Development and Functional Evaluation of The PrHand V2 Soft-Robotics Prosthetic Hand

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***Abstract*— The affordability and functionality of hand prosthetics in developing countries are still very limited. This work aims to present and evaluate the new version of the PrHand affordable robotic prosthesis (PrHand V2), built with soft robotics and compliant mechanisms. PrHand V2 implements a new frictionless tendon unification system, the thumb opposition degree of freedom was removed, and the finger flexion was improved to the previous version, PrHand V1. The Anthropomorphic Hand Assessment Protocol (AHAP) dexterity test was the first evaluation in this work; it evaluated how the prosthesis performs eight different grips. PrHand V2 was compared with a PrHand V1 and a commercial robotic prosthesis A3D from Prótesis Avanzadas SAS. PrHand V2's score on the AHAP test was 80%. This result is higher than the 69% obtained by the PrHand V1 and the 79% obtained by A3D. The Activities Measure for Upper Limb Amputees (AM-ULA) test was the second evaluation in this work; an A3D amputee user performed 23 Activities of Daily Living with PrHand V2 and an A3D. PrHand V2 obtained an average of 2.86/4, and A3D obtained an average of 2.96 without significant differences between the two tests. The soft actuation of PrHand V2 as an affordable prosthesis performs similarly to a commercial robotic prosthesis with the advantage of being more flexible to assist a trans-radial hand amputee.**

I. INTRODUCTION

In Colombia, by 2020, 533.051 people reported mobility disabilities in their upper and lower limbs [1]. In 2022, around 57,802 amputations were performed in Brazil [2]. The World Health Organization (WHO) currently estimates that more than one billion people need an assistive device, and it is expected that there will be around two billion people by 2030 [3], [4].

Robotic prosthetic hands aim to help with self-esteem and psychological traumas and to perform activities of daily living (ADL) [5]. To reduce production costs and simplify the manufacturing process, the use of 3D technologies is growing. This could be divided into two technologies; the first uses pins as joints in rigid joints [6], [7], and the second avoids rigid joints by using flexible materials and complaint mechanisms [8], [9]. One of the main advantages of the latter is that the force generated and the joint ranges of movement are more like the human hand [10]. The degree of freedom (DOF) of abduction is rarely implemented in rigid devices [11]. It is present in flexible devices, but in most of them, it is passive [12], [13].

The PrHand is an upper-limb prosthesis based on complaint mechanisms that can be classified as a soft-robotic device [14]. The prosthesis actuation system has two main actuators; the first is a servomotor controlling finger flexion with inelastic tendons that go from each fingertip to the unifying sling system that transforms all the fingers' tendons into one and goes to the motor. The extension of the fingers is made possible using internal elastic tendons, while pneumatic actuators facilitate the abduction between the fingers. The compliant finger construction allows 15 degrees of freedom (DoF), e.g. flexion, extension, abduction, and adduction of the prosthesis. The fingers have silicone coatings to increase the friction between the object and the fingers to improve grasping.

In a previous work [14], the prosthesis was evaluated with the AHAP protocol and the AM-ULA test, both with non-amputee users. The results showed that in terms of mimicking the grasps of the human hand assessed with the AHAP protocol, PrHand had comparable performance to similar prostheses in the literature. In the case of AM-ULA, the prosthesis performed better. However, during the tests, significant enhancements that could improve the prosthesis performance were identified, particularly having more control over the thumb movement and closing the fingers. The main objective of this article is to quantify the improvements over the new PrHand V2 prosthesis, evaluate its functional performance involving an amputee, and compare it with the results of a commercial prosthesis A3D (Prótesis Avanzadas, Colombia) [6].

Functional assessments are used to compare performance with other devices to evaluate the viability of the robotic hand design. The human hand has three main functions: grasping objects, manipulating, and exploring the environment, so the prosthesis evaluation aims to include those activities [15], [16]. One test that evaluates two of the aforementioned functions is the Anthropomorphic Hand Assessment Protocol

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(AHAP), in which eight grasp types are assessed with three objects per grip. This protocol evaluates how the robotic hands grasp the objects, i.e., if they can maintain an object for a while and move it in space. The result is expressed as a percentage of the degree of functionality of the robotic hand, considering the human hand functionality [17]. The case of The Activities Measure for Upper Limb Amputees (AM-ULA) test evaluated the prosthesis while carrying out 23 ADLs. The variables assessed are completing all activity subtasks, speed of completion, movement quality, skillfulness of prosthetic use, and independence [18].

II. SYSTEM DESCRIPTION

The design criteria for the new prosthesis PrHand V2 were revised based on the previous studies with the PrHand V1 prosthesis as described in [14]. For instance, it was established that silicone coating of the fingers is essential to improve friction when gripping objects. Also, it was found that the previous unifying system consumed too much energy, so reducing the friction in this system was required. In the test with PrHand V1, it was observed that the additional thumb abduction did not contribute to the grip; instead, it generated imprecise and uncontrolled grips. Therefore, mechanical changes were made in the PrHand V2 version to improve performance. The PrHand V2 version preserves the same complaint mechanism in the finger joints presented in [14], although the degree of abduction was removed, leaving the thumb at a fixed angle. The guiding rods of the unification system in PrHand V1 were removed, and the dimensions of this system were modified to reduce friction. The changes in the PrHand V2 prosthesis can be seen in Fig. 1 and the socket adaptation made to test it on an amputee patient.

This prosthesis performs four types of grip configured by the solenoid abduction actuators between the fingers. These grasp types are shown in Fig. 2 with examples of the objects evaluated in the AHAP test [19], [17]. The first (G1) is a power grip and closes the hand without inflating any actuator. The second grip type (G2) is a pulp pinch inflated by the actuator between the index and middle fingers. In the third (G3), all actuators are inflated. This grip is called a spherical grip. The last one (G4) is also a spherical grip, but the difference is that the hand is not entirely closed for large objects. The hand control was performed in ROS on a Raspberry Pi 3 (Raspberry Pi, UK).

The production cost estimated for the PrHand V2 prosthesis is $692. The prosthesis's mechanical characteristics (described on [20]) are a power grip force (GmF) of 35.80 ± 4.05N, to close the hand is required 1.43 ± 0.04 J of energy (R_E), its dissipated energy (D_E) is $0.61 \pm 4e^{-3}$J and supports a traction force (TrF) of 101.37 ± 5.66N. Table I compares some key characteristics of the two versions of PrHand. The PrHand grasping force is very similar between the two versions. However, the required energy to close the hand is slightly higher in V2. The traction force is increased in V2 while the production cost and fabrication time are almost the same for both devices.

Fig. 1. PrHand V2 underactuated Soft-Robotic prosthetic hand. a) Amputee user adaptation and illustration of finger flexion and extension (a tendon-driven compliant mechanism) and abduction degree of freedom driven by a soft silicone actuator. b) PrHand V2 prosthesis enhancements. c) Compliant grip example showing how a compliant profile is generated in the elastic tendons, adapting to the shape of the object gripped without needing prior control.

TABLE I

PRHAND V1 CHARACTERISTICS CONCERNING V2.

	PrHand1	PrHand2
GmF [N]	36.13	35.80
R_E [J]	1.28	1.43
D_E [J]	0.96	0.61
TrF [N]	78.48	101.37

The commercial A3D prosthesis is a rigid robotic hand with myoelectric control that allows four different grip types [6]. It has an independent movement of each finger and the thumb's opposition that are controlled by 12 motors. A3D is a prosthesis manufactured using 3D printing technologies and has silicone inserts to improve the grip and prevent the slipping of objects. The A3D joints are based on four-bar mechanisms with rigid pins in each degree of freedom. This prosthesis has health registrations in Latin America, so it is legally commercialized and carries quality control of the device. The cost of A3D is $3000, which is considered low compared to other commercial prostheses.

III. METHODOLOGY

This section explains functional evaluations of the PrHand V2 prosthesis, the first version of PrHand V1, and a commercial robotic prosthesis A3D. The Colombian School of

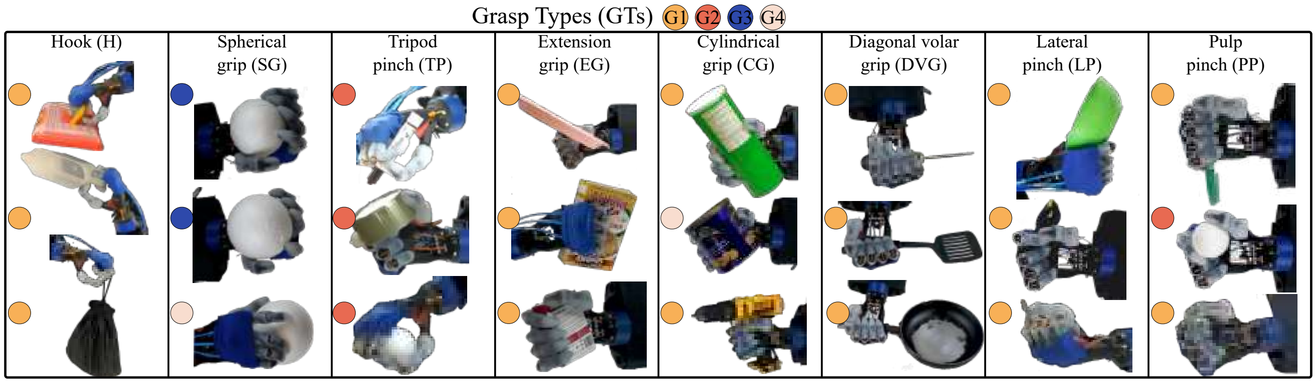

Fig. 2. AHAP objects per grasp type. The colour circles represent the grasp kind of the prosthesis PrHand V2 chosen per item where G1 is a power grip, G2 is a pulp pinch, G3 is a spherical grip with the fingers entirely close, and G4 is a spherical grip where the fingers do not close completely.

Engineering Julio Garavito ethics committee approved the protocols. The selected functional tests assessed prosthetic dexterity and functionality in daily living activities. The dexterity test focuses on evaluating the performance of the mechanical design, control and materials of the prostheses by grasping different objects. At the same time, the functional test aims to assess the prosthesis's performance in the execution of daily living activities based on the time required to execute the activities and ease of activity execution. The dexterity test was performed with five non-amputee users since this test evaluates the device design mechanically. However, the functional test was performed with a right amputee user in a controlled environment.

A. Dexterity Test

The dexterity test performed in this study is called AHAP [17] and involves holding a list of standardized objects [21]. This protocol measures how the object is grasped and whether it can be held after a 180-degree hand turn. The test score was compared to the human hand, where a score of 100 meant that the hand prosthesis behaves precisely like a human hand without any pathology [17], [19].

The AHAP specifies each step for the test, the objects to grip, the object's time to be held, the number of repetitions, the parameters for evaluating the grip, and the scores. Two persons were required to execute the AHAP protocol: the operator (the one who conducts the experiments) and the subject (the one who controls the prosthesis). The procedure for executing the AHAP test is clearly described in [14], [17].

AHAP has three variables: grasping, maintaining and the Grasping Ability Score (GAS). The ”grasping” evaluates if the prosthesis can grasp the objects as indicated in the protocol. It is assigned a value of 100 when the prosthesis holds the object, making all contacts defined in [17], 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 “maintaining” assesses whether the prosthesis has sufficient strength to hold the object for the entire time before and after turning it over and releasing it. A value of 100 is assigned when the prosthesis is holding the object the whole time 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 Grasping Ability Score (GAS) corresponds to the average of the two previous variables. This variable is a percentage of measured human hand dexterity. In brief, the closer the result is to 100, the better the device's dexterity.

For the AHAP test, the operator previously defined grip types for each object on the PrHand V2 as shown in Fig. 2.

The dexterity test AHAP was conducted with five healthy subjects between 19 and 25 years old (3 males and two females). All the participants were right-handed and were available for 4 hours to perform the test. The setup for acquiring data from each participant uses one lateral view and two superior cameras to capture the objects' grasp from different perspectives. The measurement of each grasp and each prosthesis was performed independently by three evaluators who scored each protocol variable for each prosthesis. The general setup of the dexterity test can be seen in Fig. 3 (a), and the three different prostheses can be seen in Fig. 3 (b).

Each of the three variables evaluated has a defined amount of data and a different statistical analysis method. For example, in the grasping variable, for each grip type are 45 results given for the three objects, the three attempts per object and the 5 participants (3x3x5). In addition, eight types of grip were evaluated for each prosthesis, so 360 measurements were obtained for the GAS variable.

B. Functional Test AM-ULA

After obtaining the dexterity AHAP test results, a 48-year-old Colombian amputee patient performed the second test with the PrHand V2. This user lost his right hand when he received an electric shock while performing his professional duties as a topographer. This prosthetic patient has a trans-radial amputation and has been a user of the A3D rigid robotic prosthesis for three years. Consequently, he has experience using myoelectric prostheses controlled by EMG sensors. A socket modification was required to activate the PrHand V2 prostheses, employing muscle signals. After, the AM-ULA functional test is performed [18].

The Activities Measure for Upper Limb Amputees (AM-ULA) has 23 daily activities, performed here using the hand prostheses and objects described in [18]. The evaluation of each task of the protocol is done by utilizing five parameters: 1) Completion of Sub-tasks, 2) Speed of Completion, 3) Movement Quality while performing the task, 4) Skillfulness of Prosthesis use, and 5) Prosthesis Independence. For each parameter, a score from 0 to 4 is given according to the performance. The scoring rules are clearly explained in [18].

The execution of this test requires an operator who reads each task and subtasks of the protocol, places the objects needed for each task and clarifies when the task must be performed only with the prosthesis (unilateral task) and a subject, which in this case is the prosthesis user who must perform the tasks and subtasks with the PrHand V2 and A3D hand prosthesis. The subject can choose how to perform the functions and what type of grip is selected for each. The activities in AM-ULA are listed in Table III, and the subtasks are detailed in [18]. An example is the ”brush teeth” activity; the subtasks are: hold toothpaste, uncap toothpaste, apply toothpaste to a toothbrush, and pretend to brush teeth.

The AM-ULA test was performed in a single session for each prosthesis. The complete test lasted 3 hours, including rest intervals for the user. Initially, the test was performed with the A3D prosthesis as the user has more confidence and skill with this prosthesis. For each task, a training time of 5 minutes was provided, and instructions were given on how to perform each subtask. The entire test was recorded with a camera to allow post-video processing of the results.

C. Data Analysis

Data analysis was performed in two ways: (i) descriptive statistics to organize and visualize the data graphically based on the mean and deviation, and (ii) inferential statistics to find the relevant differences between prostheses in each test performed. For these inferential analyses, the normality of the data was verified using the Shapiro-Wilk test. The statistical test selection depended on the normality of the data, the quantity, and the variance. In this case, the data did not follow a normal distribution, so the U Mann-Whitney test was used. The statistical analysis was conducted using RStudio software with a p-value of 5 %

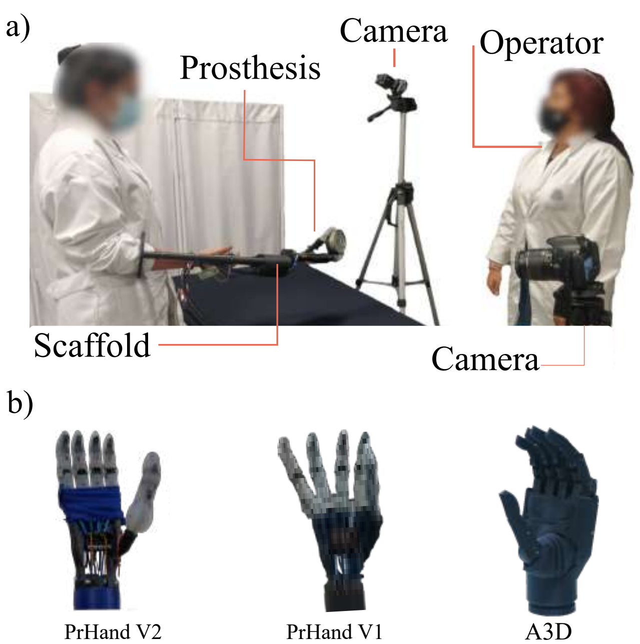

Fig. 3. AHAP setup. (a) Camera locations and key elements of the dexterity test AHAP. (b) 3 different prostheses were compared in this study.

IV. RESULTS

First, this section presents the results obtained from the PrHand V2 in the AHAP dexterity test and compares them with those of the PrHand V1 and A3D prostheses [14]. The results are summarized for each variable (grasping, maintaining, and GAS), and the mean is plotted. This identifies significant differences between the prostheses to establish the best-performing prosthesis. A statistical summary for each protocol variable and images of the grips performed from PrHand V2 are also shown. Subsequently, the AM-ULA results for each task on the PrHand V2 and A3D prostheses are presented. The overall results of this test, the data deviation and the inferential analysis between the PrHand V2 and A3D prostheses are also presented.

In Fig. 4, the eight grip types for each prosthesis and each variable are displayed in an easy-to-interpret manner employing polar plots. The results of the inferential test for each grip type are graphically displayed for the three possible prosthesis combinations (PrHand V1-PrHand V2, PrHand V1-A3D, PrHand V2-A3D).

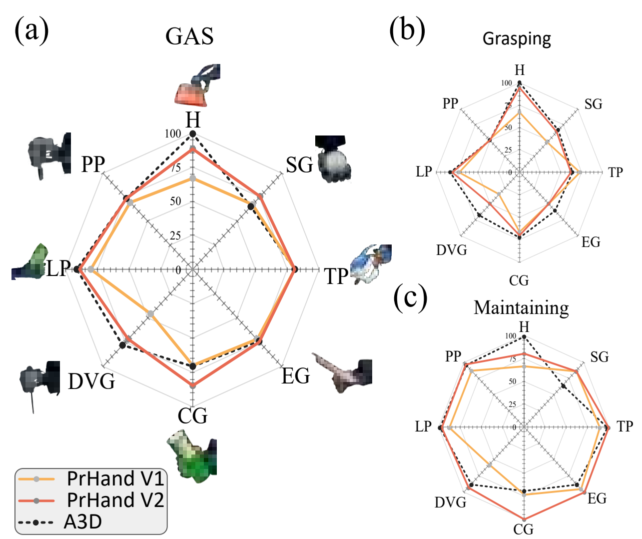

Fig. 4. AHAP results of PrHand V1 (yellow), PrHand V2 (orange) and A3D prosthesis (black) per kind of grasp: Hook (H), Spherical Grip (SG), Tripod Pinch (TP), Extension Grip (EG), Cylindrical Grip (CG), Diagonal Volar Grip (DVG), Lateral Pinch (LP) and Pulp Pinch (PP). (a) GAS results with an object example. (b) Grasping. (c) Maintaining.

From Fig. 4 for the ”grasping” variable, it can be seen that the PrHand V2 prosthesis performs better in 4 of the grips evaluated (H, SG, DVG and LP) compared to the PrHand V1. In the other four grips, the performance of the previous prosthesis was maintained. However, in TP, PrHand V2 have lower scores than PrHand V1. In the "maintaining" variable, PrHand V2 also obtains better results than PrHand V1. In the H, TP, EG, CG, DVG, LP and PP grips, the PrHand V2 performed better than the PrHand V1. In the other missing grip (SG), the result is the same and does not represent a significant difference, so for this variable, PrHand V2 is better. Finally, for the variable "GAS", it is evident that PrHand V2 has a better or equal performance to the PrHand V1 for all grip types.

Now, comparing the commercial prosthesis results concerning the PrHand V2, it is seen that for the "grasping" variable, the results show that the design improvements implemented in PrHand V2 allow performance in the Grasping variable similar to the commercial A3D prosthesis. Concerning the "maintaining" variable, PrHand V2 scored equal or better performance than the A3D prosthesis for the SG, TP, EG, CG, DVG, LP, and PP grips, so the commercial prosthesis is only better than PrHand V2 in one grip (grip H). In grips, H, EG, and DVG are the only results where there are significant differences with PrHand V2 concerning A3D. However, for all other grips, the performance of PrHand V2 is equal to A3D.

Some examples of the grips performed by the PrHand V2 prosthesis for each object are shown in Fig. 2. In this Figure, the type of grasping (G1, G2, G3, or G4) performed by the prosthesis is shown according to the operator's decision for each object. As can be seen, the PrHand V2 prosthesis grasps most objects with the same grip (G1). Nevertheless, this presents outstanding results in the variable "maintaining", which is more relevant for the AM-ULA functional test.

In summary, from the dexterity test, the results of each grip type in each variable were averaged, and the result for each prosthesis was obtained, shown in Table II. This table shows that A3D obtains the highest score in the "grasping" variable and PrHand V2 for the other two. However, the result of the inferential test shows that in none of the three variables is there a significant difference between the PrHand V2 and A3D prostheses. Therefore, according to the dexterity test, the PrHand V2 prosthesis is better than the first version and is equal to the commercial A3D prosthesis.

TABLE II
MEAN GAS AND THE MEAN SCORE FOR EACH PART OF THE TASK FOR EACH HAND PROSTHESIS WITH THE AHAP. SCORE FROM 0 TO 100. THE BOLD SCORES REPRESENT THE PROSTHESIS WITH HIGHER RESULTS PER VARIABLE.

Hand	Grasping	Maintaining	GAS
PrHand V1	57.78 ± 13.03	80.56 ± 12.17	69.17 ± 10.15
PrHand V2	65.20 ± 15.07	$\mathbf{94.32 \pm 6.70}$	$\mathbf{79.86 \pm 6.39}$
A3D	$\mathbf{70.83 \pm 14.18}$	87.78 ± 13.01	79.31 ± 10.48

The AM-ULA test results for each subtask were averaged to obtain the total score for each task. These results are presented in Tab. III. Some examples of the PrHand V2 and A3D prostheses performing the AM-ULA test can be seen in Fig. 5. The PrHand V2 prosthesis performs better in 8 out of 21 activities. The average of all the tasks for the PrHand V2 prosthesis in this protocol is **2.86 ± 0.63** with a coefficient of variation of 22.09%. The values for the A3D prosthesis were **2.96 ± 0.33** with a coefficient of variation of 11.22%. This means that A3D performed 3.37% better than PrHand V2 in activities of daily living. However, the inferential test states that there is no significant difference between the two prostheses for the AM-ULA test (p.value=0.8).

TABLE III
EACH ACTIVITY RESULTS FROM THE AM-ULA PROTOCOL ON THE PRHAND V2 AND A3D. SCORE FROM 0 TO 4

Task Name	A3D	Pr2	Task Name	A3D	Pr2
Brush teeth	3.2	2.8	**Carry laundry**	2.8	3.0
Brush hair	3.0	**3.4**	**Use phone**	3.2	**3.0**
Use cup	3.4	3.4	**Hammer**	2.2	1.4
Use fork	3.0	3.0	**Stir bowl**	3.2	**3.4**
Use spoon	2.8	2.8	**Fold towel**	3.2	**3.8**
Cut meat	3.0	2.4	**Open envelope**	3.2	3.0
Pour soda	3.4	**3.6**	**Reach overhead**	2.8	2.6
Write word	3.0	**3.4**	**Key in lock**	2.2	1.4
Use scissors	3.2	**3.4**	**Zip jacket (bag)**	3.2	2.8
Botton shirt	2.8	2.6	**Tie shoes**	2.6	**2.8**
Socks	2.8	2.2			

V. DISCUSSION

Initially, the functionality of the PrHand V2 was compared to the PrHand V1, using the AHAP protocol, to determine whether the modifications had improved the performance. The PrHand V2 was then evaluated with the AM-ULA protocol by an amputee volunteer. Considering that the volunteer is a prosthesis user, his prosthesis is evaluated with both tests to compare the PrHand prosthesis with the A3D prosthesis.

The average score of the variable grasping in PrHand V2 (65.20 %) is higher than the PrHand V1 score (57.78 %). The best result is from the A3D prosthesis (70.83 %). Considering that it is a commercial product, the performance of the PrHand V2 compares favourably. Analyzing the grasping results per grasp type (see fig. 2), it is apparent that the improved design of the PrHand V2 has improved the performance during grasping. In addition, removing the thumb abduction and adduction movements is associated with improvements in the spherical grip and diagonal volar grip of the PrHand V2 concerning PrHand V1. The A3D prosthesis performs better than the two versions of PrHand for the diagonal volar grip. However, the spherical grip result does not significantly differ from the PrHand V2. The thumb change has also influenced the tripod pinch result since its movement in PrHand V1 is less limited, with the facility to accommodate the fingers in the object. The other change is that in the PrHand V2, the fingers close more than in the PrHand V1. The results show that this improvement significantly enhances the result of the hook grip, as the PrHand V2 has higher scores than the PrHand V1. The PrHand V2 results were close to the A3D prosthesis for this type of grip, but the commercial one had a higher score. The new design does not seem to have improved the extension

Fig. 5. Examples of activities carried out with PrHand V2 and A3D of the AM-ULA protocol. a) PrHand V2 prosthesis examples performing AM-ULA activities. b) A3D prosthesis examples performing AM-ULA activities.

grip, cylindrical grip, lateral pinch and pulp pinch scores. There appears to be no significant difference between the three prostheses in the cylindrical grip and the pulp pinch.

The maintaining variable PrHand V2 (94.32 %) has significantly improved performance, having a 13.76 % higher than PrHand V1 (80.56 %) score, and the performance is better than the A3D prosthesis (87.78 %). The results per kind of grasp for this variable are shown in Fig. 4(b). During the tests, it was identified that the thumb's stability significantly influenced the extension and cylindrical grip results, where PrHand V2 exceeded the scores of the other two prostheses. In the tripod pinch and diagonal volar grip, the PrHand V2 scores do not show significant differences with the A3D prosthesis, and the worst results for those grip types are from PrHand V1. The new close fingers' capacity significantly improves the PrHand V2 scores, performing better than PrHand V1 on the hook and lateral pinch where there are thin objects. The improvements do not influence spherical grip and pulp pinch since there are no significant differences between PrHand V1 and PrHand V2. In the case of spherical grip for the A3D prosthesis, the larger sphere always falls off, lowering the score.

The GAS result (the average between the maintaining and the grasping) of PrHand V2 is not significantly different from the A3D prosthesis, 79.86 % and 79.31 %, respectively. These results confirm that the PrHand V2 performs similarly to a commercial hand prosthesis regarding the dexterity test AHAP. Table II shows the full test results per each AHAP variable, where the lowest scores are always of PrHand V1. The results per kind of grasp for the GAS variable are shown in Fig. 2(c). Of the eight grip types, five (hook, spherical grip, cylindrical grip, diagonal volar grip, and lateral pinch) showed improvement with the changes made to the prosthesis. The other three grasp kinds (extension grip, pulp pinch, and tripod pinch) do not differ significantly. The scores confirm that the adjustment made to the prosthesis improves its performance.

In [22], the AHAP was utilized to assess four underactuated and tendon-driven hand prostheses. Their GAS variable results ranged from 48 to 57. The IMMA prosthesis [23], which featured an additional degree of actuation for thumb circumduction, achieved the best result. Comparing these literature prostheses with PrHand V1 and V2, the key disparity lies in the abduction/adduction (DoF) of PrHand. Furthermore, it's worth noting that PrHand V1 and V2 prostheses attained superior results in the GAS variable, and consequently, in the grasping and maintaining variables.

The AM-ULA test results for the PrHand V2 and A3D prostheses are shown in Table III. The A3D prosthesis scores higher than PrHand V2 in 10 tasks. However, the PrHand V2 has more outstanding outcomes in 8 other functions. In the other three tasks, both prostheses have the same score. In the functions involving thin objects (Socks, shirt, zip, envelope, key, cut meat), A3D performs the activities better because its fingers close more than the PrHand V2, making the prosthesis less likely to lose its grip on the object and improve the grip speed. One factor influencing the results is that the A3D prosthesis is the volunteer's prosthesis, which means he has a training advantage with that device. Besides, the user has prostheses experience and does not need too much time for training. The best two tasks for PrHand V2 over the 21 tasks were folding a towel (3.8) and pouring soda (3.6). The two best scores of A3D prosthesis are in AM-ULA: pour soda and use a cup, with a 3.4 score. The PrHand V2 scores significantly better than A3D in tasks like brushing hair, pouring soda, folding towels, and tying shoes. However, the worst scores in the PrHand V2 were in Hammer and key-in lock tasks. Meanwhile, the A3D prosthesis scores are more constant. The A3D presented a coefficient of variation of 11%, different from the 22% presented in the PrHand V2. However, statistically, there are no differences between the evaluated prostheses in this study. So, the PrHand V2 prosthesis is functionally equivalent to a commercial prosthesis (A3D).

Only one study was identified where a prosthesis was evaluated using AMU-LA. This prosthesis, known as the Soft Hand Pro (SHP) [24], employs elastic tendons. The SHP prosthesis achieved an average protocol score of 1.94. Based

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on this, it can be inferred that PrHand V2 and PA prostheses are superior for accomplishing activities of daily living compared to the SHP prosthesis mentioned in the literature. To confirm this observation, a one-sample t-test was conducted comparing the results of the evaluated prostheses with the theoretical outcome of the SHP prosthesis. The statistical analysis revealed significant differences in the AM-ULA test results for PrHand V3 (p-value = 1.5e-6), demonstrating superior performance compared to other soft robotics-based prostheses reported in the literature.

VI. CONCLUSIONS

This work reported the improvements made to the design of the PrHand V2 prosthesis. The AHAP protocol was conducted with both versions of the PrHand prosthesis (PrHand V1 and PrHand V2) and the A3D prosthesis to validate the enhancements. The results showed that the adjustments made to the prosthesis influenced its performance. PrHand V2 versus PrHand V1 always had the best scores in the grasping, maintaining and GAS variables. In comparing PrHand V2 with the A3D prosthesis, the results of PrHand V2 were better than expected since the maintaining grasp variable had better results. The GAS variable (average grasping and maintaining) shows no significant differences with the A3D prosthesis. The most notable improvement was having more control over the thumb, which, in the results, was associated with having a better-maintaining score.

In the AM-ULA test, a real user performs activities of daily living with the PrHand V2 prosthesis, a critical test considering those situations where the prosthesis is needed to support the person's ADLs. The PrHand V2 result does not show statistically significant differences from the A3D prosthesis. One aspect that needs to be improved is grasping thin objects; the second version performed better with those items since it had better results in the maintaining variable of the AHAP in 5 of 8 grasps. However, it did not have such good results in the test, key in the lock as the A3D prosthesis. The results of both tests showed that the performance of the PrHand V2 prosthesis is comparable to a commercial prosthesis. Prostheses based on soft robotics can achieve the same functionality as rigid prostheses, with the advantages of soft materials construction, providing flexibility and compliance.

REFERENCES

[1] SISPRO, "ASIS disability indicators," 2020. [Online]. Available: http://rssvr2.sispro.gov.co/reportesAsis2

[2] TABNET-DATASUS, "Amputação desarticulação de membros superiores," 2022. [Online]. Available: http://tabnet.datasus.gov.br/cgi/tabcgi.exe?sih/cnv/qiuf.def

[3] W. H. Organization *et al.*, "Global priority research agenda for improving access to high-quality affordable assistive technology," 2017.

[4] K. Ziegler-Graham, E. J. MacKenzie, P. L. Ephraim, T. G. Travison, and R. Brookmeyer, "Estimating the prevalence of limb loss in the united states: 2005 to 2050," *Archives of physical medicine and rehabilitation*, vol. 89, no. 3, pp. 422–429, 2008.

[5] L. Resnik, S. Ekerholm, M. Borgia, and M. A. Clark, "A national study of veterans with major upper limb amputation: Survey methods, participants, and summary findings," *PloS one*, vol. 14, no. 3, p. e0213578, 2019.

[6] "Prótesis robótica de mano Colombia." [Online]. Available: https://www.protesisavanzadas.co

[7] M. A. A. Wahit, S. A. Ahmad, M. H. Marhaban, C. Wada, and L. I. Izhar, "3d printed robot hand structure using four-bar linkage mechanism for prosthetic application," *Sensors (Basel, Switzerland)*, vol. 20, no. 15, 2020.

[8] R. Mutlu, G. Alici, M. in het Panhuis, and G. Spinks, "Effect of flexure hinge type on a 3d printed fully compliant prosthetic finger," in *2015 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*. IEEE, 2015, pp. 790–795.

[9] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *The International Journal of Robotics Research*, vol. 35, no. 1-3, pp. 161–185, 2016.

[10] J. S. Cuellar, G. Smit, A. A. Zadpoor, and P. Breedveld, "Ten guidelines for the design of non-assembly mechanisms: The case of 3d-printed prosthetic hands," *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, vol. 232, no. 9, pp. 962–971, 2018.

[11] R. Abayasiri, R. Abayasiri, R. Gunawardhana, R. Premakumara, S. Mallikarachchi, R. Gopura, T. D. Lalitharatne, and D. Madusanka, "An under-actuated hand prosthesis with finger abduction and adduction for human like grasps," in *2020 6th International Conference on Control, Automation and Robotics (ICCAR)*. IEEE, 2020, pp. 574–580.

[12] A. Mottard, T. Laliberté, and C. Gosselin, "Underactuated tendon-driven robotic/prosthetic hands: design issues." in *Robotics: Science and Systems*, 2017.

[13] Y. Yan, X. Chen, C. Cheng, and Y. Wang, "Design, kinematic modeling and evaluation of a novel soft prosthetic hand with abduction joints," *Medicine in Novel Technology and Devices*, vol. 15, p. 100151, 2022.

[14] L. De Arco, O. Ramos, M. Múnera, M. Moazen, H. Wurdemann, and C. A. Cifuentes, "The prhand: Functional assessment of an underactuated soft-robotic prosthetic hand," in *The 9th IEEE RAS/EMBS International Conference on Biomedical Robotics & Biomechatronics*. IEEE, 2022.

[15] H. Zhou, A. Mohammadi, D. Oetomo, and G. Alici, "A novel monolithic soft robotic thumb for an anthropomorphic prosthetic hand," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 602–609, 2019.

[16] F. Cordella, A. L. Ciancio, R. Sacchetti, A. Davalli, A. G. Cutti, E. Guglielmelli, and L. Zollo, "Literature review on needs of upper limb prosthesis users," *Frontiers in neuroscience*, vol. 10, p. 209, 2016.

[17] I. Llop-Harillo, A. Pérez-González, J. Starke, and T. Asfour, "The anthropomorphic hand assessment protocol (ahap)," *Robotics and Autonomous Systems*, vol. 121, p. 103259, 2019.

[18] L. Resnik, L. Adams, M. Borgia, J. Delikat, R. Disla, C. Ebner, and L. S. Walters, "Development and evaluation of the activities measure for upper limb amputees," *Archives of physical medicine and rehabilitation*, vol. 94, no. 3, pp. 488–494, 2013.

[19] I. Llop-Harillo and A. Pérez-González, "System for the experimental evaluation of anthropomorphic hands. application to a new 3d-printed prosthetic hand prototype," *International Biomechanics*, vol. 4, no. 2, pp. 50–59, 2017.

[20] O. Ramos, L. De Arco, C. A. Cifuentes, M. Moazen, H. Wurdemann, and M. Múnera, "Mechanical assessment of novel compliant mechanisms for underactuated prosthetic hands," *Frontiers in Bioengineering and Biotechnology*, vol. 11, 2023.

[21] B. Calli, A. Singh, A. Walsman, S. Srinivasa, P. Abbeel, and A. M. Dollar, "The ycb object and model set: Towards common benchmarks for manipulation research," in *2015 international conference on advanced robotics (ICAR)*. IEEE, 2015, pp. 510–517.

[22] I. Llop-Harillo, A. Pérez-González, and J. Andrés-Esperanza, "Grasping ability and motion synergies in affordable tendon-driven prosthetic hands controlled by able-bodied subjects," *Frontiers in Neurorobotics*, vol. 14, 2020. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fnbot.2020.00057

[23] "Imma hand (devalhand project)." [Online]. Available: https://sites.google.com/a/uji.es/devalhand/imma-hand

[24] S. B. Godfrey, K. D. Zhao, A. Theuer, M. G. Catalano, M. Bianchi, R. Breighner, D. Bhaskaran, R. Lennon, G. Grioli, M. Santello, *et al.*, "The softhand pro: Functional evaluation of a novel, flexible, and robust myoelectric prosthesis," *PloS one*, vol. 13, no. 10, p. e0205653, 2018.