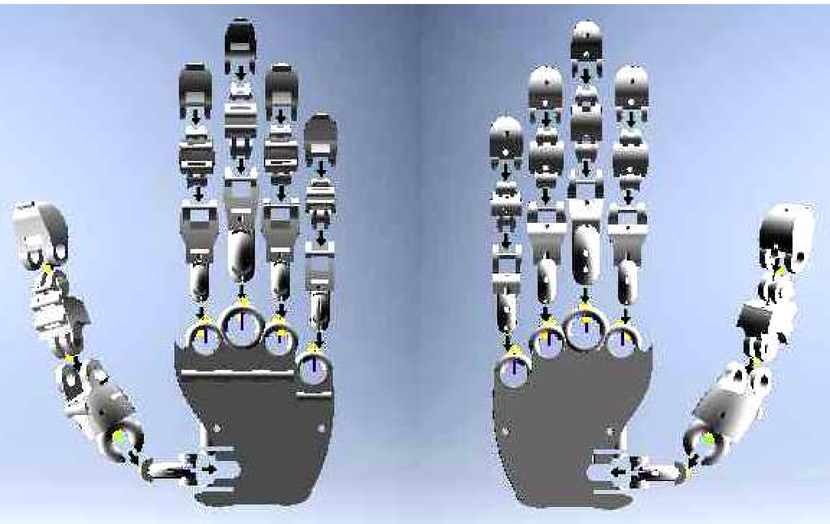

Figure 26. Right hand assembly.

Figure 27. Gear system base.

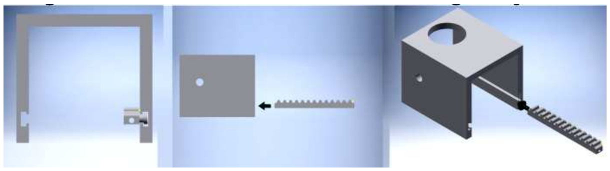

Figure 28. Zipper assembly to base.

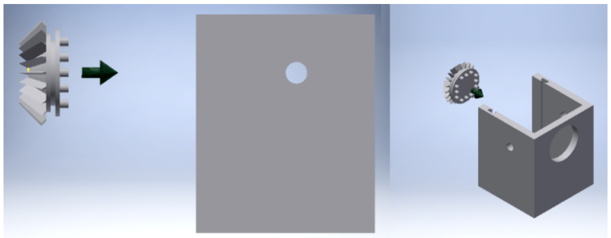

Figure 29. Main gear assembly to base.

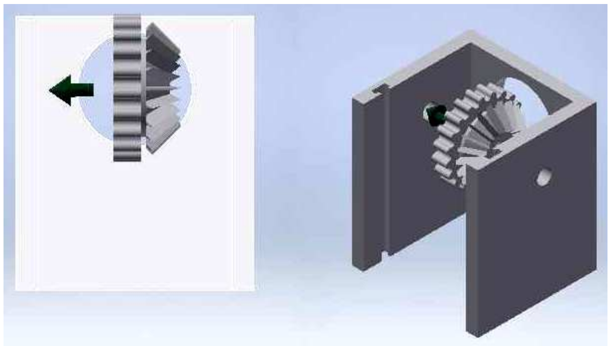

Figure 30. Side gear assembly.

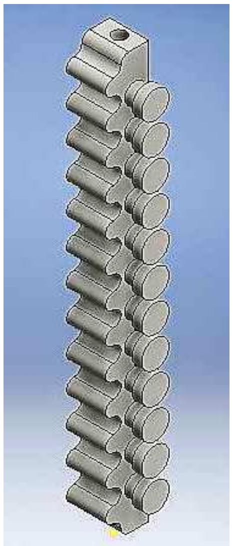

Figure 31. Track or zipper, of the movements.

one, if possible that its angle was zero, all the force of the servomotor would be exploited.

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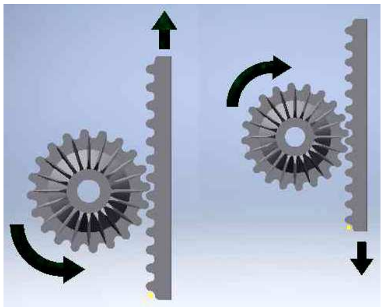

Figure 32. Change from rotary to linear motion.

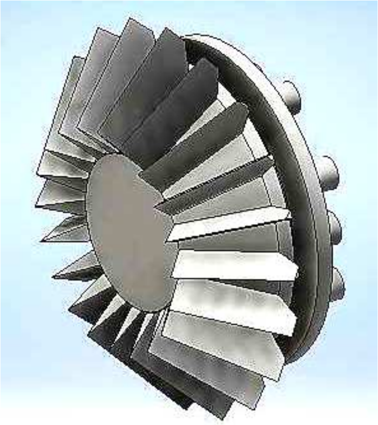

Figure 33. Main gear supported to the servomotor.

Both the motors and the actuators are fitted to the base. We leave the motors on the outside to give greater stability to the motor-actuator joint. In addition, as the actuator motors were truncated, it was necessary to calibrate them with the help of potentiometers. Due to vibrations or other factors, they are sometimes unbalanced, and as the servo motor is outside, its maintenance or calibration is simple.

In order to avoid entanglements of the excess of the hemp thread, we made holes to dislodge the excess, thus avoiding other possible mechanical damages. In this way, there is no risk of the thread becoming entangled and braking any motor. This extra thread is necessary in case of replacing some propeller or zipper or simply requires to temper the thread a little more.

The control of the prototype was done directly from the computer, which will be connected to an Arduino board, and this, in turn, will be connected to power supplies, engines, and sensors.

The servo motors used are 8 Kg. Some were truncated to change their rotation from 180 degrees to 360 degrees, this due to local availability of the motors and price.

Due to the number of ports needed both to control the motors and to read the sensors, we use an Arduino Mega development board. This card has enough ports that offer the possibility of controlling many elements, giving the possibility of adding more sensors or motors, according to the future development of the prototype.

For the control, we use force sensors. These sensors were placed on the tip of each finger. Because these had several deformations, the fingers were covered with leather, protecting the sensor, and also giving a better grip, since the material itself is very smooth. The various layers of leather increased the logging range of the sensors. Sensors were also placed in the palm of the hand.

Findings

The prototype after built was not able to meet all the angles expected in their joints. This was due to the fact that in the software environment ideal conditions are handled that are difficult to fulfill in reality. By means of simulation from the design software, we define many of the degrees of freedom that the hand has. This finally exaggerated certain movements, so that the parameters of the program and adaptations were not replicated in the same way in reality. Therefore, the vertical turns that Fig. 38 contemplates in the part of the rings or toroids between the fingers and the palm, were not reproduced in the prototype.

Thanks to the material and the honeycomb form of impression, the pieces have characteristics similar to those of the bones, such as their weight and great resistance. On the other hand, there were disadvantages thanks to the printer, for example, in the beginning, we wanted to obtain more spherical pieces, despite this once printed these were deformed and corrugated at the bottom of the piece. For this reason, we opted for a more angled design, less curved, and when printing did not have many inconveniences because of its unevenness, and due to its narrow shape, these deformations did not affect the dynamics of the piece.

As with the design of the hand, when printing the pieces it was necessary to retouch and make various finishes, such as sanding the pieces so that there was not much friction with the zippers. As a result, some zippers lost their original dimensions. This caused that due to the pressure exerted by the pinion on the rack sometimes these went off the rail and it was necessary to add a wooden bar in the box, next to the racks, this in order not to allow the derailment of these.

Another drawback relates to the motor. Because the motor shaft was not completely straight, there was vibration in the box back and forth, which caused the motor to disengage from the pinion. To solve this it was necessary to attach a small golden washer to the box. To this washer is tied a rubber to reduce vibration and prevent the engine from disengaging, thus avoiding leaving it fixed, which could have produced braking, which would be reflected in an increase in current.

Another adjustment necessary at the time of construction of the actuator was to open a hole at the top of the rack and

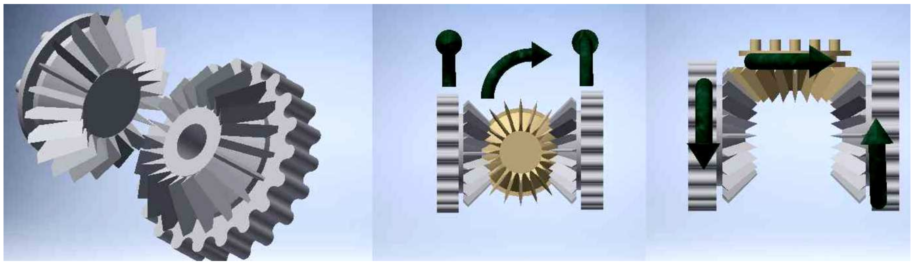

Figure 34. Change of direction of rotary motion.

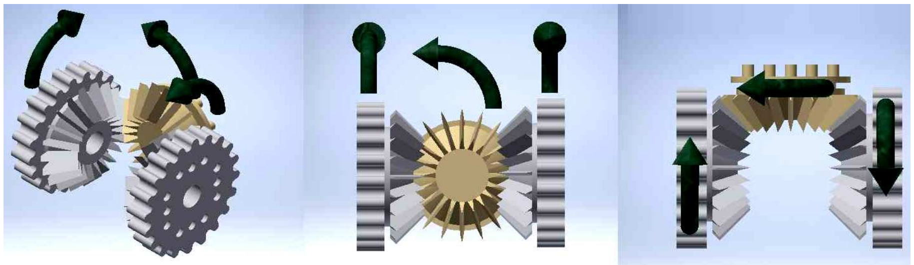

Figure 35. Turning inverter.

Figure 36. Lateral gears giving direction to the movement.

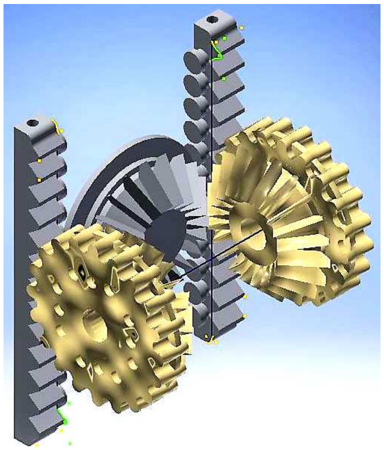

Figure 37. Lateral gears giving direction to the movement.

not through it as initially planned. These holes were mostly obstructed.

In the beginning, due to cost reasons, it was thought to generate the movement with gear motors and H-bridges. However, these motors were more delicate in the sense that when braking, the current would rise abruptly and the motor would be easily damaged. Because of this and because we found relatively comfortable servomotors, it was possible to replace the gear motors with servomotors. This change meant savings in H bridges, and easy handling, as we could operate them directly from the development board, managing to adjust both speed and displacement. In addition, the new assembly was able to withstand the overload better than the gearmotors.

Initially, the parts were intended to print on acrylonitrile butadiene styrene or ABS which is a very impact resistant plastic, also had a more convenient price compared to PLA. However, the parts were poorly resilient mechanically, and the material did not release, it was too rigid. Because of this, we opted for PLA.

It was thought to use nylon to make it act as a tendon. However, after working for a while it began to fall apart, besides that the nylon began to deform and lost the flexibility that it had in the beginning. We decided to work with hemp threads because they have good resistance to wear and do not affect the movement.

Prior to this, there were several designs, but due to their shape, these did not allow the pieces to come under pressure and ended up fractured. Consequently, it was necessary to leave between the pieces a space in the section that connects the joints, that is, the pieces have a base for the protuberance that fits with the next piece and between base and base, there

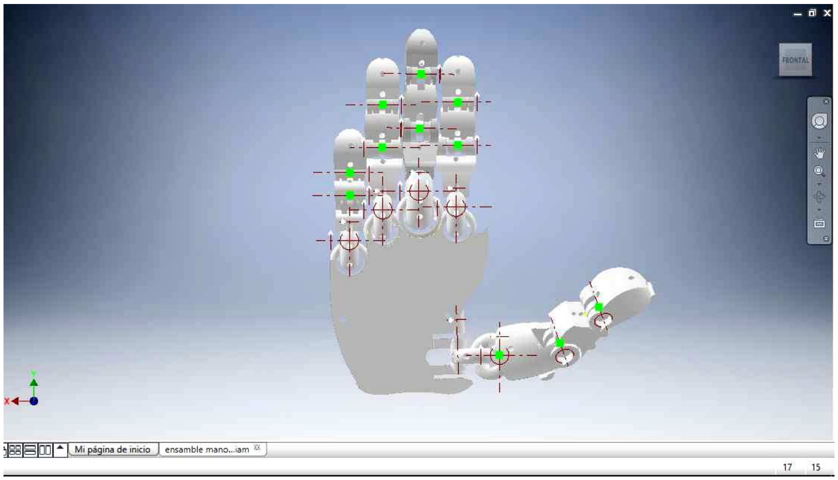

Figure 38. Simulation of hand degrees in the software.

is a space. The thickness of the base was another important aspect because if it was very thick it was not possible for it to yield and if it was very thin it would fracture. The final adjustment of the dimensions was made by trial and error.

It was also necessary to evaluate the types of joints present in the hand. In these, we found basically two of great importance: the saddle type and the hinge type. For the former, there was no need to put bumpers except for the little finger because the bumper is another continuous piece. The opening present in the pieces that are attached to the toroids of the palm was a little smaller than the thickness of these, despite this to avoid fractures the pieces were sanded so that this way there was no risk. On the other hand, for the hinged type was necessary to put stops on the back of the fingers, because without these the piece would tend to decouple and the movement would be unstable.

Another aspect that was taken into account was where the tension was generated in the pieces, that is to say, that the angle of exit of the tendon is suitable for the finger to bend, since if it is very flat it is going to need a greater force to carry out the flexion of the finger, and if it is very big it damages the aesthetics and could generate inconveniences because the thread would be more exposed (Fig. 39).

Once the hand has been assembled, we carry out functional tests with the power supplies. The measured consumption of electric starting current was 5 A. In steady state the current consumption is stabilized at 1 A.

Many of the movements are limited by the tendons, due to the limit distance that can be expected for the motors. The idea is not to exceed its point of operation, for its adjustment was opted to close the tip of the finger, then release the knuckle, and when it is bent, the knuckle is lowered. With this design and the operative adjustment of the fingers, a great variety of movements can be achieved. However, there is no direct control of the movement of each of the joints of the fingers, something similar happens with the human hand.

For the wider movements, the help of actuators was required. It was necessary to truncate some motors and change their rotary movement for a linear one since in this way the size required by the base and the movement carried out in the hand is kept under control.

Because the printed pieces differ from the digital design, they were subjected to tweaks ranging from simple filings (so that the pieces fit more smoothly without the risk of breaking the pieces) to the fact of forcing routes for the tendons. In several occasions, the original routes of the design were obstructed by the bases created in printing. In the end, many manual finishes were made to the pieces. Of particular interest was the adjustment of the parts involved with the actuators, as these require good precision because any obstruction, impurity or misplacement in the angle of operation of the part could trigger the malfunction of the actuator, in a poorly conceived movement or in the rupture of the parts of the same, in addition to risking the integrity of the motors and the development card.

For actuators, the dimensions and measurements must be precise, as their parts are small (Fig. 40). Each actuator is made up of three gears, one that is connected to the servomotor shaft part, and two at 90 degrees on each side of the servomotor shaft. Calibration is essential to get the zippers running at the same time and in the opposite direction.

To achieve the correct functioning of the linear actuator and the servo motors, these will be activated by hemp thread. This material is very resistant and will function as a tendon. Through tests with different materials, it was determined that this is the most suitable, both for its strength and for its easy travel in the actuator, from its initial position to the final position.

As already mentioned, the hand is designed to meet two characteristics: anthropomorphic scale topology, and ambidextrous handling that allows it to be used as both right

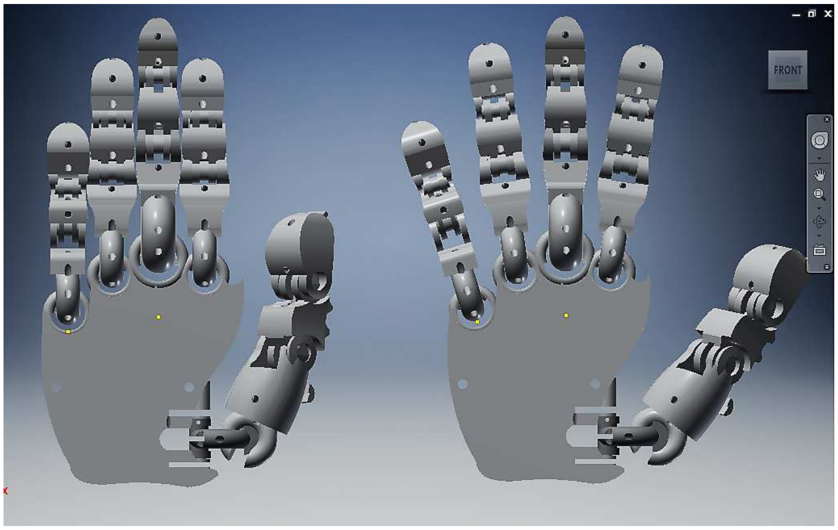

Figure 39. Final software assembly of the anthropomorphic prototype.

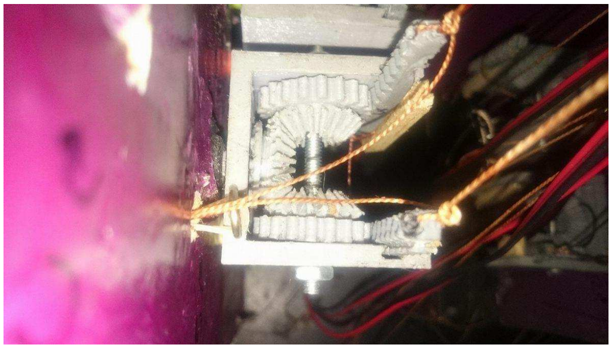

Figure 40. Actual actuator mounting.

and left hand. However, for the thumb part, it is not possible to adjust the toroid union between thumb and palm as shown in Fig. 40, but rather to adopt a new toroid or ring as shown in Figs. 41, 42, 43 and 44.

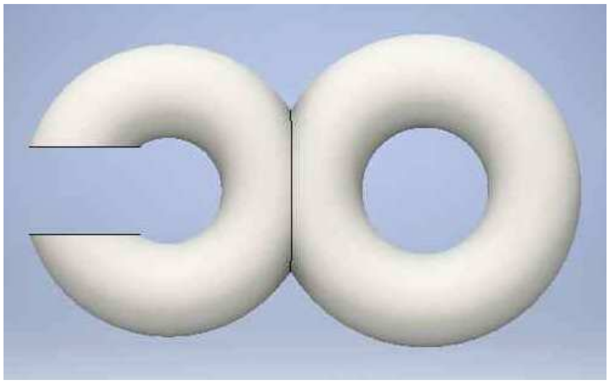

Figure 41. Reverse thumb piece.

Table 1 shows the ranges of motion in degrees measured on the prototype for each of the fingers and their joints.

Table 1

Range of motion of each finger joint.

	Tip	**Knuckle**	**Right**	**Left**
Pinky finger	60°	50°	38°	0°
Ring finger	77°	45°	40°	10°
Middle finger	40°	73°	30°	40°
Index finger	90°	40°	50°	10°
Thumb	60°	70°	0°	60°

At the tip the angle is measured from the second joint between the middle and proximal phalanx.

Conclusions

This article documents the development of an under-actuated robot hand with individual control of each finger by means of servomotors. This design took as its main basis the anatomy of the human hand, an anthropomorphic prototype, innovation, and implementation either as a prosthesis or prototype of electro-mechanized robots. Through laboratory tests, three fundamental characteristics in the movement of the actuator were evaluated: force, speed, and displacement. All with the possibility of change in different situations.

The three pinions used were designed as conical pinions of the same dimensions in order to transmit the movement without changes. In spite of this, in case of wanting to increase the force, we can play with the dimensions of the pinions. It is possible to make smaller the pinion that is connected to the motor or increase the dimensions of the side pinions, so it is possible to increase the force or do the opposite, to increase the speed of movements. In the case of displacement, if a wider range of movements is needed, what should be done is to put a longer zipper, thus covering the three needs that are required to generate the movement of the prototype.

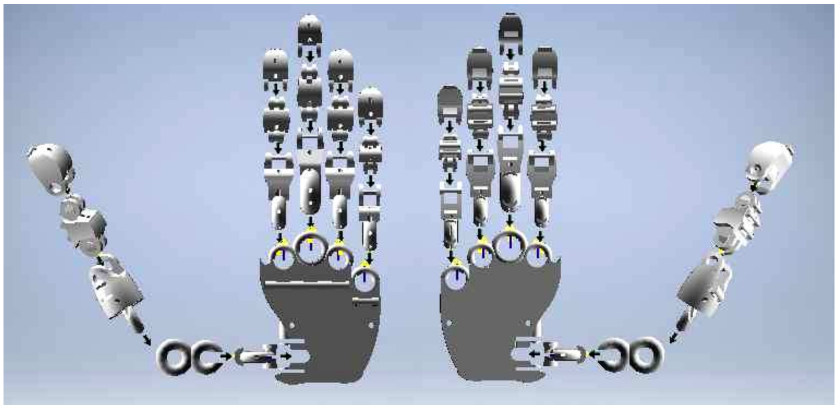

Figure 42. Left hand assembly (a).

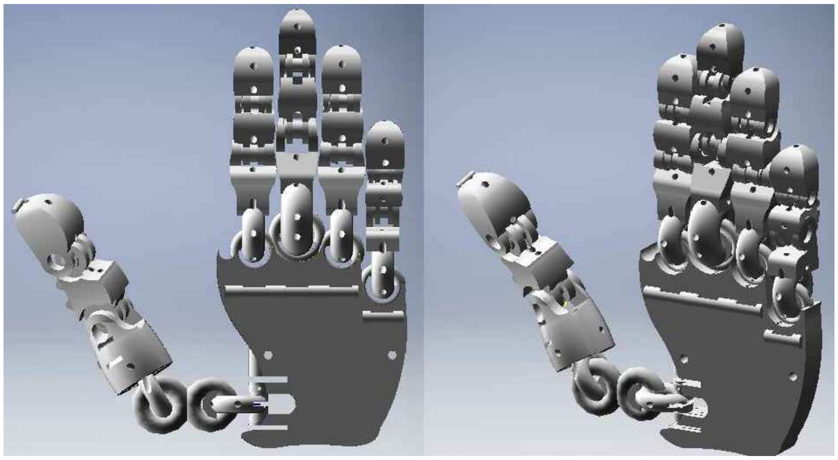

Figure 43. Left hand assembly (b).

Figure 44. Anthropomorphic hand prototype based with linear actuators as a base for movement.

Since the prototype is based on human anatomy, our prototype also has some similar limitations, some more notorious than others. Among them, we have the beginning of the movement, for example, if the finger is stretched you can not bend the knuckle at 90 degrees, but is slightly raised, or the fact that the thumb to be attached to the hand is more complicated to bend its tip. However, the prototype showed a large part of the movements of a real hand. The adduction and abduction movements were achieved, in addition, the range of some movements was increased and some own movements were developed such as the inclined finger.

In the case of the thumb, in the initial design, two tendons plus one were used as a reinforcement for the horizontal movement of the base and the other to give independence to the proximal phalanx of this finger. In spite of this, when it was tried to develop it was evidenced that putting these increased their limitations and it became more complex to move this finger. Consequently, we chose to leave this one with three tendons, in this way all the fingers were left with the same amount of tendons.

It should be noted that this project shows the possibility of creating a generic hand, i.e. a hand that could be both right and left and perhaps in the future could be designed in such a way that it is not necessary to disassemble and re-assemble to make this adjustment.

On the control side the objective was fulfilled, which was to achieve an analysis of movements, that is to say, we can control each movement individually and see what possibilities we may have or on the contrary because it does not move as we had predicted.

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