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MYOELECTRIC HAND PROSTHESIS CONTROL CONSIDERING INTERPHALANGEAL STIFFNESS

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Abstract. *Muscles usually work in pairs or groups, they function both as agonist and antagonist. When one muscle flexes the other one extends in order to allow and stabilize the movement, what also depends on the attachment's angles, bonding lengths, moments and strength directions. A variety of muscles and tendons are bounded together by more than one joint. In the fingers, some flexor and extensor tendons take place to four joints. During the movement from many ligaments, undesired torque might be generated, and they must be balanced by muscular strength. Most daily human hand movement are not precise, then the mechanical prosthesis project should be closer to a hand than to a tool. Once the mechanics of the prosthesis naturally goes to a proper movement, the control system became simpler. In this paper is presented a simpler controlling device outlined in a more intuitive way, carrying out far less restrictions in regard of positioning and prosthetic orientation. Such a system was obtained by adding passive stiffness on the prosthetic hand phalanx. Hereby all myoelectric sensors signals are adjusted to the stump, using a tensioned bracelet, which offsets the loss of contact, contributing to a global grabbing operation efficiency. The prosthetic hand stand point and orientation were carefully designed for the grabbing process success. The prototype tested in the laboratory was effective when the grab process is the focus not the manipulation.*

Keywords: *upper limb prosthesis, stiffness control, hand rehabilitation, myoelectric signals.*

1. INTRODUCTION

The hand is one of the most complex pieces of natural engineering in the human body. It allows both a manipulation with great precision and a strong grip (Cobos, 2008). Unfortunately, some people cannot take advantage of the hand movements, either because they don't have enough power and coordination or because they don't have the hand or the arm. Much is sought to facilitate the inclusion of people with disabilities in the social, as prostheses appear as one of these resources for people who have lost a limb or were born with some congenital malformation, for example. The lack or loss of the limb ends up causing major problems for the patient, both functional and psychological. The person who loses a limb suffers both from the change in their appearance, as well as from their limited lost capabilities (Sono, 2008; Capsi-Morales, 2020).

People with absence of any upper-limb usually have problems with prostheses adaptation, because these prostheses were not satisfactory developed or the training for its use was not successful. The upper-limb prostheses rejection rate is about 70% (Carvalho, 2004). It means that in a group of 10 patients that starts to use upper-limb prosthesis, 7 stops using it or use it sporadically at the beginning of the rehabilitation process.

In the last 20 years the researchers have worked to solve the problem related to the prosthesis technology, but the approaching usually don't changed significantly. The present work brings a new approach to hand prosthesis that consider stiffness and the arches of the hand due to allows an intuitive grasping process. The hand great precision movement is not focus of this work, but the grasping process. In daily life when somebody grasp an object usually it is not necessary to be concentrated on this task, as stopping and planning how to take the object, but just reach and grasp it (Aguiar, 2001).

This is the idea of this study, a prosthesis that allows the subjects to grasp most of objects without a great concentration and task planning, then the word grab could be used instead of grasp. The strategy used for developing the proposed prosthesis leads to a natural, soft, and adaptable movements, as fingers flexion and extension. This

methodology avoids a hard and complex control of the prosthesis evidenced by the first experimental result which demonstrated a flexible and effective grabbing process. In order to provide the prosthesis with a convenient stiffness, it was developed mechanisms to act on its joints using rubber cords. This mechanism insert a range of stiffness during the prosthesis movements, but if an unexpected important disturb happens probably it cannot be avoided, once it is passive system working called passive or natural stiffness. Consequently, the active or artificial stiffness, that is obtained by a joint force control system, sometimes could also be not sufficient to avoid some disturbs on the system (Montejunas, 2002). In human's hand there are some disturbs that also cannot be avoided. Therefore, the lighter and easier mechanism was chosen in this work that leads the prosthesis control to a most natural way, taking into account the arches of hand.

2. EXPERIMENTAL METHODOLOGY

The first stage of the experimental procedure of the project was the mechanical development of the prosthesis, in which the myoelectric control and the stiffness study was implemented, in a way that it approached the human hand as much as possible in terms of functionality in the operation of grasp.

According to Kapandji (2000) when you want to pick up a bulky object, the hand adapts as much as possible to its shape. In this case, the hand is excavated and arches are formed oriented in three directions: transversely, longitudinally and obliquely. The arc in the transverse direction corresponds to the concavity of the carpal massif, extending downwards through the metacarpal arch, in which the metacarpal heads are aligned.

When the hand is flat, the heads of the last four metacarpals are aligned on the same straight line. When it becomes "hollow", the heads of the last three metacarpals approach the fifth metacarpal, going forward. Thus, the heads of the metacarpals are arranged forming a curve, also understood as the transverse arch. The relationship between the arches of hand, the arch applied in the prosthesis model and the arches presented by the theory that supported this project can be observed in the "Figure 1".

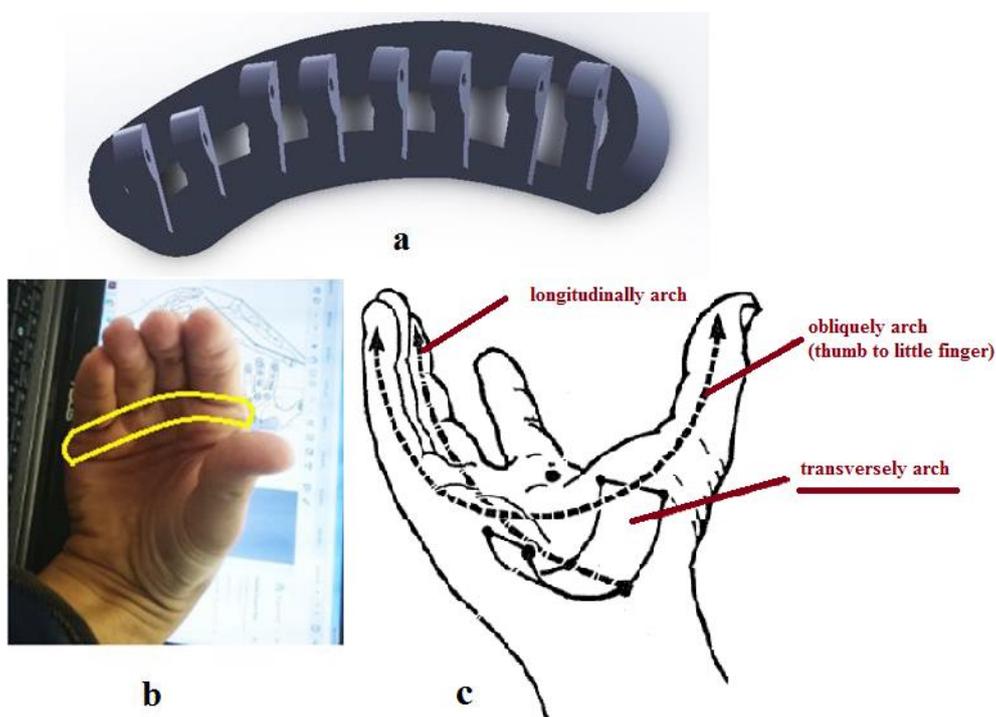


Figure 1. Relationship between Human Hand x Project Hand x Theory of Hand Arches: a) Piece of the prosthesis referring the transversely arch b) arch on the human hand c) theory of the hand arches adapted (Kapandji, 2000).

The "Figure 2" shows the prosthesis 3D model, the aim was to reproduce primarily the functionalities of the arches of the hand, so that the prosthesis would be able to produce the most natural and instinctive movements as intended. Combining the functionality obtained by the design of the arches of the hand and the flexibility implemented later, we reach the point where the grip process is allowed to the user with greater ease.

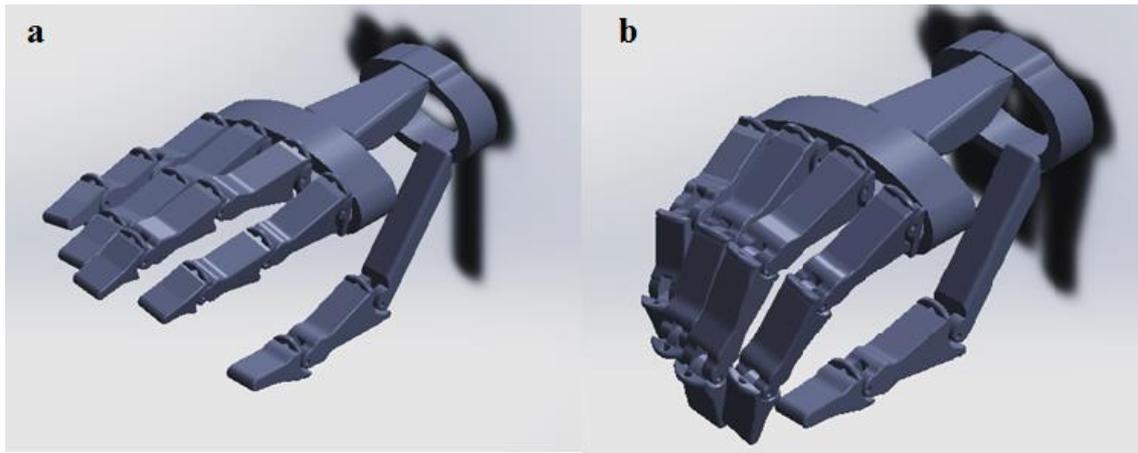


Figure 2. Myoelectric Hand Prosthesis: a) fingers extension position b) fingers flexion position.

The prosthesis, after being fully modeled, was made in a 3D printer, using a terpolymer material known as ABS, Acrylonitrile Butadiene Styrene. “Figure 3” shows a hand prosthesis and a real human hand in similar position (a to a and b to b). The focus here are the arches of the hands that allows a better prosthesis force closure, then the three arches of the hand can be considered present in the mechanical model.

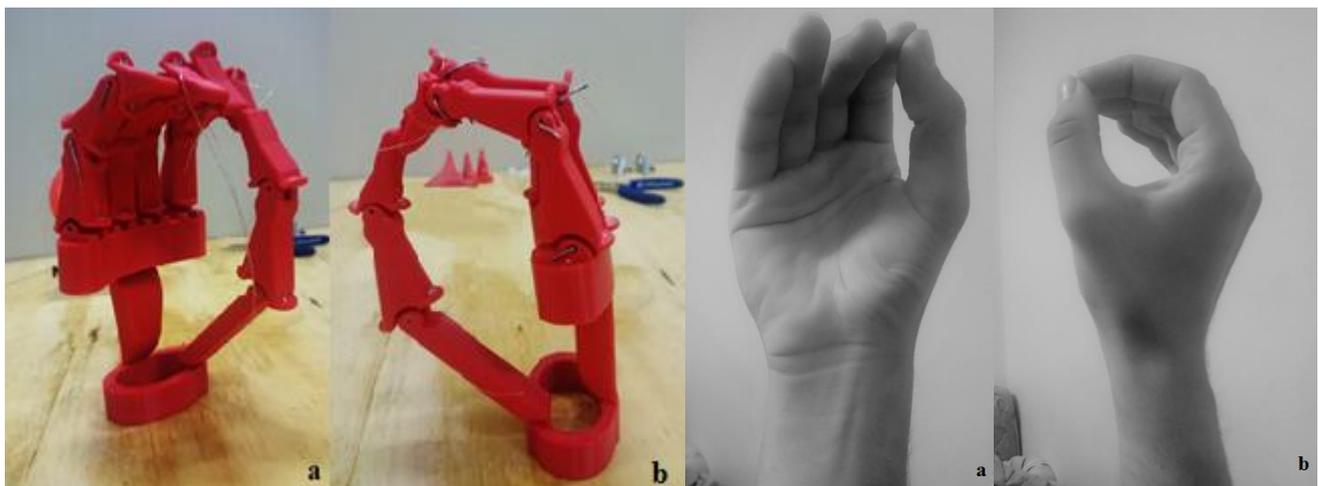


Figure 3. Arches of the hands comparison (a to a and b to b).

In the “Figure 3” can be observed that the fingers are constituted with three phalanxes. The flexion and extension movements of the fingers are performed by pulling cables connected to a motor. This system is analogous to what occurs in the human hand, however, in this case the traction is performed through the tendons, that is, in the prosthesis the cables are the tendons.

2.1 Activation system of the prosthesis

To capture the myoelectric signals from the muscles that result in the movement of the prosthesis, a bracelet containing myoelectric sensors was chosen. This choice is based on the principle these prostheses today generally use two or three myoelectric sensors placed in the arm, they are connected to the control circuit by wires, however, according to daily use, the positions and movements of the patient, sensor’s placement may shift and skin contact may be lost. With the use of the proposed bracelet is a more adjusted fixation to the patient's arm, thus, reducing the risk of system malfunctions due to lack of contact of the sensors with the skin.

The bracelet used in this case is responsible for the capture, treatment and transmission of myoelectric signals. These signals are transmitted to a Bluetooth interface connected to a microcontroller, which, according to the programming that is submitted, performs motor control, and consequently results in flexion and extension movements of the prosthesis. A generic system of movement example activation in the mechanical prosthesis can be seen in “Figure 4”.

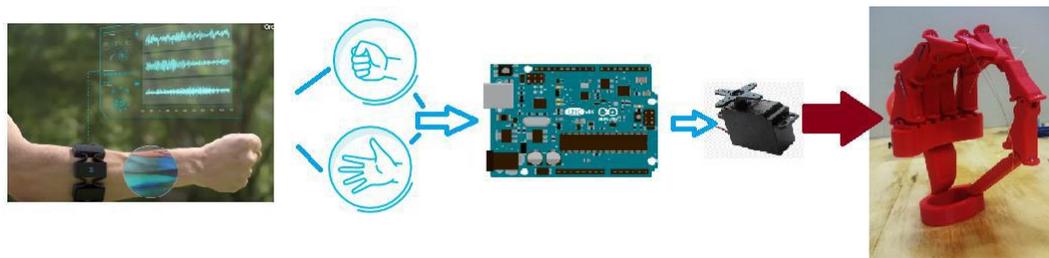


Figure 4. Control schematic for the movements of the prosthesis.

In the case already mentioned, where electrodes are commonly used to detect myoelectric signals, they need to be precisely placed in certain muscles of the patient's forearm. The bracelet applied here for this function has eight electromyographic sensors and they are distributed around its structure. In this way, the bracelet is able to capture the intention of movement coming from all the muscles that actuate the fingers present in the forearm, or even from any part of the arm.

The activation of the prosthesis motor is carried out only through an on-off control, both for flexion and extension of the fingers of the mechanical hand. First, the application of proportional drive control to the movements of the prosthesis according to the force obtained by the bracelet from the muscle was idealized. However, with the subsequent application of passive stiffness control that is presented in the next topic, the use of proportional control was discarded, since this type of control makes daily training and activation of the prosthesis difficult by the patient. Thus, the passive stiffness applied to the interphalangeal joints proves to be more efficient and makes a proportional force control unnecessary, exempting the patient from this task.

2.2 Passive stiffness applied to interphalangeal joints

In a joint mechanism, the stiffness determines the strength of the forces to be applied internally or externally to make possible a certain displacement. The flexibility of the joint determines which displacement occurs when a set of forces is applied to it. Therefore, it can be concluded that stiffness is the opposite of flexibility (Aguiar, 2001).

In this case, the stiffness is applied to the joint system of the fingers so that the flexibility is attenuated. This application makes the movements of the prosthesis similar to that of the natural hand. The attenuation of flexibility, that is, increased stiffness is analogous to the stabilizing function of muscle acting on a joint. The stabilizer function is a natural action of a muscle to stabilize a body part against some other force that is there acting, that force can be internal or external, and internal strength from performances of muscle and external force of any changes related to the environment (Hall, 2005). Many muscles or their tendons have more than one joint, for example, the biceps and triceps in the arm, as well as the hamstrings in the leg that are biarticular muscles (Burdet et al., 2013). Consequently, the stiffness presents itself as an important parameter for the choice of design materials, component geometry, format, interaction between each component and optimization of projects.

The control of stiffness applied to the interphalangeal joints of the prosthesis is performed in a passive or natural way. Such a system resembles the behavior of joint flexibility present in the human body. Joint flexibility describes the range of motion allowed in each of the planes of motion of a joint. Static flexibility refers to the range of motion present when a body segment is passively moved by an external motor force. Static flexibility is considered the best way to indicate the relative stiffness of a joint (Hall, 2005).

Passive stiffness is implemented through the application of elastic cords that run along the length of each finger of the prosthesis, both in the palm and in the dorsal region. In this way, when the cables are pulled so that the fingers perform the flexion movement, the elastic cords applied in the dorsal region act as a stabilizer muscle in its function. The same happens when the traction of the cables is to obtain the extension movement, in this case, the elastic cords is applied in the palm region and it's going to perform the muscle stabilizing function in the movement.

Another important function present in the human hand and also linked to muscle stability is performed by the deep transverse ligaments of the metacarpals. At first, the use of elastic cords to perform this function was studied, however, this implementation was discarded, as the mechanical structure of the hand was designed so that there was no gap between the joints, that is, there are no adduction and abduction movements, even if involuntary.

The elastic cords used to implement the passive stiffness of the prosthesis in the extension movement are located in the palm region and are shown in "Figure 5".



Figure 5. Elastic cords responsible for passive stiffness in the prosthesis.

The kinematics was studied with different intensity of stiffness which was obtained using different kind of elastic cords. The cords were chosen instead of traditional metal springs due to their higher extension ratios and higher range of motion. In addition, the cords are easily attached to mechanism and stiffness can be increased or decreased by simply adding or removing cords. It is possible to modify the stiffness also changing the length of the attached elastic cord.

3. ANALYSIS AND RESULTS

The elastic cords play an important role for controlling grabbing movement, allowing soft and convenient displacement. In the mechanical project the cords fit perfectly to the prosthesis and can be easily attached to the structure.

The cords are made of rubber. The physical rubber characteristics such as elasticity constant, Young's modulus, Elastic Limit and Fracture point were taken into account for verifying whether the cords were suitable or not to the project requirements.

The cord used in the prosthesis is made of natural rubber, the material elasticity constant, k , was obtained through traction tests performed in laboratory. The elasticity constant, k , was calculated taking the variation between the initial and final cord length, Δx , of the tested samples, according to Hooke's Law. The found value for k is shown in "Eq. (1)" below.

$$k = 20.66 \text{ N/m} \quad (1)$$

The modulus of elasticity E , also known as Young's modulus, is a mechanical parameter that also provides the stiffness of a solid material.

The Young's modulus of natural rubber is reported as values between 0.0015 GPa and 0.0025 GPa (Ashby, 2012). The Young's modulus value can be calculated by the ratio between the applied stress, σ , and the axial elastic strain, or percentage elongation, ε , from samples tested. According to the calculations performed, the Young's Modulus value found can be observed in "Eq. (2)".

$$E = 0.002094 \text{ GPa} \quad (2)$$

The obtained value by the calculations performed is within the range of standard values specified by Ashby (2012), being $0.0015 < 0.002094 < 0.0025$.

According to the calculations performed, it was possible to find the values of this stiffness applied to the fingers. Therefore, it was also possible to know what are the forces that the elastic cords are subjected to and submit when they are applied to the prosthesis. The elastic cords are subjected to forces when they play the role of agonist muscle, that is, when it is pulled together with the tendon in order to perform a voluntary movement of the prosthesis. However, at the

same time, they submit force, increasing stiffness, thus playing their role as an antagonist muscle and mainly as a stabilizer muscle.

With all the working parameters of the prosthesis defined (strength, stiffness, amplitude and speed), it is possible to graphically illustrate the relationships of movement, according to forces, angles and speed.

The “Figure 6” shows the flexion ranges of each finger from the force and stiffness applied by the elastic cord of each one. There is no proportional force control for closing and opening the prosthetic hand, therefore, it already acts with the maximum torque of the motor when it receives the PWM pulse from the microcontroller, however, there is a resultant from the relation of torque controlled by the motor and stiffness that the elastic cords apply to each finger when performing the flexion and extension movements.

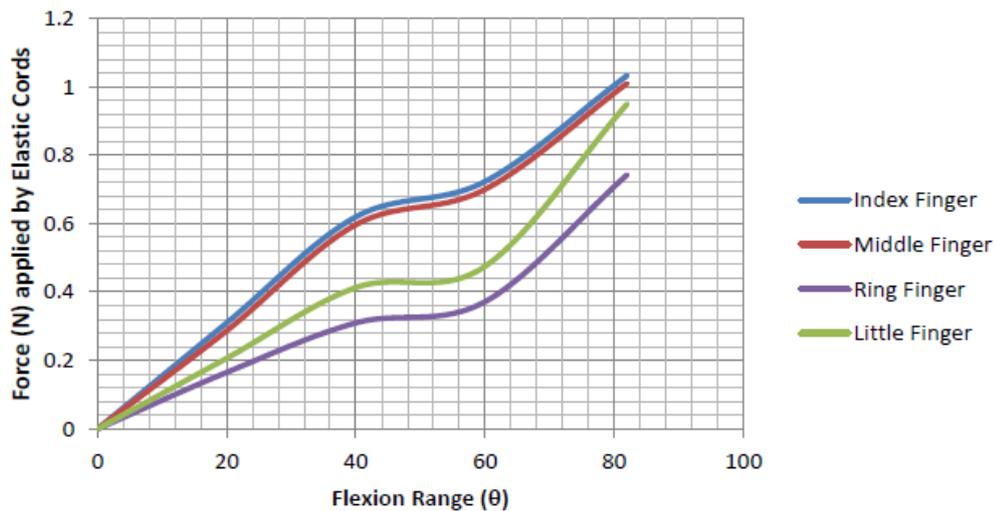


Figure 6. Graphic of Flexion Range x Force (elastic cords).

The curves presented show the behavior of the elastic cords in their muscle-stabilizing function. Similar behaviors in all fingers can be observed in the graph during the flexion and extension tests performed. From 0° to approximately 40° the “stabilizing force” that the elastic cords apply to the fingers increases in a way that can be considered linear. From 40° to approximately 60° the stabilizing force remains practically unchanged. In this way, after reaching 60°, the force increases again in a linear fashion, until it reaches maximum at the end of the movement. Such behavior is also present in the human hand.

According to Hall (2005), in the human hand this occurs in the Length-Tension relationship of the muscle. The total tension present in an extended muscle is the sum of the active tension provided by the muscle fibers with a passive tension provided by the muscle tendons and membranes. Passive tension is the force developed by a simple muscle contraction. Meanwhile, active tension represents the active force developed when a muscle contracts. The active tension is the force by the muscle and passive tension is the force suffered by the muscle.

The relationship of these stresses can be analyzed in “Figure 7”, which shows the similarity between the curves of the forces of the prosthesis can be seen in “Figure 6” and the human muscles.

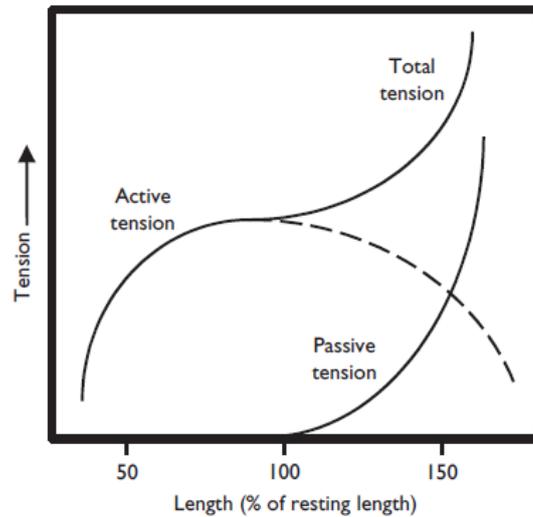


Figure 7. Length-Tension relationship in human muscle, Hall (2005).

The hand prosthesis was tested in the laboratory. The goal of this testing was to examine the prosthesis grasp function. It is desired that prosthesis allows the patient instinctively grasp diverse objects with different shapes in daily tasks. Tests examined the ability of the prosthesis in grasping objects. In this case, different objects were used, as shown in “Figure 8” below.

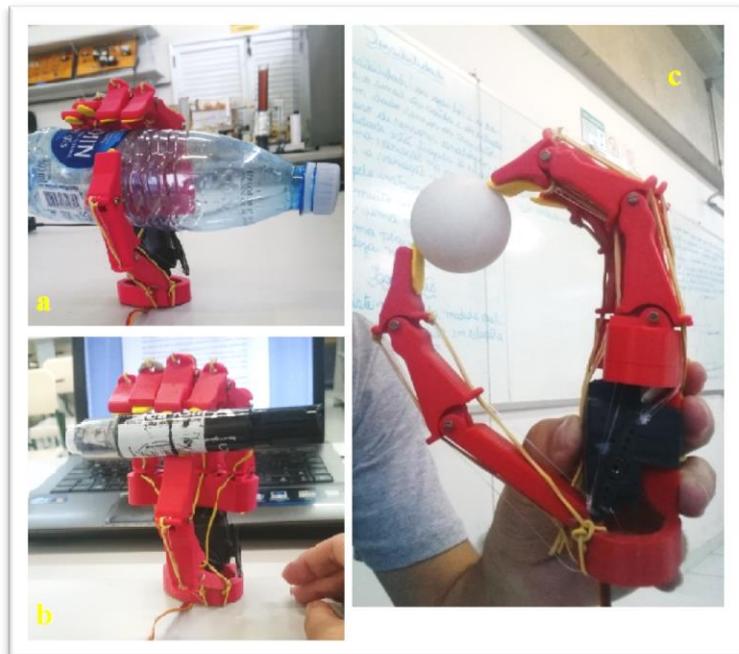


Figure 8. Grasp tests of prosthesis. a) grasping a bottle of water; b) grasping a pen; c) grasping a table tennis ball.

The preliminary results obtained in this study indicates that the benefits gained from interphalangeal stiffness and hand prosthesis shape considering the arches of the human hand, leads to an easier and secure grasp. All the tests revealed an easier way for grasping a variety of objects, especially if compared to the most common myoelectric prostheses used around the world. Usually it is necessary to stop, plan, position the gripper and finally grasp the object. The proposed gripper (hand prosthesis) allows this process to get close to the human natural way for grasping ordinary objects, just to glance the object, open the hand, put the hand on the object and then close the hand, without an extra concentration on this important task.

4. CONCLUSION

The proposed mechanical model behaved as expected, especially when combined with convenient stiffness alteration.

The application of passive stiffness through elastic cords in the interphalangeal joints proved to be an important feature. It is thanks to this application that it could be seen, according to the preliminary results that the hand acts with more natural and anthropomorphic movements during gripping. Therefore, the only control that the user needs to learn and train to be able to use the developed prosthesis is to send stimuli to the muscle with the intention of opening or closing the hand when he wants to pick up an object, because the movement control itself is left to account of the prosthesis itself, which differentiates it from conventional prostheses in this market.

The tests performed showed that the prosthesis is more successful in the process of gripping objects with considerable dimensions and more voluminous, consequently showing still little effectiveness in precision gripping processes.

It is advisable for the best operation to use the prosthesis combined with a silicone cosmetic cover that will allow an even easier and secure grasping. The next tests will be procedure with patients that already use myoelectric prostheses that will contribute to compare distinct myoelectric hand prostheses in daily grasping tasks.

5. ACKNOWLEDGEMENTS

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