The PrHand: Functional Assessment of an Underactuated Soft-Robotic Prosthetic Hand

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***Abstract*— Functional tests aim to compare the functionality of a prosthesis with a human hand. The main objective of this work is to present and evaluate an affordable prosthesis (PrHand) built with soft robotic technologies and novel joints based on compliant mechanisms. Two functional tests have been selected in this work. The first is the AHAP protocol, which evaluates how the prosthesis performs eight different grips; three variables are considered: grasping, maintaining, and grasping ability score (GAS). The results were 69.03% with 57.77% in grasping and 80.28% in maintaining. The second test is the AM-ULA, which evaluates the prosthesis by performing 23 Activities of Daily Living. PrHand prosthesis had a score of 2.5 over 4.0. The functionality of the PrHand prosthesis has similar results to other prostheses evaluated in the literature. The comparison with the human hand was 69%. PrHand presents a promising solution for amputees in developing countries regarding cost and functionality.**

I. INTRODUCTION

There were an estimated 30 million amputees without assistive devices in developing countries [1]. In Colombia, in 2019, there were more than 528,000 people with mobility disabilities in their upper, and lower limbs [2]. Through the development of robotic hands, the technology aims to help with self-esteem, psychological issues, and performing activities of daily living (ADL) [3]. Currently, it is possible to divide robotic hands made by 3D printing into two classes. Those that use pins as joints in rigid parts [4], and those that use compliant mechanisms and flexible materials to avoid rigid joints [5]. Fingers constructed with these techniques such as the compliant and underactuated mechanisms generate forces, and joint ranges equal to or greater than those of the human hand [6]. In the literature, degrees of freedom of middle finger abduction are rarely implemented, especially in devices with rigid components. The few existing ones use gearing methods, and motors [7]. Robotic hands using compliant mechanisms usually have degrees of freedom of joint abduction, but passive that gives a plus in drop tolerance and increased adaptation in grasping objects [8]. The TUAT/Karlsruhe mechanism is well-known among the underactuated prostheses. Here the finger's joints are guided by a sliding bearing, that gives independence to close each finger, and reopen by extension springs [9].

One of the methods to compare the devices is the functional evaluation, which seeks to evaluate the device's similarity with the human hand. The functional evaluation is made regarding three main functions: grasping objects, manipulating them and exploring the environment. One of the tests evaluates the prosthesis's ability to perform different types of grasping with different objects with varying dimensions [10]. Most prostheses evaluated with this test do not follow an object standard, complicating the comparison. However, the Anthropomorphic Hand Assessment Protocol (AHAP), evaluates eight grip types with three objects defined by grip type. The ARMAR was one of the devices evaluated with that protocol. The robotic hand is one part of an industrial robot and has 15 Degrees of Freedom (DOFs) actuated by two motors (one for the thumb and the other one for the other fingers); its actuation mechanism is adapted from TUTA/Karlsruhe[11]. With the AHAP protocol three versions were evaluated with results: version 1 (A1) was 45%, for version 2 (A2) 55%, for version 3 (A3) 61% [12]. The KIT Prosthetic Hand, evaluated with AHAP protocol too, is an upper limb prosthesis with 10 DOFs actuated by two motors. Its actuation mechanism is adapted from TUTA/Karlsruhe, it has a power grip force of 120N, and its cost is around 1000€ [13]. For the two versions of the prosthesis, the AHAP results were: version 1 (P1) was 72% and version 2 (P2) 79% [12].

The Activities Measure for Upper Limb Amputees (AM-ULA) protocol [14] evaluates users' activity performance by employing 23 ADLs. One of the main advantages of the protocol is that regardless of the type of upper limb prosthesis (motorized, hybrid or myoelectric) it is possible to evaluate the activity performance of users. This protocol is generally assessed with amputee patients. However, some articles use a coupling that allows a non-amputee user to manipulate the prosthesis and perform the test. An example where the prosthesis was tested with non-amputee users is the X-limb prosthesis with a score of 1.68. This prosthesis has 13 DOFs actuated by five motors (one per finger), its weight is 253gr, a power grip force of 21,5N, and its cost is around 200€ [15]. Another example is the SoftHand Pro prosthesis that

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reports having all the DOFs of the human hand except the related with the wrist, its weight is 520gr, and power grip force of 76N. Its results for the AMU-LA test were 1.69 [16].

This article describes the PrHand prosthesis, which has innovative character fingers based on compliant mechanism and allows it to be based on soft-robotics. In addition, two functional tests are chosen from the literature review to be performed on the prosthesis and to compare its functionality with state-of-the-art prostheses.

II. System description

The prosthesis was constructed using a compliant mechanism and soft actuator techniques (see Fig. 1). The finger and the palm are made of rigid material (PLA). The proposed device combines pneumatic and electric actuation as it uses a Dynamixel MX-106 motor (Robotis, USA) to drive the flexion of the five fingers and an air pump (MITSUMI, Japan) to pressurize the pneumatic silicone actuators that make finger abduction. The system uses a 12V, 5A power supply for operation. In addition, hand control was performed in ROS on a Raspberry Pi 3 (Raspberry Pi, UK).

The main design feature of the prosthesis constructed in this study is the finger flexion and extension mechanism. The mechanism is based on the compliant mechanisms built from a single material [17]. Two circumferences joined by a tension element such as a rigid thread (Sufix 832, USA) are used, allowing rigid materials for construction, such as PLA. Finger flexion is achieved using the tensile force generated to the joint through a tendon, as shown in Fig. 1(b). Unlike a traditional revolute joint, this joint does not rotate about a fixed axis, but rather the joint rotates and translates tangentially around a circumference. This novel joint is more similar to the human body joints [18].

The design is constructed with guided soft joints [19]. Each finger link is made of rigid material (PLA), and 2.85 Filaflex (Recreus, Spain) tendons with elastic properties make the fingers perform. The fingers of the prosthesis have an internal elastic tendon that acts as a force opposite to the flexion. This avoids the use of an actuator responsible for the extension. The tendon is located at the limit of the movement of the circumferences that generates a return force to the original position (see Fig. 1(d)). The rigid tendon is located in the outer part of the finger. When the motor is actuated so that the hand closes, the rigid tendon carries the finger to flexion resulting in the elastic tendon deforming elastically. When the motor moves to open the hand, the elastic tendon returns the finger to its initial position. The design of the PrHand is characterized by the Ecoflex 00-50 silicone coating around the fingers, except at the joints because the silicone generates a high bending constraint (see Fig. 1(b)). The initial position of the thumb is placed at 90 degrees relative to the palm.

To achieve abduction movements in the prostheses, silicone actuators are controlled by 3-way normally open mini solenoid valves with two positions for each actuator (Generic 3/2, China). Each solenoid valve is actuated through the raspberry independently according to the type of gripping to be performed. To reduce power consumption, the activation of the air pump is also controlled by the raspberry. The pump is only turned on when pressure is required at the actuators. In total, this design has 15 degrees of freedom. As can be seen in Fig. 1(c), each prosthetic finger has three degrees of freedom: two degrees of freedom (proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints) are responsible for flexion of the prosthetic fingers, and the other degree of freedom is to generate abduction in the main fingers. This distribution of joints in the main fingers does not consider the degree of freedom of the human hand's distal interphalangeal (DIP) joint.

Were chosen four grasp types that were configured to do with the abduction actuators. The first (G1) is a power grasp and closes the hand without inflating any actuator. The second grasp type (G2) is the pulp pinch inflating the actuator between the index and middle finger. For the third (G3) one, all actuators are inflated. The grasp is called a spherical grip. The last one (G4) is a spherical grasp too, but the difference is that the hand is not fully closed for big-size objects.

Since only one motor is used in the design of these devices for finger flexion, the five tendons (one per finger) must be unified into a single tendon tensioned by the motor. The proposed system provides similar benefits to the TUAT/Karlsruhe [9] mechanism. However, as here is proposed to use soft robotics replacing the pulleys with elastic tendons and using a smaller quantity of elements, it seems less complex. It is called a unifying mechanism and consists of a sliding mechanism that collects the elastic tendons of the fingers and joins them to a moving part that slides utilizing two parallel rods. The rigid tendon connected to the motor generates the sliding mechanism movement, see Fig. 1 (a). The mechanism should correctly hold the elastic tendons, preventing their displacement during gripping. The elastic elements of this mechanism are the same size for each finger. For control, the entire system is powered by a 12-volt supply that passes through a regulator that provides 5 volts to power the various electronics. Also, two physical pushbuttons are used to control the bending of the fingers and the activation of the pneumatic actuators. The raspberry pi controls the motor position, the activation time of the air pump, and the solenoid valves. The user chooses the desired grasp type; with one of the pushbuttons, and with the other pushbutton, closes and opens the hand.

The production cost estimated for the PrHand prosthesis is \$692,67 (638,87€). The prosthesis's mechanical characteristics are a power grip force of 36.13 $\pm$ 2.03N, to close the hand is required energy of 1,28 $\pm$ 0.13J, its dissipated energy is 0.96 $\pm$ 0.12J and support a traction force of 78.48 $\pm$ 0.00N.

III. Methodology and Materials

The ethics committee approved the protocols of the Colombian School of Engineering Julio Garavito.

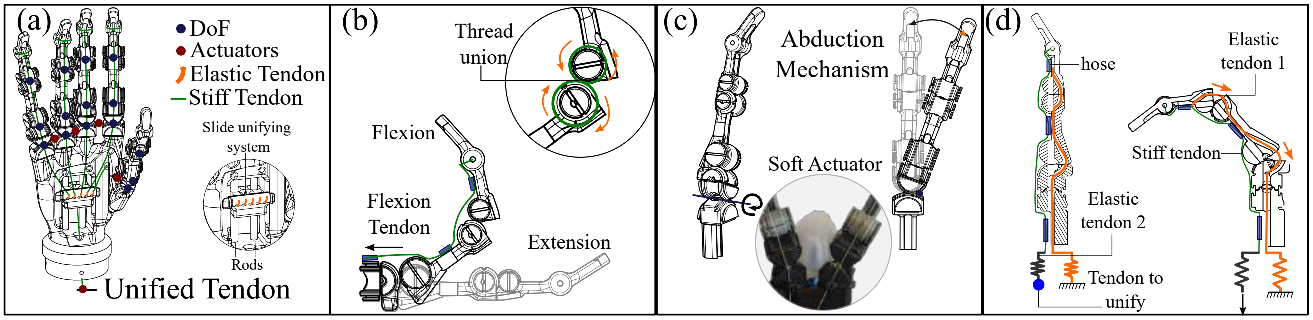

Fig. 1: General system of PrHand prosthesis: (a) PrHand prosthesis with five control actuators and a sliding mechanism to unify the tendons (5 tendons to 1). (b) Explanation of how the finger flexion and extension are generated based on the compliant mechanism of two tangential circumferences at a single point. (c) Abduction degree of freedom driven by a soft silicone actuator. (d) Internal view of the fingers used in the prosthesis in the neutral and flexion positions. The ducts used by the extension tendon 1 in the PrHand prosthesis and the forces generated in the flexion movement are shown.

A. Anthropomorphic Hand Assessment Protocol (AHAP)

A scaffold is built to allow non-amputee subjects to manipulate the prosthesis. The types of grips evaluated and their respective objects were taken from the general YCB (YaleCarnegie Mellon University-Berkeley) objects set [12]. The protocol establishes the steps for the test, the times, the number of repetitions, the way to record the videos, the parameters for evaluating the grip, and the scores. For the test, two persons are required, the operator (the one who conducts the experiments) and the subject (the one who controls the prosthesis). The procedure consists of: First, the operator shows the object and the correct grasping posture/task to the subject. In a second place, the operator helps the subject practice the grasp/task for about one minute. Three, the operator hands the object over to the subject for the test. Fourth, the subject actuates the artificial hand for grasping the object with the palm pointing upwards. The operator releases the object as soon as the artificial hand has grabbed the object. Five, the subject maintains the grasp for three seconds. Six, this step is followed immediately by step 5, and the sequence of steps 4–5 is repeated three times. While maintaining the grip, the subject naturally rotates the hand with low acceleration for the palm to point downwards (180°) and keeps the grip for three seconds in this position. The subject releases the object, which is taken by the operator. The test is performed three times per object and with five subjects. For the evaluation, the videos are recorded during the test, and three evaluators measure the parameters of the protocol.

For the evaluation, there are three variables. The first one is grasping, which evaluates if the prosthesis can grasp the object as indicated in the protocol. It is assigned a value of 100 when the prosthesis holds the object making all contacts, 50 when the prosthesis does not hold the object precisely as indicated but grasps it, and 0 when the prosthesis cannot grasp the object. The second is maintaining, which assesses that the prosthesis has sufficient strength to keep the object held for the entire time before and after turning the object over and releasing it. A value of 100 is assigned when the whole time the prosthesis is holding the object, and it does not move, a score of 50 when any moment of the test the held part moves and 0 when the object falls. Finally, the variable Grasping Ability Score (GAS) corresponds to the average of the two previous variables. This variable is a percentage of similarity with the human hand concerning the evaluated functionality, considering that the closer the result is to 100 the better. The tests are recorded from two perspectives. The first is a side view that is more than one meter away from the test scene and the other from the top, to observe the type of grip in detail.

For the test execution, the grasp types are chosen for each object. For all objects that can be picked up using a hook, the grasp type G1 has been applied. For the bigger sphere of the spherical grips objects, G4 is used. Grasp type G3 is used for the other two objects, namely the softball and mini soccer balls. For all tripod pinch objects, G2 is deployed. For all the objects of the extension grip, G1 is the most suitable. G4 was used for coffee, and for the other cylindrical objects, G1 was applied. For diagonal volar grip, lateral pinch and pulp pinch objects, G2 are utilized (see Fig. 2).

B. Activities Measure for Upper Limb Amputees (AM-ULA)

This test uses an EMG sensor that captures the signals coming from the muscle and transforms them into an electrical signal. The sensor makes the pushbutton function that closes and opens the hand, and coupling is constructed to allow non-amputee subjects to manipulate the prosthesis. The Activities Measure for Upper Limb Amputees protocol (AM-ULA) [14] was followed, in there is specified the task, the objects, and the evaluation parameters. The test evaluates 23 activities of daily living in terms of: completing all the subtasks of each of the activities, speed in completing the task, quality of movement, ability to use the prosthesis and independence. For each tasks, the operator reads the instructions indicating each of the subtasks to be performed to complete the task. Some unilateral tasks, which ideally should be performed only with the prosthesis, should be noted. The user is free to choose the grasp type that seems better (between G1, G2, G3, and G4). The test was performed on five non-amputee subjects.

For the evaluation, a score from 0 to 4 (from incapable to excellent) of the five variables described after this is taken, and an average is made first by task and then overall; some variables do not have a score of 0, as they are not applied. The first one is complete all subtasks, corresponds to the person performing all the subtasks described in the protocol to complete the task, is scored with 0 or 4, where a score of 0 is assigned when not performing all subtasks and 4 if performing all tasks; the scores 1, 2, and 3 are described in the protocol as all the tasks, so for this case, were not considered. The speed at which he completes the tasks is scored from 1 to 4, with 1 being very slow to slow and 4 being a speed similar to that of a non-amputee. The quality of movement is related to the amount of compensatory movement that the person makes with the body to use the prosthesis during the performance of the task. It is scored from 1 to 4 where 1 makes many compensatory movements and discomfort is seen in the prosthesis and 4 excellent movements are seen with the prosthesis. There are no compensatory movements and no discomfort is seen when using it. The ability to use the prosthesis is related to the prominence of the prosthesis during the task. It is scored from 0 to 4, where 0 is that the prosthesis was not used during the task and 4 is that the prosthesis did not lose grip during the task, the type of grip is optimal and the prosthesis was not only stabilized the object during the task. Finally, independence is related to using assistive devices to perform the task. It is scored 1 or 4, where 1 is using some assistive device and 4 is not using any; scores 2, and 3 are described in the protocol as using some assistive device, so for this case were not taken into account.

The videos recorded during the test were used for scoring and three raters were used. Two cameras were placed, the first one facing the subject to observe the manipulation of objects with the prosthesis. The second camera, located laterally, was used mainly to identify compensatory movements by the subject.

IV. Results

The average results for each grip type of the grasping variable are shown in Table I. The grip types that most closely resemble the theory, with a percentage higher than 50%, are: lateral 75.53 ± 5.64%, tripod pinch 72.20 ± 9.88%, hook and cylindrical with 66.67%. The grip types with coefficients of variation (CV) higher than 5%, considered variables for this test, are: Tripod pinch, spherical and lateral. The PrHand prosthesis had a grasping average of 57.77 ± 0.52%. A normality test was performed because the grasping variable follows a normal distribution. Subsequently, a T-student statistical test was performed for a single sample, where the theoretical values were the results found in the literature (for the ARMAR hand, version 1 (A1) was 52%, for version 2 (A2) 59%, for version 3 (A3) 62%, for the KIT Prosthetic Hand version 1 (P1) was 65% and version 2 (P2) 68% [12]). The test resulted in significant differences between PrHand and the literature results.

TABLE I: AHAP results for grasping, maintaining, and GAS variables by grasp type

Grasp type	Grasping	Maintaining	GAS
Hook	66.7 ± 0.0 (0.0%)	67.7 ± 6.4 (9.4%)	67.2 ± 3.2 (4.8%)
Spherical	47.7 ± 4.5 (9.5%)	84.5 ± 11.4 (13.4%)	66.1 ± 7.6 (11.5%)
Tripod pinch	72.2 ± 9.9 (13.7%)	88.9 ± 7.8 (8.7%)	80.6 ± 7.4 (9.2%)
Extension	50.0 ± 0.0 (0.0%)	94.5 ± 4.9 (5.2%)	72.2 ± 2.5 (3.4%)
Cylindrical	66.7 ± 0.0 (0.0%)	72.2 ± 14.1 (19.5%)	69.4 ± 7.0 (10.1%)
Diagonal volar	33.3 ± 0.0 (0.0%)	57.9 ± 8.2 (14.2%)	45.6 ± 4.1 (9.0%)
Lateral	75.5 ± 5.6 (7.5%)	88.8 ± 11.6 (13.1%)	82.2 ± 5.4 (6.6%)
Pulp	50.0 ± 0.0 (0.0%)	87.8 ± 13.3 (15.1%)	68.9 ± 6.6 (9.6%)
Average	57.8 ± 0.5 (0.9%)	80.3 ± 2.5 (5.6%)	69.0 ± 2.5 (3.6%)

The average results for each type of grip of the maintaining variable are shown in Table I. The grip types that had better percentages with results higher than 80%, which means that it gripped the object with more strength by not moving during the test or falling, are: extension 94.47 ± 4.92%, tripod pinch 88.93 ± 7.78%, lateral 88.80 ± 11.63%, pulp 87.80 ± 13.29% and spherical 84.47 ± 11.36%. For this variable, all coefficients of variation by grip type are higher than 5%, which means that they are variable. This means that the data tend not to follow a homogeneous distribution. The three grip types with the highest CV are: cylindrical, diagonal volar and spherical. The PrHand prosthesis had a score of 80.28 ± 4.52%. A normality test was performed because the maintaining variable follows a normal distribution. Subsequently, a T-student statistical test was performed for a single sample, where the theoretical values were the results found in the literature: for A1 was 37%, for A2 50%, for A3 60%, for P1 was 79% and P2 91% [12]. The test resulted in that no significant differences between PrHand and P1; there is significant difference rest of the prostheses.

The mean results for each grip type for the GAS variable are shown in Table I. Most results scored higher than 60%, except diagonal flying grip with 45.60 ± 4.12%. The 3 best scoring grips were: lateral 82.17 ± 5.44%, tripod pinch 80.57 ± 7.38% and extension 72.23 ± 2.64%. For this variable, most of the coefficients of variation by grip type are greater than 5%, i.e., these grip types are variable. The three grip types with higher CV are: spherical, cylindrical and pulp. The average GAS for PrHand is 69.03 ± 2.48%. A normality test was performed because the GAS variable follows a normal distribution. Subsequently, a T-student statistical test was performed for a single sample, where the theoretical values were the results found in the literature (A1 45%, A2 55%, A3 61%, P1 was 72% and P2 79% [12]). The test resulted in no significant differences between PrHand and P1 prosthesis; with the rest of the prostheses, there is a significant difference. Fig. 2 shows the PrHand prosthesis performing the protocol grasping postures.

Table II shows the average score per task of the AM-ULA test. The highest scoring unilateral task was using the combing brush with 3.34 ± 0.17, and the highest-scoring bilateral task was using the telephone with 3.69 ± 0.04. Tasks with a coefficient of variation greater than 5% are considered variable. Taking off a shirt, writing, and putting on a shirt had a higher CV.

The mean score in the AM-ULA test is 2.50 ± 0.16 with

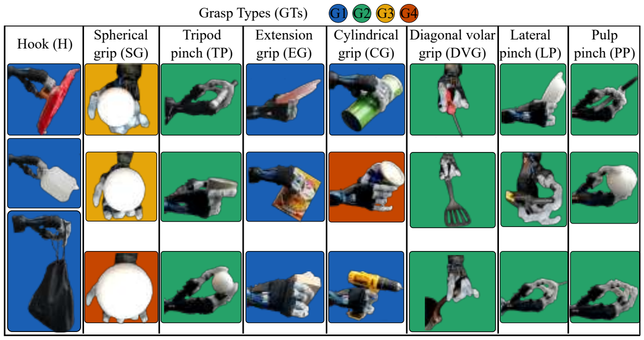

Fig. 2: PrHand prosthesis performing some of the grips of AHAP protocol

TABLE II: AM-ULA results by task

Item	Average	SD	CV (%)
Brush teeth	3,13	0,46	14,65
Brush hair*	3,34	0,17	4,95
Put on t-shirt	1,38	0,36	25,98
Remove t-shirt	1,69	1,32	77,96
Button shirt	2,00	0,17	8,33
Zip jacket	0,66	0,06	9,52
Tie shoes	2,69	0,32	12,00
Use cup*	2,71	0,08	2,76
Use fork*	2,25	0,17	7,52
Use spoon*	2,00	0,07	3,61
Cut meat	2,39	0,09	3,92
Pour soda	3,59	0,02	0,70
Write word*	1,98	0,65	33,04
Use scissors	2,55	0,09	3,68
Door knob*	2,66	0,19	7,06
Key in lock*	0,76	0,03	3,28
Carry laundry	3,06	0,07	2,45
Use phone	3,69	0,04	1,13
Hammer	2,19	0,19	8,63
Fold towel	3,21	0,05	1,5
Open envelope	3,03	0,11	3,57
Stir bowl	3,30	0,13	3,91

*Unilateral tasks

a coefficient of variation of 6.28%. A normality test was performed because the AM-ULA score follows a normal distribution. Subsequently, a one-sample T-Student test was performed to compare PrHand with the literature results (X-limb [15] 1.68 and SoftHand Pro [16] 1.69) . Significant differences were found between the two prostheses in the literature. Fig. 3 shows the PrHand prosthesis performing some protocol tasks performed during the test.

Fig. 3: Non-amputee user performing some of the tasks of AM-ULA protocol with the PrHand prosthesis

V. Discussion

Regarding the grasping variable, spherical grips, as observed during testing, are challenging to perform for prostheses because of the position of the thumb. In the case of PrHand, it is completed the grasping, but not exactly as the protocol indicated. In the tripod and lateral grips, how the object was delivered had a significant influence on the result, which is why they were among the higher scores in the type of grip, but at the same time they had the highest CV. The object's shape also significantly influenced the way it was grasped, which could cause that the object is not grasp as the protocol stated, as in the case of the hook grip. In the case of the diagonal volar grips, the degrees of freedom of the hand will be an essential factor since, in the case of PrHand, its degrees of freedom did not allow it to grasp the objects as indicated in the protocol, but it did grasp them. In comparison with the literature, the average score of the variable grasping is in the range; however, it is not the lowest. In general, PrHand grasps the objects but not with as much similarity to what is indicated in the protocol.

In the maintaining variable, the silicone coatings are essential because they are the ones that generate the friction force that allows the objects to be gripped and stay still for the most part. The force with which the prosthesis grips the objects depends on the object's size. If the objects are large, the prosthesis will not be able to grip them, or if they are tiny, the contacts may not be enough to maintain them. Regarding the comparison of literature, the element that generates friction is quite essential considering that version 3 of the ARMAR hand was the version that had the best result and the KIT Prosthetic Hand prosthesis had high scores, where its buds are made of silicone.

In the GAS variable, the grip that PrHand performs best is the lateral grip. Compared to the literature, its score is higher, which is associated with the contrary movement of the thumb that influences the accommodation of all the fingers to be similar to that indicated by the protocol. The diagonal volar grip is the one that had the lowest score for the PrHand prosthesis, being a grip that its score is very similar to that of the prostheses in the literature, which leads to the conclusion that it tends to be a complex type of grip. In the overall mean of the GAS variable, the PrHand prosthesis is within the means, outperforming all three versions of the ARMAR hand and scoring lower only with the second version of the KIT prosthetic hand. One of the advantages of PrHand is the fact that used only one motor for its performance.

For the AM-ULA results, the task with the best score was the cell phone task, one of the most manageable tasks since the prosthesis only had to hold the cell phone. On the other hand, the one with the lowest score was the zipper up task. This is related to the difficulty of the prosthesis grasping small objects. For tasks with a higher coefficient of variation, such as putting toothpaste on the toothbrush, putting on the shirt, taking off the shirt, putting on socks, tying shoelaces and writing, the main factors for finding changes in these variables were the speed of execution of the task rather than the performance of the prosthesis in performing them. The tasks whose CV was less than 5% showed for that objects. The grasp is more stable in terms of repeatability. In comparison with the results found in the literature review, the results of the AM-ULA test for the

PrHand prosthesis are better than the average. One crucial aspect was that the prosthesis could assist the user in all tasks. One of the improvements in general for the prosthesis shown is the manipulation of small and thin objects.

VI. Conclusions

The PrHand hand prosthesis, an underactuated prosthesis based on soft robotics and compliant joints, was constructed and functionally evaluated. This study presents the prosthesis, and describes its parts and its novel joint mechanism. Functional tests are performed on whether the prosthesis can perform various types of grasping and resemble what the human hand does and whether it can perform different activities of daily living. In the results of the AHAP test, the grip that can perform more similar to the human hand is the lateral grip, the grip that grips with higher firmness is the tripod, and in the end the prosthesis has a 69.03% of similarity with the human hand. One of the factors that greatly influenced the results was the object's size since very large or very small objects could not be grasped well by the prosthesis and sometimes even could not be grasped at all. In the AM-ULA test results, the best performing task is holding the cell phone. The task with the lowest score was the zipper up, and this, has an essential factor that the zipper is small, and the prosthesis has difficulty with this type of object. Most of the variation coefficients are higher than 5% in this test. An essential factor is that one of the qualifiers of the test is the speed at which the task is performed, being a very variable factor per person.

Although the results do not show improvements in the AHAP functionality test concerning the literature, the prosthesis used fewer actuators which results in a benefit. Nevertheless, the functional assessment related to making daily life tasks has a good result. So it could be that in terms of how the prosthesis locates its fingers is not like the human hand but allows it to make daily life tasks. One aspect that could improve the prosthesis functionality is to enhance the control of the thumb movement. One aspect that could improve the prosthesis functionality is improving the control and the design of the actuator of the thumb. Also, a detailed evaluation of the functionality with and without the abduction actuation will help understand the proposed system's additional benefits. Talking about the mechanical structure could be simply attaching spring to tendons. Nevertheless, the advantage of the tendon here implemented is the adaptability of the prosthesis closure to objects. Additionally, the easy acquisition of these materials even in developing countries. One of the limitations of this study was the limited number of subjects and the lack of involved amputees in the study. However, the future works involve some improvements in a new version of the device and performing tests with amputee patients.

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