# Development and Functional Evaluation of The PrHand V3 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 V3), built with soft robotics and compliant mechanisms. PrHand V3 implements a new frictionless tendon unification system, the degree of freedom of thumb opposition was removed, and the finger flexion was improved to the previous version, PrHand V2. The study contributes by evaluating these mechanical changes and conducting the first functional assessment of PrHand V3 with an amputee user. 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 V3 was compared with a PrHand V2 and a commercial robotic prosthesis A3D from Prótesis Avanzadas SAS. PrHand V3's score on the AHAP test was 80%. This result is higher than the 69% obtained by the PrHand V2 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 V3 and an A3D. PrHand V3 obtained an average of 2.86/4 and A3D obtained an average of 2.96/4 without significant differences between the two tests. The soft actuation of PrHand V3 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 (including amputations) in their upper and lower extremities [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].

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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], [10]. 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 [11]. The degree of freedom (DOF) of abduction is rarely implemented in rigid devices [12]. It is present in flexible devices, but in most of them it is passive [13], [14].

PrHand is an upper-limb prosthesis based on complaint mechanisms that can be classified as a soft-robotic device [15]. 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. Each compliant finger contributes 3 out of the total 15 degrees of freedom (DoF) in the prosthesis PrHand V2: 2 DoF for flexion/extension and 1 DoF for abduction/adduction. The fingers have silicone coatings to increase friction between the object and the fingers to improve grasping (see Fig. 1(a).)

In a previous work [15], The PrHand V1 and V2 prostheses were evaluated using two functional assessments: the Anthropomorphic Hand Assessment Protocol (AHAP) [16] and the Activities Measure for Upper Limb Amputees test (AM-ULA) [17], 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 performance comparable to similar prostheses in the literature. In the case of AM-ULA, the prosthesis performed better. However, during the tests, significant enhancements were identified that could improve prosthesis performance, particularly having more control over thumb movement and closing the fingers. The study's contribution lies in the evaluation of the mechanical enhancements incorporated into PrHand V3 and the first functional assessment conducted with an amputee user. This illustrates the practical utility of the prosthesis and its potential as an economical alternative to existing commercial options.

## II. SYSTEM DESCRIPTION

The PrHand V3 design was refined based on PrHand V2's shortcomings, incorporating significant mechanical improvements [15], [18]. The silicone finger coating enhanced grip friction, while the redesigned unification system reduced friction and energy consumption by eliminating guiding rods. Thumb abduction was removed, as it hindered grip quality and precision. As a result, PrHand V3 now has 14 DoF. PrHand V3 further refined these changes, maintaining full silicone coating, optimizing motor force alignment, and reducing energy consumption. All these changes were proposed based on the findings from the previously conducted mechanical testing study [18], which guided the improvements made in the PrHand V3. Changes in PrHand V3 can be seen in Fig. 1 and the adaptation of the socket for testing in an amputee patient.


Fig. 1. PrHand V3 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 V3 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.

This prosthesis performs four types of grip configured by solenoid abduction actuators between the fingers. These grasp types are shown in Fig. 2 with examples of objects evaluated in the AHAP test [19], [16]. 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 (G4) is also a spherical grip, but the difference is that the hand is not completely closed for large objects. The hand control was performed in ROS on a Raspberry Pi 3 (Raspberry Pi, UK).

The estimated production cost for the PrHand V3 prosthesis is \$692. The prosthesis's mechanical characteristics (described on [18]) are a power grip force (GmF) of $35.80 \pm 4.05$N, to close the hand is required $1.43 \pm 0.04$ J of energy (R_E), its dissipated energy (D_E) is $0.61 \pm 4e^{-3}$J and supports a traction force (TrF) of $101.37 \pm 5.66$N. Table I compares some key characteristics of the two versions of PrHand. To understand how the values in the Tab. I are calculated, it is recommended to refer to the previous study [18] . The PrHand grasping force is very similar between the two versions. However, the required energy to close the hand is slightly higher in V3. The traction force is increased in V3 while the production cost and fabrication time are almost the same for both devices.

TABLE I
PRHAND V2 CHARACTERISTICS CONCERNING V3.

| | PrHand V2 | PrHand V3 |
|---|---|---|
| **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 grip and prevent 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 has quality control of the device. The cost of A3D is \$3000, which is considered low compared to other commercial prostheses.

The PrExHand V3 prosthesis has a palm length of 10.0 cm, hand length of 21.5 cm, palm width of 7.0 cm, and thickness of 3.0 cm, with 15 degrees of freedom (8 actuated). It is made from PLA, filaflex, and nylon. The weight is 550g. The A3D has a palm length of 8.0 cm, hand length of 18.9 cm, palm width of 7.9 cm, and thickness of 3.4 cm, with 10 degrees of freedom (6 actuated). It is made from Nylon X and ABS Pro, weighing 441 grams.

## III. METHODOLOGY

This section explains functional evaluations of the PrHand V3 prosthesis, the first version of PrHand V2, and a commercial robotic prosthesis A3D. The Colombian School of Engineering Julio Garavito ethics committee approved the protocols. The selected functional tests assessed prosthetic dexterity and functionality in activities of daily living. The dexterity test focuses on evaluating the performance of the mechanical design, control, and materials of the prostheses

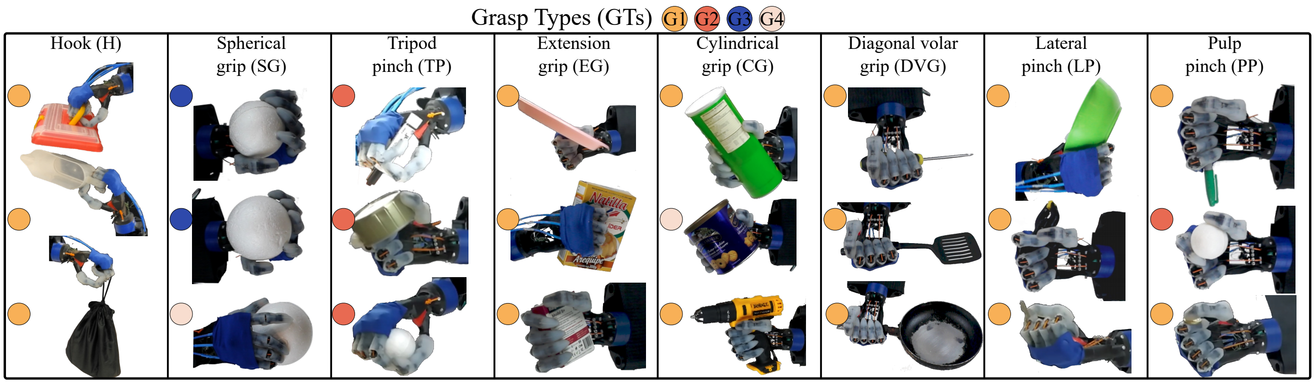


Fig. 2. AHAP objects per grasp type. The colour circles represent the grasp kind of the prosthesis PrHand V3 chosen per item where G1 is a power grip, G2 is a pulp pinch, G3 is a spherical grip with the fingers entirely close, and G4 is a spherical grip where the fingers do not close completely.

by grasping different objects. At the same time, the functional test aims to assess the performance of the prosthesis in the execution of activities of daily living based on the time required to perform the activities and the 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 [16] and involves holding a list of standardized objects [20]. 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 with the human hand, where a score of 100 means that the prosthesis of the hand behaves precisely like a human hand without any pathology [16], [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 [15], [16].

AHAP includes three variables: grasping, maintaining, and the Grasping Ability Score (GAS). The ”grasping” measures whether the prosthesis can grasp objects as per protocol. It scores 100 if all contacts defined in [16] are made, 50 if the object is grasped but not precisely as indicated, and 0 if it cannot grasp. The ”maintaining” measures the prosthesis's strength to hold the object throughout testing. It scores 100 if the object remains held without moving, 50 if it moves during the test, and 0 if it falls. The GAS is the average of these two variables, representing the percentage of human hand dexterity. A score closer to 100 indicates better dexterity.

For the AHAP test, the operator previously defined the grip types for each object on PrHand V3 as shown in Fig. 2.

In PrHand V2, PrHand V3, and the A3D prosthesis, two push buttons are used: one preselects the solenoid valves for each grip type (GT), and the other activates them, controlling the hand's opening and closing. The system is aware of the hand's state; pressing button 2 activates the pneumatic system to perform the selected GT and close the hand if it is open. Pressing button 2 again opens the hand by deflating the abduction actuators. The motor position for hand closing is predefined, so the user only needs to press button 2. The protocol operator, not the user, selects the GT. If the chosen GT does not grasp the object firmly, the operator can select another GT to ensure the scores are met, preventing the object from slipping.

The AHAP dexterity test involved five healthy right-handed volunteers (3 males, 2 females) aged 19-25, available for 4 hours. Data were acquired using one lateral and two superior cameras. Each grasp and prosthesis were independently evaluated by three evaluators. 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, 45 results are 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*

A 48-year-old Colombian amputee with a transradial amputation, experienced with the A3D rigid robotic prosthesis, performed a second test with PrHand V3 after the AHAP dexterity test. A socket modification was made to activate PrHand V3 using muscle signals. The AM-ULA functional test was then performed [17]. For the this test, the same control scheme used for the dexterity test was applied. This scheme involves two push buttons; however, in this case, button 2 is activated via an EMG signal, while button 1 must be pressed with the user's healthy hand. This control scheme is also used by the commercial A3D prosthesis, making it the most straightforward for the user to operate.

The AM-ULA has 23 daily activities, performed here using the hand prostheses and objects described in [17].

Some examples can be seen in Fig. 5. 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 performance. The scoring rules are clearly explained in [17].

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 V3 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 [17]. 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 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 selection of the statistical tests 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. Statistical analysis was performed using the RStudio software with a p-value of 5 %

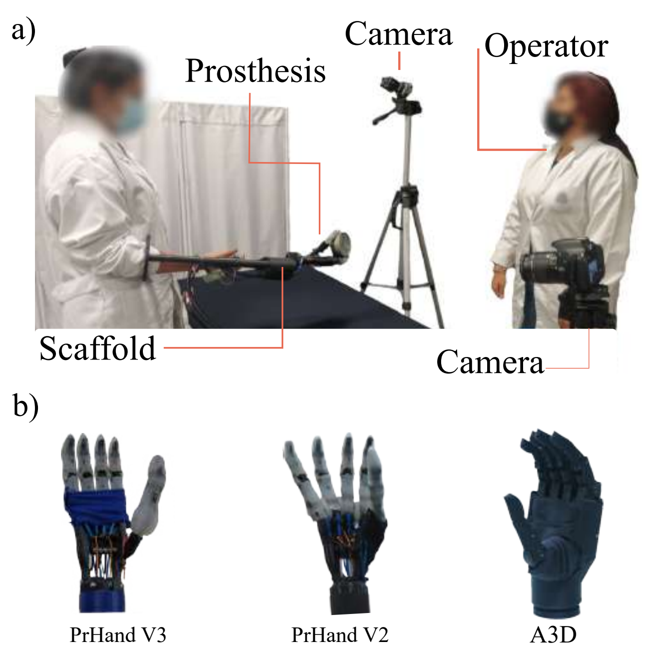


Fig. 3. AHAP setup. (a) Camera locations and key elements of the dexterity test AHAP. (b) 3 different prostheses were compared in this study.

## IV. RESULTS

In Fig. 4, polar plots display eight grip types, each variable, and the mean results for the three prosthesis combinations (PrHand V2-PrHand V3, PrHand V2-A3D, PrHand V3-A3D).

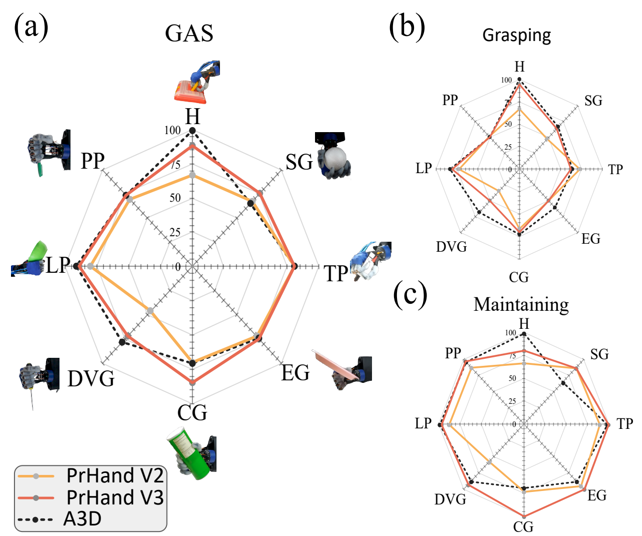


Fig. 4. AHAP results of PrHand V2 (yellow), PrHand V3 (orange) and A3D prosthesis (black) per kind of grasp: Hook (H), Spherical Grip (SG), Tripod Pinch (TP), Extension Grip (EG), Cylindrical Grip (CG), Diagonal Volar Grip (DVG), Lateral Pinch (LP) and Pulp Pinch (PP). (a) GAS results with an object example. (b) Grasping. (c) Maintaining.

From Fig. 4 for the variable ’grasping’, it can be seen that the PrHand V3 prosthesis performs better in 4 of the grips evaluated (H, SG, DVG and LP) compared to PrHand V2. In the other four grips, the performance of the previous prosthesis was maintained. However, in TP, PrHand V3 have lower scores than PrHand V2. In the ”maintaining” variable, PrHand V3 also obtains better results than PrHand V2. In the H, TP, EG, CG, DVG, LP and PP grips, PrHand V3 performed better than PrHand V2. In the other missing grip (SG), the result is the same and does not represent a significant difference, so for this variable, PrHand V3 is better. Finally, for the variable ”GAS”, it is evident that PrHand V3 has a better performance to the PrHand V2 for all grip types. The graph corroborates these statements, and they are supported by thorough statistical analysis. Better performance indicates significant differences between the data sets, validating the results obtained.

Now, comparing the commercial prosthesis results concerning the PrHand V3, it is seen that for the ”grasping” variable, the results show that the design improvements implemented in PrHand V3 allow performance in the Grasping variable similar to the commercial A3D prosthesis. Concerning the "maintaining" variable, PrHand V3 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 V3 in one grip (grip H). For the "Grasping" variable, significant differences between PrHand V3 and A3D were only observed in grips H, EG, and DVG. In all other grips, PrHand V3 performed equally to A3D.

Some examples of the grips performed by the PrHand V3 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 V3 prosthesis grasps most objects with the same grip (G1). However, this presents outstanding results in the variable "maintaining", which is more relevant for the AM-ULA functional test.

The dexterity test results, summarized in Table II, show that A3D excels in grasping, while PrHand V3 is superior in the other variables. The value for each variable was calculated by averaging the results across all the grip types evaluated within that variable. However, inferential tests reveal no significant differences between PrHand V3 and A3D in any variable. This suggests that PrHand V3 is superior to its predecessor and comparable 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 V2 | $57.78 \pm 13.03$ | $80.56 \pm 12.17$ | $69.17 \pm 10.15$ |
| PrHand V3 | $65.20 \pm 15.07$ | $\mathbf{94.32 \pm 6.70}$ | $\mathbf{79.86 \pm 6.39}$ |
| A3D | $\mathbf{70.83 \pm 14.18}$ | $87.78 \pm 13.01$ | $79.31 \pm 10.48$ |

The results of the AM-ULA test for each subtask were averaged to obtain the total score for each task. These results are presented in Tab. III. Some examples of PrHand V3 and A3D prostheses performing the AM-ULA test can be seen in Fig. 5. The PrHand V3 prosthesis performs better in 8 out of 21 activities. The average of all tasks for the PrHand V3 prosthesis in this protocol is $\mathbf{2.86 \pm 0.63}$ over 4 with a coefficient of variation of 22.09%. The values for the A3D prosthesis were $\mathbf{2.96 \pm 0.33}$ over 4 with a coefficient of variation of 11.22%. This means that A3D performed 3.37% better than PrHand V3 in activities of daily living. However, the inferential test indicates that there is no significant difference between the two prostheses for the AM-ULA test (p-value = 0.8).

## V. DISCUSSION

PrHand V3 was initially compared with PrHand V2 using the AHAP protocol with non-amputee volunteers to assess performance improvements. PrHand V3 was evaluated using

TABLE III

EACH ACTIVITY RESULTS FROM THE AM-ULA PROTOCOL ON THE PRHAND V3 AND A3D. SCORE FROM 0 TO 4

| Task Name | A3D | Pr3 | Task Name | A3D | Pr3 |
|---|---|---|---|---|---|
| **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 | | | |

the AM-ULA protocol by an amputee volunteer. Considering that the volunteer is a prosthesis user, the tests were conducted with the A3D prosthesis that he uses.

The PrHand V3's grasping score (65.20%) exceeds that of PrHand V2 (57.78%), though A3D remains superior (70.83%). Considering that it is a commercial product, the performance of the PrHand V3 is favorable. Analyzing grasp-type results (Fig. 4 (b)), PrHand V3's design enhancements boost grasping performance. Removing thumb abduction/adduction improves spherical and diagonal volar grip compared to PrHand V2. While A3D excels in diagonal volar grip, spherical grip results are comparable to PrHand V3. Thumb modifications also influence tripod pinch, with PrHand V2's more flexible thumb facilitating object accommodation. PrHand V3's improved finger closure significantly enhances hook grip, with results approaching A3D's, though the commercial product remains slightly superior. The new design has not significantly improved extension grip (EG), cylindrical grip (CG), lateral pinch (LP), or pulp pinch (PP) scores. For EG and LP, improvements were hindered by the new thumb's limited freedom, which is crucial for precise object positioning. While CG results were already satisfactory, the simplicity of this grip makes further improvements unnecessary. PP remains the most challenging grip for all prostheses, reflecting the difficulty of grasping very small objects like the human hand.

The PrHand V3's maintaining score (94.32%) significantly outperforms PrHand V2 (80.56%) by 13.76% and surpasses A3D (87.78%). Fig. 4(c) details grasp-type results. Thumb stability positively impacted cylindrical and extension grip, where PrHand V3 excelled. In tripod pinch and diagonal volar grip, PrHand V3's scores were comparable to A3D, while PrHand V2 struggled. Improved finger closure enhanced hook and lateral pinch performance in PrHand V3, surpassing PrHand V2, especially with thin objects. The new design did not significantly improve spherical or pulp pinch grips. A3D's spherical grip performance suffered due to frequent sphere drops. Similar finger dimensions and silicone coatings among the other prostheses led to comparable maintenance results, highlighting A3D's inferior performance in this grip type. While pulp pinch results were satisfactory, the grasp patterns differed from human hand movements,


Fig. 5. Examples of activities carried out with PrHand V3 and A3D of the AM-ULA protocol. a) PrHand V3 prosthesis examples performing AM-ULA activities. b) A3D prosthesis examples performing AM-ULA activities.

emphasizing the need for customized grasping strategies to meet the specific needs of prosthetic hand users, especially when handling small or slender objects.

The GAS result (the average between the maintaining and grasping) of PrHand V3 is not significantly different from the A3D prosthesis, 79.86 % and 79.31 %, respectively. These results confirm that the PrHand V3 performs similarly to a commercial hand prosthesis regarding the dexterity test AHAP. Table II shows the complete test results for each AHAP variable, where the lowest scores are always for PrHand V2. The results per kind of grasp for the GAS variable are shown in Fig. 4(a). Of the eight types of grip, five (hook, spherical grip, cylindrical grip, diagonal volar grip, and lateral pinch) showed improvement with the changes made to the prosthesis.

The GAS results (average of maintaining and grasping) for PrHand V3 and A3D are not significantly different (79.86% vs. 79.31%), indicating comparable dexterity test performance. Table II provides complete test results, with PrHand V2 consistently scoring lowest. Fig. 4(a) illustrates grasp-type results. Five of eight grasp types (hook, spherical grip, cylindrical grip, diagonal volar grip, and lateral pinch) improved with PrHand V3's design changes. 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 [21], the AHAP was used to evaluate four underactuated and tendon-driven hand prostheses. The results of their GAS variable ranged from 48 to 57. The IMMA prosthesis [22], which featured an additional degree of actuation for the circumduction of the thumb, achieved the best result. When comparing these prostheses from the literature with PrHand V2 and V3, the key disparity lies in the abduction/adduction (DoF) of PrHand. Furthermore, it is worth noting that PrHand V2 and V3 prostheses attained superior results in the GAS variable, and consequently, in the grasping and maintaining variables.

The AM-ULA test results (Table III) show A3D's superiority in 10 tasks, while PrHand V3 excels in 8. Three tasks yielded identical scores. A3D's superior performance with thin objects (socks, shirt, zip, envelope, key, cut meat) stems from its closer fingers, ensuring better grip and speed. The volunteer's familiarity with A3D due to prior use and general prosthetics experience likely contributed to its performance advantage. Among the 21 tasks, the PrHand V3 performed best in folding a towel (scoring 3.8) and pouring soda (scoring 3.6). In comparison, the A3D prosthesis achieved its highest scores in the AM-ULA protocol for pouring soda and using a cup, both with a score of 3.4. The PrHand V3 scores significantly better than the A3D prosthesis in tasks such as brushing hair, pouring soda, folding towels, and tying shoes. However, the PrHand V3 performs poorly in tasks like using a hammer and inserting a key into a lock. In contrast, the A3D prosthesis demonstrates more consistent performance in all tasks. The A3D presented a coefficient of variation of 11%, different from the 22% presented in the PrHand V3. However, statistically, there are no differences between the prostheses evaluated in this study. So, the PrHand V3 prosthesis is functionally equivalent to a commercial prosthesis (A3D). It is noteworthy that while the PrHand V3 has a price range of $692, the commercial A3D prosthesis is priced at $3,000. This comparison illustrates the cost effectiveness of PrHand V3. Although both prostheses achieve the same test results, the commercial prosthesis offers more grip combinations, which can be cognitively complex. In contrast, PrHand V3 uses compliant mechanisms, avoiding the need to change grips and simplifying manipulation.

While this study did not focus on mechanical testing, it examines grip force (GmF), energy ($R\_E$ and $D\_E$), and traction (TrF). PrHand V3's GmF is similar to previous versions, with no significant difference from PrHand V2 (p-value = 0.87). Energy consumption shows PrHand V3 requires more energy to close the hand than PrHand V2 but is the most energy-efficient during operation. Stability improves in PrHand V3 (CV=0.7%) compared to PrHand V2 (CV=13%). PrHand V3 achieves a TrF of 101.37 N, a notable improvement over PrHand V2. Except for GmF, all results between PrHand V2 and V3 show significant differences.

Only one study was identified in which a prosthesis was evaluated using AMU-LA. This prosthesis, known as the Soft Hand Pro (SHP) [23], employs elastic tendons. The SHP prosthesis achieved an average protocol score of 1.94. Based on this, it can be inferred that PrHand V3 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 V3 prosthesis. The AHAP protocol was conducted with both versions of the PrHand prosthesis (PrHand V2 and PrHand V3) and the A3D prosthesis to validate the enhancements. The results showed that the adjustments made to the prosthesis influenced its performance. PrHand V3 versus PrHand V2 always had the best scores in the grasping, maintaining and GAS variables. In comparing PrHand V3 with the A3D prosthesis, the results of PrHand V3 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 V3 prosthesis, a critical test considering those situations where the prosthesis is needed to support the person's ADLs. The PrHand V3 result does not show statistically significant differences from the A3D prosthesis. Enhancements are required for grasping thin objects; the PrHand V3 outperformed by scoring higher in 5 out of 8 AHAP grasp tests. Nonetheless, it was less proficient in the 'key in the lock' test when compared to the A3D prosthesis during the AM-ULA assessment. In essence, the PrHand V3 demonstrated excellent dexterity with small items, yet faced difficulties in practical daily tasks where the commercial prosthesis excelled. Overall, the PrHand V3's performance is on par with that of a commercial prosthesis. Soft robotics prostheses can rival rigid prostheses while providing flexibility and compliance advantages.

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