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The Anthropomorphic Hand Assessment Protocol (AHAP)

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ABSTRACT

The progress in the development of anthropomorphic hands for robotic and prosthetic applications has not been followed by a parallel development of objective methods to evaluate their performance. The need for benchmarking in grasping research has been recognized by the robotics community as an important topic. In this study we present the Anthropomorphic Hand Assessment Protocol (AHAP) to address this need by providing a measure for quantifying the grasping ability of artificial hands and comparing hand designs. To this end, the AHAP uses 25 objects from the publicly available Yale-CMU-Berkeley Object and Model Set thereby enabling replicability. It is composed of 26 postures/tasks involving grasping with the eight most relevant human grasp types and two non-grasping postures. The AHAP allows to quantify the anthropomorphism and functionality of artificial hands through a numerical Grasping Ability Score (GAS). The AHAP was tested with different hands, the first version of the hand of the humanoid robot ARMAR-6 with three different configurations resulting from attachment of pads to fingertips and palm as well as the two versions of the KIT Prosthetic Hand. The benchmark was used to demonstrate the improvements of these hands in aspects like the grasping surface, the grasp force and the finger kinematics. The reliability, consistency and responsiveness of the benchmark have been statistically analyzed, indicating that the AHAP is a powerful tool for evaluating and comparing different artificial hand designs.

1. Introduction and related work

Within the last years there has been considerable progress in the development of anthropomorphic artificial hands both for robotic applications [1,2] and prosthetic hands [3]. 3D-printing technologies have facilitated the advancement of low-cost artificial hands [4]. However, there has not been a parallel development of objective methods to evaluate or compare the performance of the different hand designs. The necessity of specific benchmarking in this field has been recognized by several standardization organizations as the National Institute of Standards and Technology (NIST) [5] and different researchers [6–9]. It has also been a recurrent topic for specific workshops in the last editions of international robotics conferences. In general, standardized performance testing or benchmarking is a fundamental tool that is crucial for the progress of any activity of research and development. It provides the ability to replicate and compare quantified results to enhance understanding of the effectiveness of an approach for improving product designs.

The development of anthropomorphic hands in the robotics community seeks to achieve highly dexterous end-effectors and a human like appearance, especially in service robots and human–robot cooperation [1,10,11]. The complexity of these anthropomorphic hands challenges the design of the grasping performance benchmarks. Additionally, any benchmark applied to a physical hand evaluates the combination of the mechanical design and the applied control strategy. The wide range of developed hardware, following a variety of design objectives, as well as the different underlying control algorithms make a fair comparison hard. Moreover, the differences between robotic and prosthetic hands should be considered if we want to establish a common benchmark for hand design. In prosthetic hands the need for standalone hardware poses challenging restrictions on the actuation and embedded mechatronics. On the other hand, control parts, which are vital for the success of robotic grasping as for example the correct pre-grasp pose of the arm, are not part of the prosthetic control system as they are performed by the user of the prosthesis.

Early benchmarks in robotic manipulation were proposed for teleoperation tasks including Duplo blocks as standardized objects to grasp and manipulate [12]. A general metric for the grasping skill of planar grippers was later presented using cylindrical test objects of varying size [13]. As an initiative of the NIST, Falco et al. [5] proposed a framework for standardized benchmarking of robotic hands. They classified the performance tests into three levels: component tests, system tests and functional tests. Several

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benchmarks proposed for hand exoskeletons are also inspired by these robotic gripper evaluation methods [14]. A metric comparing complex control algorithms on arbitrary hardware was presented by Van Wyk et al. applying a peg-in-hole-task evaluation [15]. Recently, Quispe et al. [9] proposed a general taxonomy for benchmarking of manipulation tasks for service robotics and describe recommendations about how to define useful testing protocols.

In contrast, performance assessment of prosthetic hands has been based on specifically designed protocols or questionnaires. Lindner et al. [16] compared the contents of outcome measures that have been developed to evaluate the functional performance among upper limb prosthesis users. The comparison was based on the International Classification of Functioning, Disability and Health (ICF) with an emphasis on the psychometric properties. Although many of the selected measures were based on interviews, the authors highlighted that other hand function measures "such as the Southampton Hand Assessment Procedure (SHAP) [17], Box and Block test [18], Jebsen Taylor hand function test [19] and Assisting Hand Assessment (AHA) [20], which are designed primarily for measuring hand function, are potentially useful measures for upper limb prosthetics" [16]. In the literature there are few studies that compare prostheses using the Box and Block test [21] and the SHAP [22].

Some works have addressed the question of defining indices for measuring the anthropomorphism of artificial hands in robotics or prosthetics [23–25]. The comparison of the workspace of the fingertips or joints is used in [23,24] in order to measure the ability to mimic the human hand. The study of Liu et al. [25] concentrates especially on the mechanical properties, splitting them into physical and actuation properties of the prosthetic hands. While these metrics give a good overview over the design specifications of prosthetic hands, they pay only little attention to the grasping capabilities and do not include grasping tests.

A key point for developing widely accepted benchmarks for grasping is to use a commonly available set of objects. Several sets of virtual objects have been proposed for grasp planning research in service robotics [26,27], but the availability of the physical objects is sometimes limited [7]. With the Yale-CMU-Berkeley Object and Model Set (YCB set) [7] – a collection of physically available objects of daily living for robotic grasping and manipulation benchmarks – the comparability of grasping experiments on robot hands was notably facilitated. In addition, the authors also proposed a structure for protocols and benchmarks and implemented several test procedures including the YCB Gripper Assessment Benchmark to assess the capabilities of robotic grippers using objects from the shape and tool categories of the YCB set. This protocol was adjusted by Jamone et al. [28] to consider the physical grasping capabilities of the iCub hand, an anthropomorphic robotic hand applied by several research groups. This protocol offers a baseline to evaluate control algorithms on the iCub hand by assuming the human brain as the best possible controller.

The standardized performance tests proposed so far in the literature try to quantify dynamic and kinematic capabilities (finger and grasp forces, closing time, etc.) or very specific tasks, such as pick-and-place or pouring, among others. However, if we try to measure the anthropomorphism, it is necessary to replicate the most characteristic grasp types (GTs) in the human hand and to include a variety of objects used in activities of daily living (ADLs). In a previous work by the authors [29] a preliminary protocol was proposed to test the grasping performance, including the most characteristic GTs and using different common objects. This protocol was used to obtain the coordination motion among the fingers of a new low-cost 3D-printed hand prototype, the IMMA hand. However, statistical validations are still needed for this work. Other studies seek to evaluate anthropomorphic prosthetic hands [30,31] and robotic hands [32,33] by applying the Cutkosky's Taxonomy [34] or the GRASP Taxonomy proposed by Feix et al. [35]. However, they do not use a common set of objects and are tailored to specific hand designs. Therefore, they do not present a repeatable or comparable index for measuring the grasp dexterity among arbitrary hands.

Pushing forward the approaches for benchmarking presented above, some indicatory questions arise: How to define a benchmark to evaluate the grasping capability of anthropomorphic artificial hands both for robotic and prosthetic applications? How to prove that an artificial hand is able to replicate the main types of human grasps? How to produce a benchmark easily replicable and able to compare different hand designs in order to foster future improvements of the grasping capabilities?

The objective of this paper is to establish a universal experimental benchmark to evaluate the ability of both robotic and prosthetic anthropomorphic hands to produce successful grasps in a human-like manner. The standardized protocol should be a functional test including the main GTs typical of human grasping in ADLs [17,36–40]. Moreover, the objects used in the protocol should preferably be contained in a standardized set to enable the repeatability of the tests performed. In contrast to other standardized protocols such as SHAP [17], the proposed protocol should evaluate both the functionality and the human-like execution of the different GTs, according to the human strategies. In addition, we aim to define a protocol, which can be used in different stages of the development cycle. Different alternatives for the mechanical design of the hand, the actuation method or the control algorithms should be comparable applying the proposed protocol.

2. The anthropomorphic hand assessment protocol (AHAP)

2.1. Methodology

The objective of this study is to propose a benchmark providing a reliable measure of the grasping ability of anthropomorphic hands. Grasping ability is understood here as the ability of the hand not only to effectively grasp a representative set of daily life objects, but also to maintain a stable grip under motion of the arm without external forces. We follow the terminology proposed by Calli et al. [7] which defines a protocol as an experimental setup for a given manipulation task including the procedures to follow as well as a scoring scheme as a benchmark for the quantification of performance of the measured device or control algorithm. In order to define the benchmark, several steps were followed:

1. Selection of a representative set of grasp types (GTs) or grasp postures.
2. Selection of objects of different size, shape and weight, typically grasped with these GTs.
3. Definition of a preliminary protocol for testing the hand while grasping the selected objects.
4. Definition of a scoring system to obtain a numeric outcome measure from the test.
5. Test the preliminary protocol with different versions of an anthropomorphic robotic hand with distinct contact surface characteristics.
6. Statistical analysis of reliability, consistency and responsiveness of the protocol.
7. Modifications of the protocol and the scoring method in order to improve the reliability of the benchmark.
8. Test the improved protocol with the same robotic hand used in step 5 for the preliminary protocol.
9. Statistical analysis of reliability, consistency and responsiveness of this final protocol.

10. Application of the improved protocol to compare the grasping ability of two versions of an anthropomorphic prosthetic hand in order to validate the sensitivity of the protocol to fine-granular changes in the design of the hand.

The purpose of the protocol is to assess an anthropomorphic artificial hand's ability to firmly grasp a variety of objects and perform other manual tasks adopting different prototypical postures (GT), specified for each object/task and commonly used by the human hand in ADLs. The hand is operated by a human subject and the protocol is therefore applicable to prosthetic and robotic hands.

By applying this protocol, we obtain the following results:

- The total Grasping Ability Score (GAS) quantifying the proficiency of the hand to perform all the postures/tasks.
- The partial GAS quantifying the proficiency to perform each specific posture/task.
- A qualitative impression of the advantages and disadvantages of the hand, its control method and its actuation device.
- A starting point to identify possible reasons for the failed grasps/tasks. The protocol allows an experimental identification of the difficulties in grasping and a classification of the limitations (e.g. finger orientation, friction between hand and object, finger coordination with the actuation device, feedback, force capability, etc.)

To be able to compare different artificial hands and to evaluate the possible influence of the actuation and control methods, the details of the tested setup including information on the artificial hand and the actuation device or actuation control used are also requested with the evaluation. A fair comparison of different artificial hand designs is possible if the same actuation or control method is used for all of them.

2.2. Grasp types and objects

The proposed protocol is divided in 26 tasks as shown in Table 1. It involves eight different GTs, coincident with those used in our previous study [29]: pulp pinch (PP), lateral pinch (LP), diagonal volar grip (DVG), cylindrical grip (CG), extension grip (EG), tripod pinch (TP), spherical grip (SG) and hook grip (H). The selection was made based on the results of a previous field study about grasps applied in ADLs [36] and on previous research in the area of human grasp analysis, prosthetics and rehabilitation [17, 37–40]. The AHAP includes all the main GTs included in those works, accounting for more than 90% in grasp frequency. PP and TP account together for 29%–48%, LP for 9%–20%, CG for 12%–25% and the rest of GTs for 18%–36%.

We complemented our set of GTs with two non-grasping postures: platform (P) and index pointing/pressing (IP), given their importance for a multigrasp prosthetic hand [41].

Three different objects of the YCB set [7] have been selected for each GT in order to account for variations in size, shape, weight, texture and rigidity. This selection includes a representative subset of the possible variety of objects in ADLs within the limitation of objects available in the YCB set. For each non-grasping posture, one object of the YCB set was selected. In total the 25 objects shown in Table 1 are used for the benchmark. These objects include all different categories of the YCB set: (1) food items, (2) kitchen items, (3) tool items, (4) shape items and (5) task items. The main dimensions and weights of the objects can be found in [7].

2.3. Protocol and benchmark

The proposed protocol is applicable to anthropomorphic artificial hands which can be either robotic or prosthetic. The hand should be actuated by a human subject, either a disabled person wearing the prosthesis or an able-bodied person using an actuation or control device. For each task the objects are handed over to the subject by an operator holding them in the correct position for successful execution of the grasp. For different hand geometry, kinematics or control strategies, small variations in the orientation to present the object can be allowed, always pursuing the correct GT. Table 1 shows the approximate final position/orientation of the object with respect to the artificial hand in order to guide the operator and to increase the reproducibility. The operator releases the object once the grasp is performed by the artificial hand. The subject should be in a standing position during the test and located near a table. The subject will be instructed about the right grasping posture for each object/task and is allowed to practice with the object during a minute prior to the test. The correct GT is indicated by the operator and the subject should try to reproduce the demonstrated posture with the artificial hand as accurate as possible. Some damping material should be used on the floor and table near the subject to protect the objects in case of a grasp failure.

As explained above, several improvements were applied to the preliminary protocol according to an analysis of its reliability, consistency and responsiveness.

Table 2 shows the steps for the Anthropomorphic Hand Assessment Protocol (AHAP) and Table 3 explains its scoring system. The criteria for assessing GT correctness in the AHAP, taking into account some previous definition of the GTs [36,37], are listed in the Appendix. The score of each grasp/task is provided by the operator. The test has a duration of approximately 80–100 min.

Scores for the three objects of each GT are added to obtain the final score for this grasping posture. Scores for all the objects/tasks are added to obtain the final score of the artificial hand. Normalized scores can be obtained by dividing by the maximum possible scores. Thus, the GAS can be expressed as a percentage of human grasping ability. The maximum GAS that an anthropomorphic artificial hand could achieve (100%) corresponds to the healthy human hand. The minimum GAS of 0% describes an artificial hand unable to grasp any object.

The most significant changes of this improved protocol (AHAP) with respect to the preliminary version refer to the execution and scoring for step 4. In the preliminary protocol this step was repeated for a maximum of three trials only in the event of failure in previous trials, with a decreasing score after each trial (1, 0.6, 0.4 points). The score given for a stable grasp with incorrect type was 0.2 points independent of the trial number it was achieved in. Moreover, in the preliminary protocol a detailed definition of requirements to fulfill for a GT to be considered correct (Appendix) was absent.

3. Experimental evaluation

3.1. Tested hands

The presented protocol aims to evaluate the grasping ability of anthropomorphic artificial hands in robotic and prosthetic applications. We therefore validated it with a five-fingered robotic hand and a prosthesis to cover a wide range of use cases. These hand designs pursue different objectives in replication and augmentation of human grasping abilities. In the following paragraphs their individual specifications in design and control are described in detail.

Table 1
Grasp types and objects (YCB set) used in the protocol (T_i indicates the task order of the protocol).

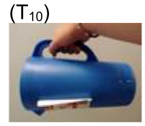
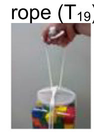
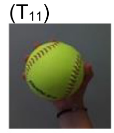
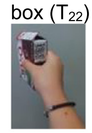
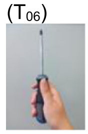
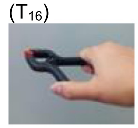
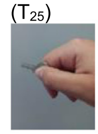
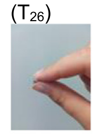
Grasp types (GTs)	Objects and tasks order		
Hook (H)	Skillet lid (T_{01}) 	Pitcher base (T_{10}) 	Wood blocks with rope (T_{19}) 
Spherical grip (SG)	Plastic apple (T_{02}) 	Softball (T_{11}) 	Mini soccer ball (T_{20}) 
Tripod pinch (TP)	Large marker (T_{03}) 	Tuna can (T_{12}) 	Golf ball (T_{21}) 
Extension grip (EG)	Plate (T_{04}) 	Cracker box (T_{13}) 	Chocolate pudding box (T_{22}) 
Cylindrical grip (CG)	Chips can (T_{05}) 	Coffee can (T_{14}) 	Power drill (T_{23}) 
Diagonal volar grip (DVG)	Phillips screwdriver (T_{06}) 	Spatula (T_{15}) 	Skillet (T_{24}) 
Lateral pinch (LP)	Bowl (T_{07}) 	XS clamp (T_{16}) 	Key (T_{25}) 
Pulp pinch (PP)	Small marker (T_{08}) 	Plastic pear (T_{17}) 	Washer 10 mm (T_{26}) 
Index pointing/pressing (IP)	Timer (T_{09}) 		
Platform (P)	Plate (T_{18}) 		

Table 2
Steps of the Anthropomorphic Hand Assessment Protocol (AHAP) for each object.

Step	Description
1	The operator shows the object and the correct grasping posture/task to the subject. Detailed information about the posture/task for each object and the order to be followed can be found in Table 1 (Section 2.2).
2	The operator helps the subject to practice the grasp/task for about one minute.
3	The operator hands the object over to the subject for the test. For index-pressing task (T_{09}) the timer is fixed to the table surface.
4	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 grasped the object. The subject maintains the grasp for three seconds. For the index-pressing task (T_{09}) the subject presses the button to start the timer and waits for three seconds. This step is followed immediately by step 5 and the sequence of steps 4–5 is repeated three times.
5	While maintaining the grip, the subject rotates the hand in a natural way with low acceleration for the palm to point downwards (180°) and keeps the grip during three seconds in this position. For the index-pressing task (T_{09}) the subject presses the button again to stop the timer (maximum time to execute three seconds). For the platform position this step is not executed.
6	The subject releases the object, which is taken by the operator.

Table 3
Scoring system of the Anthropomorphic Hand Assessment Protocol (AHAP).

Step	Task	Score (for each trial)	Scoring criteria
4	All	1	The grasp is completed with the correct grasp type. Detailed instructions to evaluate the grasping posture can be found in the Appendix.
		0.5	The grasping posture is different to the one specified in the Appendix.
		0	The artificial hand cannot grasp the object.
5	All the tasks except T_{09} and T_{18}	1	No visible motion of the object with respect to the hand is detected (for T_{19} only the motion for the portion of the rope located in the grasping area is considered).
		0.5	The object moves with respect to the hand but is not dropped.
		0	The object is dropped.
	T_{09}	1	Completed with the correct grasp type.
		0.5	Completed with a grasp type different to the one specified in the Appendix.
		0	Not completed in less than three seconds.
	T_{18}	–	Not additional point for this task.

3.1.1. ARMAR-6 v1 hand

The ARMAR-6 v1 hand (ARMAR hand hereinafter), shown in Fig. 1, is a prototypical robotic hand designed for the humanoid robot ARMAR-6 [42]. It is the first version of this hand, which has undergone significant design changes in the meantime.

Altogether it has 15 degrees of freedom split up into three flexion joints per finger. Force transmission within the fingers is implemented with Dyneema tendon of 1 mm diameter. The hand is driven by two DC motors (1741U024CXR, Faulhaber GmbH) at 24 V with a 37:1 planetary gear (Faulhaber Series 17/1). While the thumb is actuated individually by one motor, all other fingers are actuated by a second motor via a force distributing lever mechanism adapted from the TUAT/Karlsruhe mechanism [43,44]. It allows the fingers to close completely even when some of them are blocked, thereby enabling the hand to wrap around arbitrarily shaped objects. All finger joints are guided by sliding bearings and their passive reopening is ensured by extension springs. Although this movement is not supported by the springs, the finger mechanics are fully compliant and allow over-extension. This provides an inherent safety regarding self-collision and object contacts.

Matching to the size of the robot arm system, this hand is larger than the human model, as can be seen in Table 4.

All customized hand parts except for the lever of the mechanism are manufactured by fused deposition modeling from ABS plastic. The lever is made of high strength aluminum. The hand design includes pads amplifying the surface friction in fingers and palm. Throughout the experiments presented herein, the amount of applied friction pads was gradually increased including the bare plastic surface, five pads in the fingertips and an additional four pads in the palm as is shown in Fig. 1. The pads are cut from an anti-slip foil (Kager Industrieprodukte GmbH).

The hand is controlled with an Arduino board included in the palm. A serial interface including a comprehensive set of commands allows a simple velocity control of both motors as well as the approach of several dedicated finger positions. Control commands can be issued from any computational device providing serial communication.

Table 4
Sizing dimensions of the hands used for evaluation.

Dimension (mm)	ARMAR hand	KIT Prosthetic Hand
palm length	144	111
hand length (wrist to tip of the middle finger)	253	189
palm width	100	87
palm depth	47	30

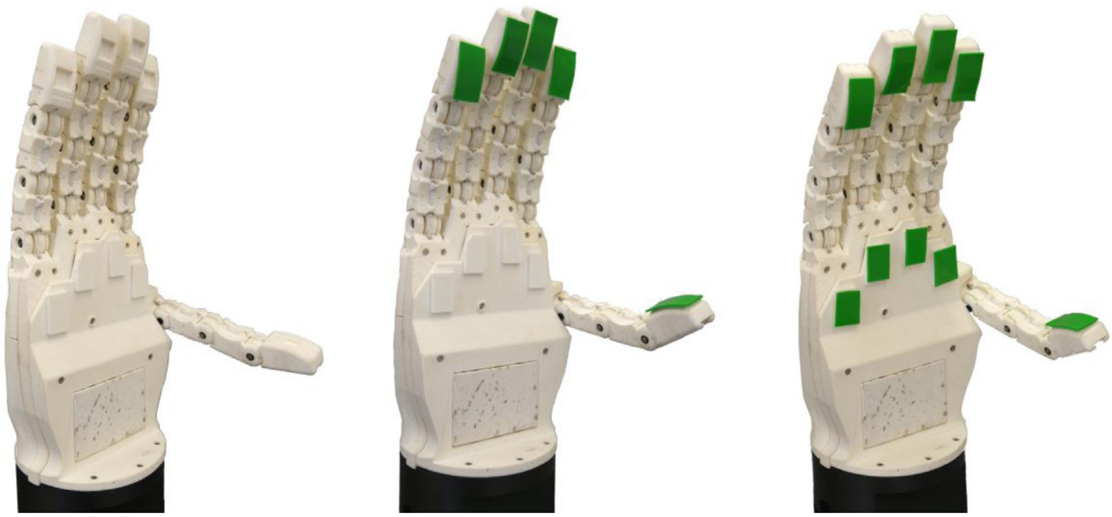


Fig. 1. The three configurations of the ARMAR hand with different sets of friction pads; from left to right versions A1, A2 and A3.

3.1.2. KIT prosthetic hand

The KIT Prosthetic Hand shown in Fig. 2 is a 3D-printed prosthesis including an underactuated mechanism, sensors and an embedded control system [45]. It comprises 10 degrees of freedom with two flexion joints in each finger. The prosthesis is actuated by two DC motors (2224U012SR, Faulhaber GmbH) with an 86:1 transmission gear (Faulhaber Series 20/1R). It contains incremental encoders (Faulhaber IEH2-512). Similar to the ARMAR hand, a mechanical force distribution resembling the TUAT/Karlsruhe mechanism [43,44] is implemented to drive the four long fingers. Compared to the mechanism of the ARMAR hand, several improvements regarding the size and the amount of friction have been made.

The prosthesis is sized conforming a 50th percentile male human hand according to the German standard specification (DIN 33402-2). The resulting dimensions are noted in Table 4. It has a fingertip force of up to 11.82 N, a hook grasp force of 120 N and a hand closing time of ∼1.3 s.

While the prosthetic hand supports various means of communication protocols, such as control including Bluetooth Low Energy and a direct serial interface, and control methods, we only employ a simple velocity control of the two motors by three buttons for the evaluations conducted herein.

Within this paper, we evaluate the final and published version of the KIT Prosthetic Hand (P2), depicted in Fig. 2, and a preliminary version representing an earlier state of our development (P1). Both variants mainly differ in the placement of the mechanical parts within the finger joints and the lengths of the finger segments, which are not defined in the mentioned standard and were updated inspired by the human reference model of the Master Motor Map [46] and studies from our previous work [47].

3.2. Benchmarking tests

To begin with, the preliminary protocol was executed with the three different configurations of the ARMAR hand with a gradually increasing number of friction pads attached to the hand as is shown in Fig. 1. The first test performed with the preliminary protocol was on the hand without any pad (A1), the second was with five pads in the fingertips (A2) and for the third we applied four additional pads in the palm (A3).

Afterwards, these three configurations of the ARMAR hand were tested in the same order with the improved protocol (AHAP).

Finally, two versions of the KIT Prosthetic Hand (P1 and P2) were tested with the improved protocol (AHAP) in order to analyze the sensitivity to other changes in the design of a hand.

The motors of all the hands tested in this study were operated by different able-bodied subjects, members of the authors' research groups, with similar experience in using the hand to grasp objects, ensuring comparability between the tested anthropomorphic hand designs. The ARMAR hand was actuated from a laptop where velocity control commands were sent to the hand via a serial interface and the KIT Prosthetic Hand was controlled via a custom-made interface using velocity control with three buttons, one to close the four fingers, one to close the thumb and one to open all the fingers and thumb. The subject performing the test was responsible for actuating the motors in the best way to perform the grasp correctly, according to the different GTs. By using this method, the finger closing sequence and velocity are controlled by the human operating the hand. The hands' control did not include automatic motions based on preprogrammed grip patterns. As the hands evaluated are driven by an underactuated mechanism, the performed grip pattern is based on the object shape and the synergistic mechanical coupling of the adaptive fingers.

3.3. Validation of the benchmark

The validity of the benchmark for measuring and comparing the grasping ability of anthropomorphic hands relies mainly on the following aspects, which are taken from psychometric outcome measures [16]:

- Intra- and inter-rater reliability: If the same hand is tested more than once by the same or by different raters, the results should be very similar.
- Internal consistency: The different tasks of the benchmark test should contribute to evaluate complementary aspects of the grasping ability without contradictory or inconsistent results.
- Responsiveness: The metric obtained from the benchmark is expected to vary under relevant changes of the grasping ability of the hand.

In order to evaluate these characteristics enabling also a comparison between the preliminary protocol and the improved one, several statistical analyses were conducted using SPSS statistical package (version 25, SPSS Inc, Chicago, USA).

Fig. 2. The final version of the KIT Prosthetic Hand (P2) fully opened (left) and while grasping the power drill (right)

In order to assess the inter-rater reliability, the tests were video-recorded and the videos were independently reviewed by five different raters from the authors' research groups to obtain the GAS.

Intra- and inter-rater reliability were assessed with the intra-class correlation coefficient (ICC) [48]. Inter-rater reliability was obtained for both the initial and improved protocols in order to get an indication of the improvement, whereas intra-rater reliability was only obtained for the improved protocol. Following the recommendations from Koo et al. [48], inter-rater reliability was assessed with ICC based on a single-rated, absolute-agreement, two-way random-effects model. The data for each rater were the scores (from 0 to 2 for the initial protocol and from 0 to 6 for the improved protocol) corresponding to each of the 26 tasks and for all the 3 hand versions (26 × 3 cases). Intra-rater reliability for the improved protocol was assessed with ICC based on a single-rated, absolute-agreement, two-way mixed-effects model. For each of the three trials, the scores (from 0 to 2) corresponding to each of the 26 tasks for the 3 hand versions and for all the 5 raters were considered (26 × 3 × 5 cases). Values of ICC greater than 0.9 are considered as indicative of excellent reliability, values between 0.75 and 0.9 indicate good reliability and only moderate reliability can be claimed below 0.75 [48].

The internal consistency of the benchmark to adequately reflect the grasping ability of the hands was assessed with the Cronbach's alpha through the scores for the different 26 tasks (from 0 to 2 for the initial protocol and from 0 to 6 for the improved protocol) corresponding to the three ARMAR hand versions for the five raters (3 × 5=15 cases). A good internal consistency is commonly considered if Cronbach's alpha is above 0.8, whereas it can be considered excellent above 0.9.

The responsiveness of the benchmark under changes in the hand design was assessed with the mean and standard deviation of the GAS obtained by each hand model. A significant difference in the means as compared to the standard deviation under several repetitions or raters is indicative of a good responsiveness. To quantify the responsiveness with a standard measure we used the standardized response mean (SRM) [49] of different hand model pairs. We computed SRM for a pair of hands by dividing the mean difference across raters of the GAS for those hands by the standard deviation of these differences. SRM is a standardized non-dimensional value. A value greater than 0.8 is considered indicative of a high responsiveness [49]. Different values of SRM were obtained comparing firstly each combination of two versions of the ARMAR and secondly the two versions of the KIT Prosthetic Hand.

Table 5
Mean GAS and mean score for each part of the task (grasping and maintaining) for each hand model with the AHAP.

Hand	Grasping	Maintaining	GAS
A1	52%	37%	45%
A2	59%	50%	55%
A3	62%	60%	61%
P1	65%	79%	72%
P2	68%	91%	79%

4. Results

4.1. Grasping ability score (GAS)

Mean value and standard deviation across raters of the GAS of the different hands using the protocols presented above, evaluated independently by five different raters according to the videos of the tests, are depicted in Fig. 3. It shows the results for the three versions of the ARMAR hand (A1, A2 and A3) using the preliminary protocol and those for these three versions of the ARMAR hand and the two versions of the KIT Prosthetic Hand (P1 and P2) using the improved protocol (AHAP).

The results reflect the expected improvement in the GAS in both hands with the changes in the design (from A1 to A3 for ARMAR hand and from P1 to P2 for KIT Prosthetic Hand).

Moreover, the results highlight a significant reduction of the standard deviation across raters with the AHAP (ranging between 1.19%–2.15%) with respect to the preliminary protocol (9.14%–10.20%).

The GAS involves both the ability to replicate the human-like GTs and the effectiveness for maintaining these grasps under motion. Table 5 shows the normalized score obtained by each hand for both parts of the task (grasping and maintaining).

In addition, Fig. 4 shows an analysis of the partial GAS for each GT (Table 1) obtained by the different tested hand models. This analysis could be interesting, for example for cases where the artificial hands have a specific purpose and the reproduction of some, but not all of the GTs is important. Index pointing (IP) and hook grasp (H) obtain the highest partial GAS for both hand types. The platform (P) posture was properly obtained with the ARMAR hand but not with the KIT Prosthetic Hand owing to the difference in hyperextension capabilities of both thumb designs. Pulp pinch (PP) and spherical grip (SG) are among the GTs with a higher scattering in the partial GAS depending on the hand design, as slight changes of the friction conditions have a high impact on

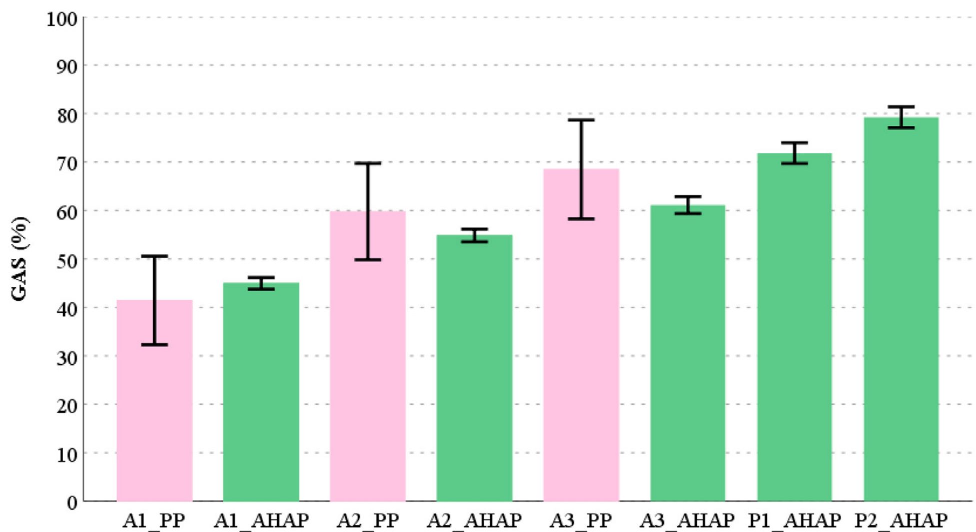


Fig. 3. Mean value and standard deviation across raters of the GAS with the preliminary protocol (PP) and with the improved protocol (AHAP) for each hand model (A1: ARMAR-6 v1 robotic hand without any pad, A2: ARMAR-6 v1 robotic hand with five pads in the fingertips, A3: ARMAR-6 v1 robotic hand with five pads in the fingertips and four pads in the palm, P1: preliminary version of the KIT Prosthetic Hand, P2: final and published version of the KIT Prosthetic Hand).

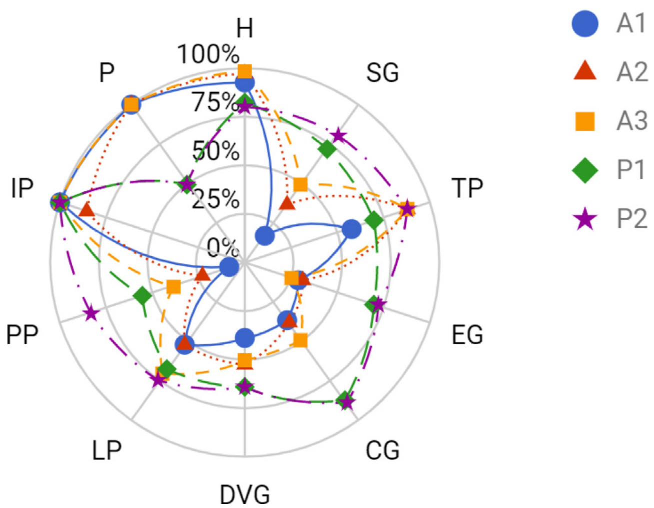


Fig. 4. Mean Grasping Ability Score (GAS) grouped by grasp type (GT, Table 1) obtained for each hand model with the Improved Protocol (AHAP). H: hook, SG: spherical grip, TP: tripod pinch, EG: extension grip, CG: cylindrical grip, DVG: diagonal volar grip, LP: lateral pinch, PP: pulp pinch, IP: index pointing/pressing, P: platform. A1: ARMAR-6 v1 robotic hand without any pad, A2: ARMAR-6 v1 robotic hand with five pads in the fingertips, A3: ARMAR-6 v1 robotic hand with five pads in the fingertips and four pads in the palm, P1: preliminary version of the KIT Prosthetic Hand, P2: final and published version of the KIT Prosthetic Hand.

the success of these GTs. A significant difference can be observed in the partial GAS obtained by the ARMAR hand configurations and the KIT Prosthetic Hand versions for extension grip (EG) and especially for cylindrical grip (CG) due to the achievable grasp force.

4.2. Validation of the benchmark

Table 6 shows the results of the statistical analysis undertaken to evaluate the validity of the benchmark for quantitatively measuring and comparing the grasping ability of anthropomorphic hands. Additionally, the responsiveness can also be assessed in Fig. 3.

The inter-rater reliability was clearly improved by the adaptations in the protocol from moderate/good for the preliminary protocol to excellent (greater than 0.9) for the improved protocol (AHAP). In addition, the results of the improved protocol indicate a good intra-rater reliability (above 0.8). The internal consistency of the test is good, with a Cronbach's alpha between 0.8 and 0.9, and very similar for both protocols. This similarity seems reasonable provided that the items of the test (the different tasks) are the same in both cases. The responsiveness of the test to changes in the hand design is considered high, with values clearly above 0.8 for the SRM for all the comparisons of hand pairs in both the preliminary and improved protocols.

4.3. Qualitative impressions from the grasp trials

The protocol allows to record additional subjective results from the observations made during the grasp trials. These should be annotated by the operator and/or the subject. Although this information is not part of the quantitative comparison provided by the benchmark, it offers an additional possibility to note and discuss findings and insights gained throughout the grasping process, which can be helpful for later design improvements.

To demonstrate the merit of such comments for the further development of tested prototypes, some exemplary cases from the evaluations presented in this study are discussed in detail.

The surface properties of the hand parts in contact with the object are prominently reflected in grasp stability. While especially the influence of friction is well known and quantified in robotic simulations, the presented protocol is able to corroborate this coherence and numerically prove the benefit even with small improvements of the hand's characteristics. During the first evaluation of the ARMAR hand without any pads, the problem of objects slipping out of a grasp was clearly notable in seven objects. Amongst others especially the plastic fruits, the small marker and the tuna can were affected and could not be grasped at all. According to this observation, the hand was gradually equipped with high friction pads, as described in Section 3.1.1. As a result, the grasping performance improved notably with all mentioned objects being successfully grasped at least once.

Especially for heavy objects and those with an uneven distribution of mass, a high force is critical for grasp success. This can be directly noted in the results with the ARMAR hand. Also with the pads on fingertips and palm applied, it has still difficulties

Table 6
Results of the validation of the benchmark.

Validation aspects	Statistical parameters	Preliminary protocol		Improved protocol (AHAP)	
Inter-rater reliability [95% confidence interval]	ICC	0.771 [0.670-0.846]		0.969 [0.957-0.978]	
Intra-rater reliability [95% confidence interval]	ICC	-		0.839 [0.813-0.863]	
Internal consistency	Cronbach's alpha	0.897		0.846	
Responsiveness	SRM	A1-A2	2.4	A1-A2	8.2
		A2-A3	4.4	A2-A3	5.7
		A1-A3	3.4	A1-A3	21.5
		–	–	P1-P2	7.8

with grasping the plate, the coffee can, the power drill and the skillet. Due to its improved motor control and reduced friction in the transmission, the KIT Prosthetic Hand is designed to be strikingly stronger than the ARMAR hand, which is reflected in the grasping results of the respective objects. While the latter is not able to hold the grip with the palm pointing downwards with any of those objects, the KIT Prosthetic Hand is able to perform a successful hand turning motion at least twice for all of them.

The influence of finger kinematics on the grasp quality is more difficult to identify. However, the evaluations of the two versions of the KIT Prosthetic Hand prove its visibility in the presented protocol. The original dimensioning of the finger phalanges included rather long proximal and short distal finger segments. In addition, the distal interphalangeal joints are fixed at an angle of 20° for both prosthetic designs. The fingertips were therefore unable to touch the palm, as the total length of intermediate and distal finger phalanges was too short compared to the proximal phalanx. This caused motion when rotating objects held with a hook grasp and complicated the grasping of thin objects like the markers. For the second version the lengths were updated according to a thorough study of human kinematics. By these means the grasping behavior could be improved for both markers and the wood blocks with a rope.

The relevance of the thumb opposition has attracted attention during the tests using this benchmark. The thumb opposition is influenced by both the orientation of the thumb and the abduction/adduction degree of freedom. Limitations in this aspect imply difficulties to correctly reproduce the diagonal volar grip and the lateral pinch GTs.

5. Discussion

Latest reviews on benchmarks and testing methods in the field of prosthetics [8] and robotics [9] emphasize the relevance of assessing artificial hand functional abilities with standardized testing methodologies. In most of the previous studies assessing artificial hand prototypes some preliminary grasping tests are included, but the comparability among research groups is very limited as they differ in the used objects and evaluation metrics.

In this study we propose an experimental protocol and benchmark applicable to both robotic and prosthetic anthropomorphic hands: the Anthropomorphic Hand Assessment Protocol (AHAP). The AHAP defines a total Grasping Ability Score (GAS) that quantifies numerically the capability of performing everyday grasps. This benchmark does not only provide a basis of comparison, but also a way to recognize possible improvements to the designs of the hands analyzed. The AHAP is inspired by a proposed preliminary protocol [29] with major improvements based on the statistical validation. We analyzed the intra- and inter-rater reliability, internal consistency and responsiveness (Table 6) verifying the robustness of the AHAP across raters and proving the comparability of the results also across different hands and testing conditions. The improvements were additionally demonstrated by a significant decrease of the standard deviation of the GAS evaluated by five different raters (Fig. 3). The variations between the results of the GAS for different configurations of the hands are higher than the standard deviation. It can therefore be concluded that the proposed benchmark is a powerful tool for evaluating and comparing different artificial hand designs.

The AHAP uses the YCB set of objects proposed by Calli et al. [7]. The use of an internationally available set of objects facilitates the comparison among hand developers. We developed the protocol according to the recommendations included in [7] where some examples are proposed. Unlike the protocols included in that study, the AHAP covers a wide range of aspects of the manipulation problem using objects of different sizes, shapes, weights, textures and rigidities from all different categories of the YCB set (food, kitchen, tool, shape and task items). The GAS obtained from the AHAP considers the ability to produce correctly each important human GT, and also the ability to maintain it under motion of the arm. It is evident that forces acting on the object during the execution of real tasks can be higher than those acting when turning the hand with the grasped object, but the objective of the AHAP is not to obtain the force limits for each GT. The objective is more focused on the ability to reproduce the different human GTs, which mainly depends on the kinematic structure of the hand, its control scheme, and the properties of the materials in the contact areas, in particular stiffness and roughness. The force limits are also affected by these parameters, but these limits depends also on the dynamic capability of the actuators and they should be investigated with specific protocols and metrics. We hypothesize that separating the different design aspects in the evaluation can be more efficient for improving artificial hands design. Nevertheless, in the AHAP the force limits are implicitly considered through the use of objects of different weights ranging from 0.7 to 950 g.

A common task both in robotics and prosthetics is to pick up an object from a table in a random position. However, in the proposed protocol we did not want to include the additional difficulties related to environmental grasp constraints and collision-free motion planning that arise if the hand is connected to a robotic arm or an able-bodied adaptor for a human operator. We instead focused the protocol on the ability of the hand for firmly grasping, using human-like GTs, when the object is presented in the correct position for the success in the grasp. By including simple grasping tasks, we avoid adverse influences possibly arising from complex tasks. We thereby provide a simple, transparent method to evaluate prehension. In addition, the benchmark tries to evaluate the anthropomorphism of the artificial hands based on their capability to perform the most frequently used human GTs in ADLs. Obtaining the highest GAS should be desirable for any anthropomorphic hand, taking into account that both humanoid robot's hands and prosthetic hands should behave human-like. Nevertheless, some specialized robotic hands may have specific requirements for their applications shifting importance to some of the GTs presented in the

AHAP. In those cases, the results of the GAS can be individually evaluated for each GT (Fig. 4), allowing a detailed and precise representation of the hand's abilities.

It is worth to note that the AHAP goes beyond previous studies [28,31] by evaluating the grasping ability of artificial anthropomorphic hands independently of their actuation or control system. However, a fair comparison of one of the main aspects such as the mechanical design of the hands, the actuation method or the control algorithms, is only possible when the other ones are fixed.

In this study we applied the AHAP to evaluate three different configurations (A1, A2, A3) of the ARMAR hand (a robotic hand from KIT) and two versions of the KIT Prosthetic Hand (P1, P2). The results show that the mean GAS increased from A1 to A3 due to the addition of friction pads, shifting from a value of 45% for A1 to 55% for A2 and 61% for A3. Furthermore, the improvement of the mean GAS from P1 (72%) to P2 (79%) proves the effectiveness of the improvement in the finger kinematics of the last version of the KIT Prosthetic Hand.

The proposed GAS assesses both the ability to replicate the human-like GTs and the effectivity of these grasps maintaining them under motion. It thereby evaluates the anthropomorphism and the functionality of robotic and prosthetic hands. For the hands tested, as shown in Table 5, the A3 has a similar score for replicating the GTs (62%) as for maintaining them (60%), while the P2 has a comparable score for replicating the GTs (68%) but a significantly higher score for maintaining them (91%). That means that the better GAS of the final version of the KIT Prosthetic Hand compared to the last configuration of the ARMAR hand is caused by the higher ability to maintain a grasp under motion. This result is due to an improvement in the grasping force, applying considerably stronger motors, a more intuitive control and reduced friction in the transmission.

According to the definition of Falco et al. [5] the AHAP is considered a functional test and could complement some other component and system tests proposed in the literature [5,8,9,25]. Additionally, it could be interesting to compare the assessment of different anthropomorphic hands using the AHAP and with analytical metrics proposed in the literature that give an index of the anthropomorphism of artificial hands [23,24].

6. Conclusions

In this paper, we present a new experimental, standardized and reproducible benchmark that has been statistically validated. We propose an evaluation protocol (AHAP) that includes the most frequently used GTs in ADLs performed by humans and a wide range of objects included in an internationally available object set (YCB set). With the proposed benchmark a reliable measure of the grasping ability of anthropomorphic robotic and prosthetic hands can be obtained, evaluating the functionality and anthropomorphism of the achieved grasps. In a thorough study we analyzed the GAS of three configurations of a robotic hand (ARMAR hand) and two versions of the KIT Prosthetic Hand. We offer a validated tool to evaluate and compare the different aspects of artificial hands: the mechanical design, the actuation system and the control strategy. The results obtained with the benchmark could be used for comparison of several hand designs but also to foster future improvements of their grasping capabilities. We used the benchmark to demonstrate the improvements of the tested hands in aspects as the grasping surface, the grasp force and the finger kinematics. Nevertheless, in future works the AHAP could be used to compare different force transmission systems such as tendons and bar linkages or different control strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

To evaluate the grasp type (GT) correctness the following instructions have to be considered for each GT:

- *Index pointing, pressing:* The GT is considered correct if the palmar side or the tip of distal phalange of the index finger is contacting the object and starting the timer (stopping for maintaining grip score).
- *Platform:* The GT is considered correct if there is contact between the object and the palm and the angle between any phalange (long fingers and thumb) and the palm is less than 30°.
- *Hook:* The GT is considered correct if there is contact between the object and the palmar side of at least three long fingers.
- *Spherical grip:* The GT is considered correct if there is contact between the object and the palmar sides of the thumb, all the phalanges of at least three long fingers and the palm.
- *Tripod pinch:* The GT is considered correct if the object is contacted by the radial side of the middle finger and by the palmar side of the distal phalanges of the thumb and the index finger.
- *Extension grip:* The GT is considered correct if there is contact between the object and the palmar side of the distal phalange and the intermediate phalange (if exist) of at least three long fingers and the palmar side of the thumb. In any case, the angle between the distal phalange axes and the object side must be less than 30°. For the boxes the contact of the thumb and finger phalanges must be in the opposing sides of the box with bigger area.
- *Cylindrical grip:* The GT is considered correct if the angle between the main axis of the thumb and the main axis of the object's grip area is greater than 60° and there is contact between the object and the palmar sides of the thumb, all the phalanges of at least three long fingers and the palm.
- *Diagonal volar grip:* The GT is considered correct if the angle between the plane defined by the thumb phalanges and the symmetry plane of the object is less than 30° and there is contact between the object and the palmar sides of the thumb, the palm and at least three long fingers.
- *Lateral pinch:* The GT is considered correct if there is contact between the object and, at least, the palmar side of the distal phalange of the thumb and the radial side of the index finger.
- *Pulp pinch:* The GT is considered correct if the object contacts with the palmar sides of the distal phalange of the thumb and the distal phalange of only one long finger, without any contact of the object with the palm.

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