ARTICLE IN PRESS

Engineering Science and Technology, an International Journal xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Affordable 3D-printed tendon prosthetic hands: Expectations and benchmarking questioned

Javier Andrés-Esperanza [1,*], Jose L. Iserte-Vilar [2], Immaculada Llop-Harillo [3], Antonio Pérez-González [4]

Department of Mechanical Engineering and Construction, Universitat Jaume I, 12071 Castellon, Spain

ARTICLE INFO

Article history:
Received 27 December 2020
Revised 1 May 2021
Accepted 24 August 2021
Available online xxxx

Keywords:
3D printing
Benchmarking
Grasp
Hand prosthesis
Biomechanics

ABSTRACT

The popularization of 3D-printing has allowed enhancing affordable prostheses for persons with amputations in developing countries, yet manufacturers are not subjected to any control from any medical regulatory authority. Adopted evaluation protocols seem to cherish optimistic expectations. A reduced performance test, derived from the Southampton Hand Assessment Procedure and two bench tests, to evaluate the mechanical advantage in the fingers and the slip resistance, are proposed to assess affordable tendon-driven devices. Ultimately, five models amongst those most commonly found in the scientific literature and the Internet have been evaluated. Three subjects participated with the aid of an able-bodied adaptor. The reduced test of performance provides consistent results but with a more direct interpretation of the failed patterns of prehension. All these models create far more expectations than the results deliver. With the supplementary material provided, an affordable benchmarking can be established with this reduced performance test and the two bench tests. They can lead to improved designs, prescriptions and regulations.

1. Introduction

The World Health Organization (WHO) estimates that 2.4 million of the 3 million upper-limb amputees worldwide live in low and medium-income countries (LMICs) [1]. Their amputations result mainly from diseases such as diabetes and polio, or land mines left behind after war. The popularization of 3D-printing technology, specifically utilizing *fused deposition modelling* (FDM) printers, has allowed enhancing low-cost (LC) prosthetic hands under the *Do It Yourself* (DIY) premise. For the scope of this work, LC mainly refers to affordable 3D-printed devices, costing less than $500 [2,3], that can be freely downloaded as a ready-to-print file either from web repositories (such as *www.instructables.com* or *www.thingiverse.com)* or non-profit initiatives [4–6]. This trend has not eluded using the latest open-source microcontrollers to give room to *electric powered* (EP) prostheses with the promise of a greater dexterity, by actuating each finger independently. This sort of device attempts to cover the most basic needs in the minimum time and money, yet it may not be recognized as a *medical device*, as manufacturers are not subjected to any control from any medical *regulatory authority* [7].

This increasing tendency of printing affordable devices has motivated some reviews of the state of the art of the existing models [1,2,8,9], but most of these researches did not include grasp experimentation and the outcomes reported were mainly on device kinematics.

The Southampton Hand Assessment Procedure (SHAP) [10] has been recognized as a tool to assess the effectiveness of hand prostheses. Dally et al. [11] and Phillips [12] performed the SHAP with e-NABLE's LC Body Powered (BP) hands [6] (with all fingers bending all together) with discouraging results. Lately, the SHAP has been confronted with a great diversity of myoelectric hand prostheses with one [13–18] or two [19,20] motor functions (hand open/close, and wrist pro/supination), or some multi-articulated myoelectric [15,21–23]. While the latest EP models may boost user expectations, validations of some of these measures are underway: some researchers [15,23] have stated that SHAP is reliable so that results from independent investigators can be compared, while others [20] have indicated that it was of little consistency. To make matters worse, SHAP scores themselves may be submitted to a deeper review, as the opacity in the calculated data [24,25] hinders the research on to give clear advice to both users and designers.

* Corresponding author.
E-mail addresses: fandres@uji.es (J. Andrés-Esperanza), jiserte@uji.es (J.L. Iserte-Vilar), illop@uji.es (I. Llop-Harillo), aperez@uji.es (A. Pérez-González).

Peer review under responsibility of Karabuk University.

[1] ORCID: 0000-0001-9298-5393.
[2] ORCID: 0000-0002-2654-4466.
[3] ORCID: 0000-0002-9378-1947.
[4] ORCID: 0000-0003-0210-7728.

https://doi.org/10.1016/j.jestch.2021.08.010
2215-0986/© 2021 Karabuk University. Publishing services by Elsevier B.V.

All in all, the ability of a prosthetic hand to achieve a grasp like that of the human hand depends on many factors such as the mechanical design, the actuator capabilities, the motion controllers, the grasp configuration, the properties of the surfaces, and the object size [26]. Recently, Mio et al. [27] reviewed the state-of-art of the tests to evaluate the mechanical design of BP devices. Some were classified as *mechanical resistance* testing methods, mainly devoted to compromise the weakest subset of the hand (i.e. one finger), and some others as *mechanical performance* testing methods, focused on the whole hand to estimate how good the grasp of a hand is. Some of the reviewed procedures consisted of particular bench-top testing or able-body assessment [11,28,29], or were based on evaluations of robotic grippers [26].

All in all, reality continues to make it clear the need to standardize tests to characterize and compare the mechanical design of all typologies of hand prostheses. A proper benchmark should also provide insight into the improvements leading to the better user experience when dealing with activities of daily life (ADL). The present work compares several of the most widely known LC EP prostheses for transradial amputees, found in the literature and the Internet, and with reported clinical cases: InMoov, Dextrus v2.0, Ada v1.1, and Limbitless hands. This comparison is carried out by using the SHAP and two other tests focused on: (i) the mechanical advantage (MA) of the transmission system and (ii) the anti-slip properties in the hand-object contact. The final objective of this study is to define a reproducible benchmark suitable for LC hands being used in LMICs. These test batteries would facilitate the analysis and proposal of improvements in this type of prostheses.

In the next section, the set of hands to be evaluated, the set-up for their evaluation, and all the essays are described. The following two sections are devoted to analysing and discussing the results. The results obtained motivate a reflection on how the functionality of these devices can be affected by the architecture and the grip performance of the selected materials. This will lead to the conclusion that the three tests conducted throughout the study are complementary for designers to gain insight into improvements they can make. Finally, as the three tests performed throughout this research are so easily replicable, they are proposed as a benchmark for the design of affordable prosthetic hands.

2. Materials and methods

Five prosthetic hands have been evaluated using the SHAP and two bench tests proposed to evaluate their mechanical design. SHAP has proven to give equivalent scores for subjects with limb-loss and able-bodied subjects with the aid of an able-bodied adaptor (ABA) [30], so most of the studies in the literature have been carried out in this second manner [13,17–19,22,31]. Therefore, in this study, it has been used an ABA to perform the SHAP. This ABA [32] fits on the forearm of the healthy subject and allows independent actuation of each of the fingers of the prosthesis. Three healthy subjects have performed SHAP tests. The Ethics Committee of the UJI approved the study and written informed consent was obtained from all participants.

The two sets of experiments designed to evaluate the mechanical design of the same five hands have been carried out with a specifically designed bench. They lay in the context of *mechanical performance testing methods* [27], where the efficiency in force transmission from the actuators to the fingers and grasping capabilities were measured. The description of the different prostheses selected, the actuating devices, and the tests are detailed in the following paragraphs.

2.1. Affordable prosthetic hands

Controzzi et al. [47] specified six important issues to be considered during the design and development phases of an EP prosthetic hand, namely: (a) *kinematic architecture*, (b) *actuation principle*, (c) *actuation transmission*, (d) *sensors*, (e) *materials*, and (f) *manufacturing method*. In the scope of the affordable designs for LMICs, an *underactuated kinematic architecture*, issue (a), which means having fewer degrees of control (DoCs) than degrees of freedom (DoFs), vastly represent the preferred option. It is mainly achieved by linking the motion of the joints in each finger with nylon threads running into sheaths, in an analogy with the tendons in the human hand. Besides making maintenance and assembly very easy, this *actuation transmission* (issue (c)) facilitates the adaptation to the shape of the grasped object and avoids any impact damage on the dorsum during extension, by being compliant. This also allows DC motors, issue (b), to be located remotely, reducing the dimensions and weight of the fingers. Regarding issues (e) and (f): apart from a 3D printer generally using *acrylonitrile butadiene styrene* (ABS) or *polylactic acid* (PLA) as row material (used in conventional orthotics [8,48]), most affordable designs require additional items, such as screw/bolts, elastic cords, nylon line, and Velcro® that should be easily obtainable [8]. Moreover, the use of compliant materials (thermoplastic elastomers such as Ninjaflex® (Fenner Inc.)) in the manufacturing of joints may elude the necessity of an additional digit extension system. For the scope of affordable devices, both assembly and maintenance are far easier when the hand is used as an open-loop device with no-feedback from any sensor, issue (d). After all these observations, a subset of affordable EP prosthetic hands was selected from those most commonly found in the scientific literature and the Internet [49] (see Table 1) on the following basis: (i) being available for downloading (to be 3D-printed) and assembling in a domestic workshop, and (ii) with reported clinical use in transradial amputees.

The hands meeting these criteria are summarized in Fig. 1 and Table 2, namely: InMoov, Dextrus v2.0, Ada v1.1, and Limbitless hands. The same 0.8 mm nylon thread (ultimate tensile stress of 220.5 N) was employed as a tendon coupling the flexion of the consecutive joints in each digit. All of them were manufactured using FDM, and none of them has any sensors. It should be noted that these hands try to mimic human hand anatomy. Consequently, the joints of the fingers in these prosthetic devices will be named by analogy, from distal to proximal: distal interphalangeal (DIP), proximal interphalangeal (PIP), metacarpophalangeal (MCP), and carpometacarpal (CMC). Note that the thumb may have only one interphalangeal (IP) joint. Not all prostheses have been designed with the same number of joints: for the sake of clarity in further sections, mimicked joints are listed in Table 2. Time and cost have been estimated on the basis of the model of printer used, namely a Colido® mod. X3045 with Repetier-Host (*www.repetier.com*) software.

For each hand and prior to FDM printing, a wrist add-on with two holes was merged with the downloaded file in order to make it easier to fasten them to the able-bodied adaptor and the bench described in the following sections (see Fig. 1). Some details of the studied prosthetic hands are:

- InMoov: it was originally intended as a part of an open-source 3D-printed humanoid robot [37]. Each finger can be mounted in such a manner to achieve an active two-way control, flexion and extension. To ease the routing of the nylon threads, each phalanx comes divided into two parts to be glued. For the sake of easiness and to evaluate grasping skills, elastic bands with their ends tied to the fingertip of each digit and the dorsum of

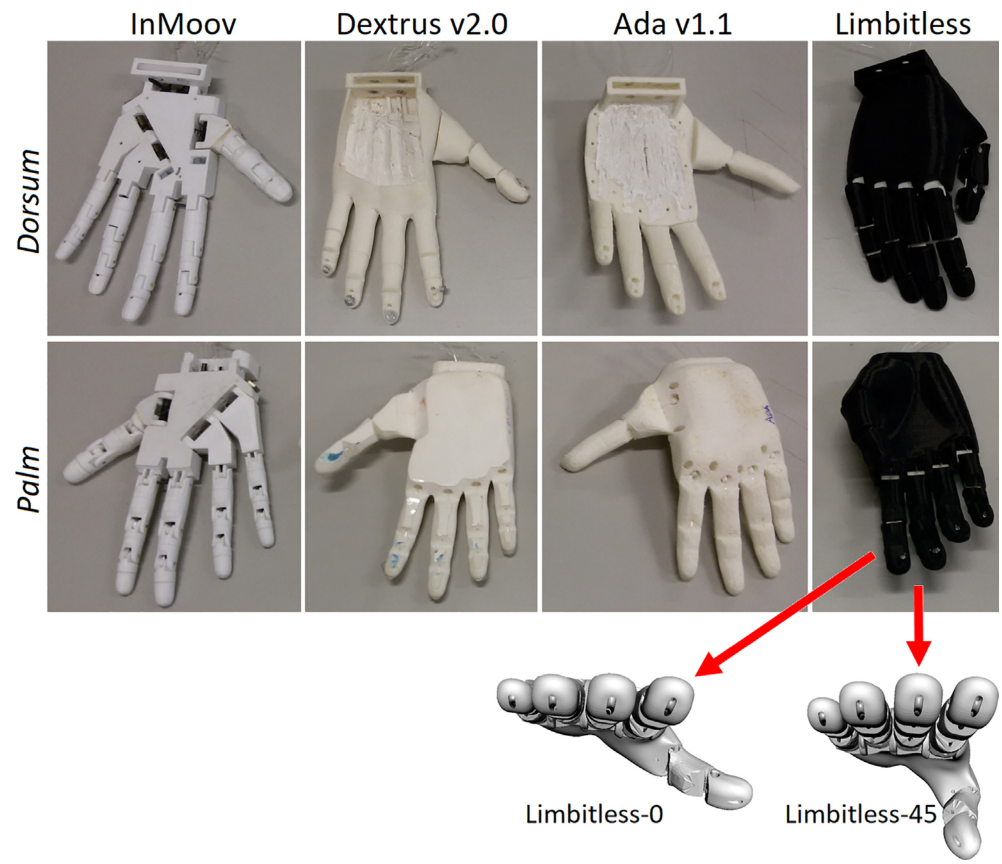

Fig. 1. From left to right, dorsal (top) and palmar (bottom) views of InMoov [37], Dextrus v2.0 [40], Ada v1.1 [42], and Limbitless [45] hands used for the present study. Below, view of the two thumb versions for the Limbitless: Limbitless-0 (left), and Limbitless-45 (right).

the palm were used for digit extension. Cut bike spokes were employed for the digit joints, and a regular bolt for the palmar joint.

- Dextrus v2.0: Its rubberized and flexible unibody design made of Ninjaflex® makes this hand very easy to assemble: the nylon threads just need to be routed. This hand has flexible joints fully integrated within the design, making the substitution of individual fingers impossible if broken. For the sake of brevity, in the present document, we will recall this model simply as Dextrus [40].
- Ada v1.1: from the same authors of the Dextrus, and with the same design principle of simplicity, the main differences are: (i) this rubberized unibody hand is printed with the palm facing up, so the joints store more elastic energy for extension; (ii) the previous fact allows the palm to be waved; (iii) the distal phalanx is rigidly attached with the medial phalanx. Therefore, each digit can be considered with only two segments. For the sake of brevity, Ada [42] will be the name used hereinafter.
- Limbitless [45]: It was developed by the University of Central Florida Armory based on the BP Flexy-Hand [50]. It is available with either a palmar abduction of 45 degrees of the thumb or without any palmar abduction at all. For the sake of clarity, we will recall these models as Limbitless-0 and Limbitless-45, respectively (see Fig. 1). The design was originally intended to work with one actuator, thus closing fingers and thumb together. Instead, this fact was unobserved and each tendon was pulled independently as in the other models used for this research.

2.2. Able-bodied adaptor (ABA)

Based on a previous design of the authors [51], the ABA shown in Fig. 2 was designed and 3D-printed looking for less distal separation of the artificial hand to the arm of the subject [32]. It is attached to the forearm of an able-bodied subject employing a ro Cuff® (*www.trsprosthetics.com*) and allows controlling any of the LC prosthetic hands presented in the previous section by pulling its tendons with one's own fingers. It was used for the SHAP test.

2.3. Test bench

A bench was designed with commercial aluminium modular systems (Item®) [52]. In it, the hand is anchored using a swivelling circular flange. The tendons to the fingers flow through its hollow centre: for the scope of equity, each of the digits of all the hands was actuated by a hanging weight of 20 N tied to the free end of its corresponding tendon, see Fig. 3. The weights are suspended by means of pulleys of negligible friction on a second support.

Table 1
Current LC electric hand prosthesis found in the literature and the Internet.

Ref. Name	Publications / websites	OpenSource (download link)	Clinical use
InMoov	[2,33,34] / [35–38]	[37]	[38]
Dextrus	[1,2,33,39] / [4]	[40]	[41]
Ada	(...) / [4,5,38]	[42]	[43]
Limbitless	[1,2] / [6,44]	[45]	[44,46]

Table 2
Main design characteristics of the selected LC EP hands for transradial amputees used for the present study.

Hand	InMoov	Dextrus v2.0	Ada v1.1	Limbitless
Kinematic architecture	Underactuated (17 DoFs > 5 DoCs)	Underactuated (15 DoFs > 5 DoCs)	Underactuated (10 DoFs > 5 DoCs)	Underactuated (14 DoFs > 1 DoCs)
- Number of joints†	*3f (+2 in the palm, at ring and little fingers), 3th*	*3f, 3th*	*2f, 2th*	*3f, 2th*
- Long fingers joints	DIP, PIP, MCP	DIP, PIP, MCP	PIP, MCP	DIP, PIP, MCP
- Thumb joints	IP, MCP, CMC	IP, MCP, CMC	MCP, CMC	IP, MCP
Actuation principle	5 Servo motors (either HobbyKing HK15298, Tower Pro MG995, or equivalent)	5 DC linear actuators (Actuonix PQ12-63:1 linear actuator)	5 DC linear actuators (Actuonix PQ12-63:1 linear actuator)	1 Servo motor (Hitec HS-5645MG - Digital High Torque MG Servo)
- Motors location‡	FArm	Palm	Palm	FArm
- Control board / battery location‡	FArm	Other	FArm / Other	FArm / NA
Materials (% infill)	PLA (30%)	Ninjaflex® (35%)	Ninjaflex® (35%)	PLA (25%) / Ninjaflex® (joints, 25%)
Overall size (HB/HL, mm)	95/194	87/185	86/192	89/200
Weight (g) w/o actuators	201.5	131	121	144.5
License	CC BY-NC 3.0	CC BY-SA 4.0	CC BY-SA 4.0	CC BY-NC 3.0
Printing time	22 h	28 h	35 h	16 h
Material cost	$6	$11	$14	$6

(†) 3f: three joints at fingers; 2f: two joints at fingers; 3th: three joints at the thumb; 2th: two joints at the thumb. DoC as originally intended for each model.
(‡) Palm: inside palm (or on palm dorsum for control board and battery); FArm: Actuators/control board/battery in forearm.

2.4. Southampton Hand Assessment Procedure (SHAP)

In the present research, the SHAP was followed to assess the functional performance of the aforementioned prostheses. Light et al. [10] established the SHAP after the analysis of grasp patterns and their frequency of use in ADL. It measures the hand function relative to undamaged persons by measuring the time-to-accomplishment of 26 tasks, namely: 12 tasks consisting in moving six light abstract objects (LAO, made of balsa wood, see Fig. 2) and six heavy abstract objects (HAO, made of metal), and 14 simulated ADL. A complete description and denomination of the tasks can be found on the SHAP website [53]. The time scores for each of the tasks are uploaded to this same website, which processes them into an overall Index of Functionality (IoF). The SHAP scoring system is based on a nonlinear combination of the performance in the different tasks [10]. The nominal score for a SHAP test is 100 (IoF of a typical healthy human hand over all the tasks) with lesser scores indicating a degree of impairment and greater scores indicating exceptional performance. Additionally, it provides some other Functionality Profile (FP) scores that describe the specific performance of the subject through the SHAP with regard to six functional grasps (spherical, power, tip, tripod, lateral, and extension). They use the same scale as the IoF.

The SHAP was particularly suitable for the present research since it tests both ADL and tasks with abstract objects, those last being the foundation of a vast range of different tasks. However, the exact nature of the nonlinear mathematics beneath the SHAP scores cannot be retrieved because of intellectual property rights. The Linear Index of Function (LIF), an alternative scoring system presented by Burgerhof et al. [24], was used in the present research to improve transparency in research and lead to a more rational comprehension of the assessment at stake. It is calculated on the basis of transformed time scores (T_s) registered for each of the SHAP tasks, as a sort of percentage of mastery which takes a task limit time value of eight times the normative mean time (n) documented for the healthy hand [10].

$$T_s = \frac{8 \cdot n - t}{8 \cdot n - n} \cdot 100 = \frac{8 \cdot n - t}{7 \cdot n} \cdot 100 \quad (1)$$

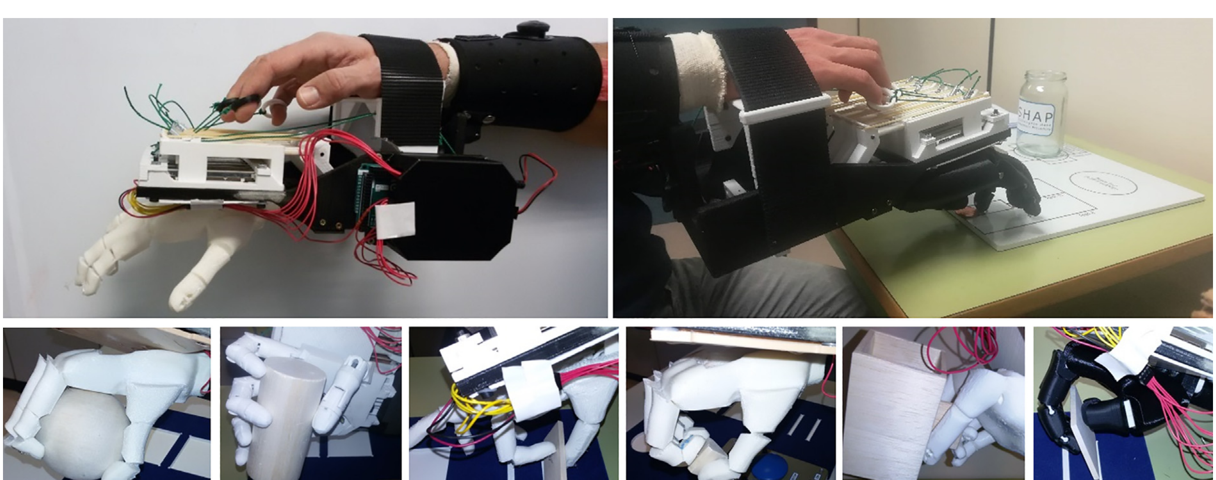

Fig. 2. Able-bodied adaptor, ABA was used to test the hands performing the SHAP (Light et al., [10]). Below, light abstract objects are shown in an attempt to be grasped, namely (from left to right): Spherical, Power, Tip, Tripod, Lateral, Extension.

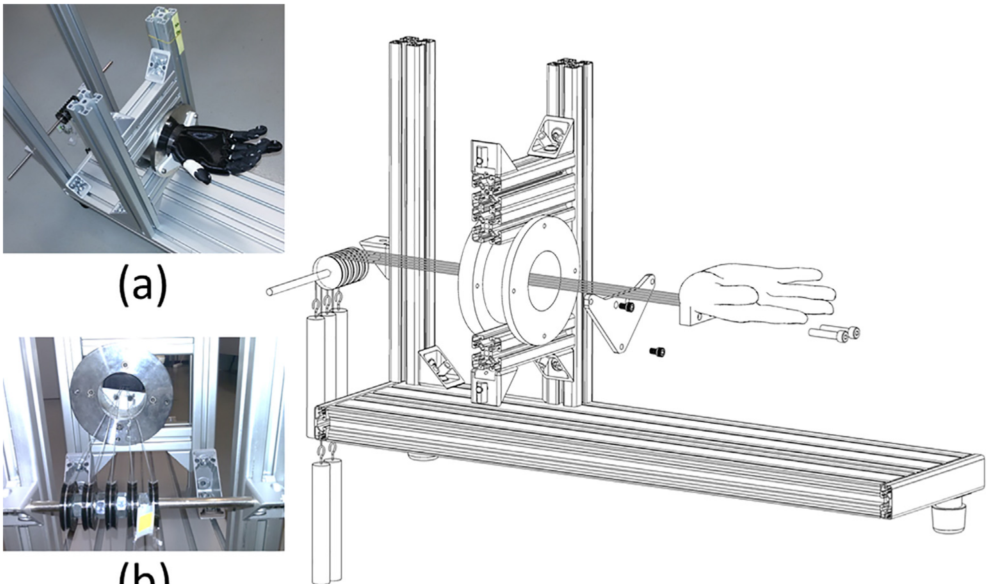

Fig. 3. Set up of one hand on the bench: (a) the palm is anchored to the swivelling circular flange, (b) the tendons flow through the hollow centre of the flange towards the pulleys on a second support.

This scoring system also provides some other LIF scores specific to the aforementioned six functional grasps. For the sake of clarity, the suggested equivalences between both Light's and Burgerhof's scoring systems are, respectively: *IoF* with *LIF*, and the *FP* with that $LIF_{prehension\ pattern}$ specific for each *prehension pattern*. Besides, three additional scores will be calculated by using the formulation proposed by Burherhoff [24]. LIF_{LAO} and LIF_{HAO} are the mean values of all 6 T_s for the 6 tasks performed with the 6 LAO and the 6 HAO, respectively, and LIF_{ADL} is the mean value of all 14 T_s for the 14 simulated ADL:

$$LIF_{LAO} = \frac{1}{6} \cdot \sum_{l=1}^{6} T_{s_l} \tag{2}$$

$$LIF_{HAO} = \frac{1}{6} \cdot \sum_{h=1}^{6} T_{s_h} \tag{3}$$

$$LIF_{ADL} = \frac{1}{14} \cdot \sum_{d=1}^{14} T_{s_d} \tag{4}$$

To assess the performance, each prosthesis was confronted with the SHAP consecutively by three different able-bodied subjects using the ABA. The order of the devices was: Limbitless-45, Dextrus, Limbitless-0, Ada, and InMoov. The familiarization with the ABA is fast because it lies in the natural task of pulling the corresponding thread for each finger, with visual, haptic, and proprioceptive feedback. Although the subjects of this study were already familiarized with it, it was their first experience performing the SHAP. Therefore, each subject was allowed to practice for 5 min with the set of abstract objects before testing. With these considerations, the subject's learning curve is placed on a plateau. Furthermore, for each subject, a minimum time of two weeks was established between the testing of a prosthesis and the next, to minimize the learning effect and to avoid fatigue effects.

According to the SHAP manual [53], the tasks were self-timed: the subject started each task seated and with the prosthetic hand open, and pressed a timer before and after execution. Note that if the subject is unable to complete a task in 100 s, the task is considered as failed.

As the abstract objects are shaped to encourage the use of the six standard prehensile patterns cited previously, they are named accordingly to that same pattern [10,54], e.g. *Lightweight Spherical*, or *Heavyweight Lateral* (*Spherical L*, or *Lateral H*, respectively, for the sake of brevity. See Fig. 2). However, only the time to completion of the task is taken into account regardless of the ability of the hand to adopt these patterns.

Since abstract tasks focus on prehensile ability, they involve minimal transports to limit the influence of gross upper-limb function. The averaged distance between the two marks on the table indicating the start and end of a movement is of 80 mm for the spherical, power, and lateral objects, and of 35 mm for the tip, tripod, and extension objects. However, body movements are not restricted and the SHAP makes obvious the importance of the wrist in performing some ADL tasks. In some instances, the subject was allowed to stand to better utilize the movement of the torso to compensate for the volume of the ABA. Also, in those ADL in which the grasping of a tool was particularly challenging (knife, screwdriver), the contralateral hand was allowed to assist in initially picking it up, as recommended by Light et al [10].

2.5. Evaluation of the mechanical advantage

After attaching the hand to the test bench, and for the thumb and the index finger (this one being the representative architecture of the other fingers), the digit in question was held at three different postures (extended, fully flexed, and semiflexed, the latter considering half the range of the joints, see Fig. 4). Then, sequentially and from distal to proximal, each phalanx at each posture was released so that this phalanx (as well as the remaining distal phalanges, if any) were naturally bent by the force acting the tendon. A PCE-FM50® force meter, connected to a computer via the RS-232 serial port and with a strap attached to its end-effector, was used to register the instantaneous closure force in the middle section of the phalanx during the entire travel from flexion to extension, and back. The speed of execution of the movement was intended to be steady and identical in the extension and the subsequent flexion. In order to get averaged closure force measurements, each force recording was repeated three times.

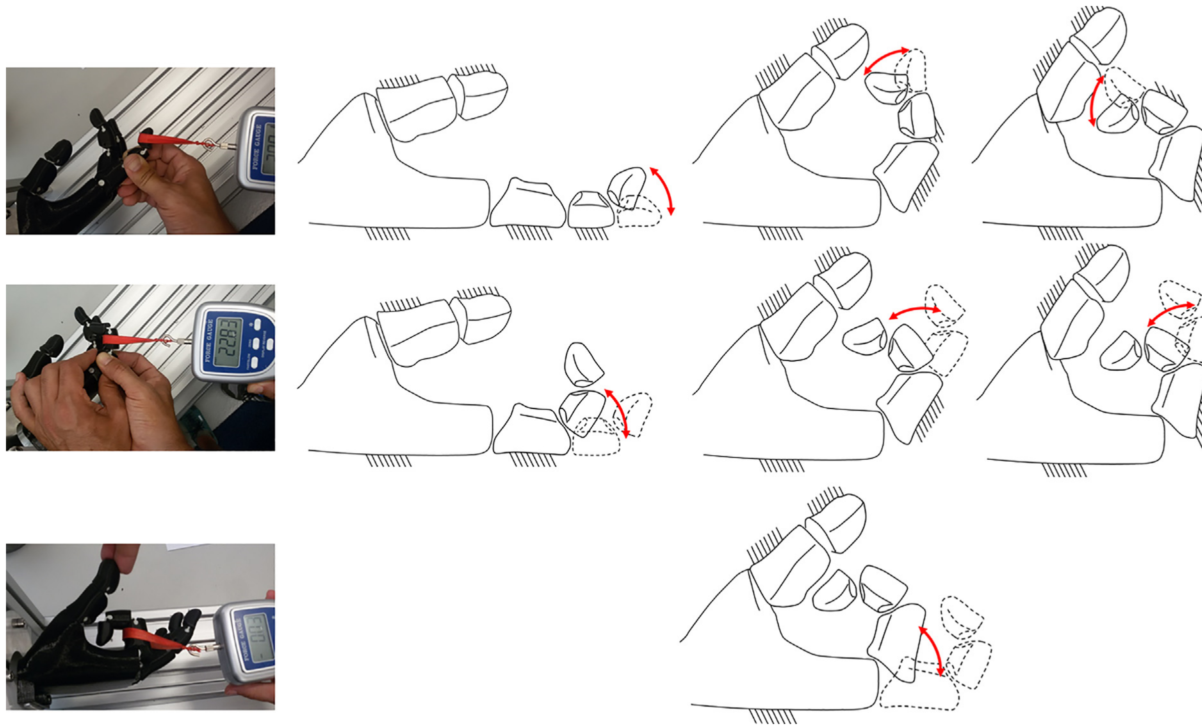

Fig. 4. Evaluation of the MA of the index for the distal (top), medial, and proximal (bottom) phalanges, in the extended (left), semiflexed (middle), and fully flexed (right) postures of the precedent segments.Set up of one hand on the bench: (a) the palm is anchored to the swivelling circular flange, (b) the tendons flow through the hollow centre of the flange towards the pulleys on a second support.

For each phalanx, an Averaged Mechanical Advantage Peak (AMAP) value was calculated by dividing the averaged peak force values by the acting force that pulls the tendon of the digit (20 N). It should be noted that 20 N was sufficient to get distinctive results amongst the different hands and to avoid getting stuck due to static friction. Too much force (40 N) proved to distort both Dextrus and Ada flexible hands.

2.6. Evaluation of the slip resistance

The measure of interest in this test is the maximum pull force ($F_{pull,max}$) attainable before gross sliding, for a given hand and object under a full force wrap grasp [55]. The drop in pull force after the peak, at force/time graph recorded for each repetition, points out a shift from static to dynamic Coulomb friction.

Most of the existing studies involve the use of a cylindrical object to carry out a test measuring the slip resistance (SR) [26,28,55], but none of them has yet become an international standard in terms of cylinder diameters or surface characterization. The experiment set for the present research measured the SR with three 100 mm length cylinders of 22, 32, and 50 mm in diameter (sizes S, M and L, respectively, the last one having the same dimensions than the SHAP abstract object). Additionally, one plate of the same dimensions as the SHAP's extension plate was also used, see Fig. 5. Each of these objects was carefully covered with a sheet of paper adhered to its surface, thus having the texture of a regular sheet.

After attaching the prosthetic hand to the test bench with the palm facing up to minimize the effect of gravity, each object was presented and grasped. Again, the pulling force for each tendon was set to a value of 20 N for all the hands. A cable was attached to the object. In the other end of the cable, a PCE-FM50® force meter aligned with it recorded the pull force. This pull was exerted towards the little finger to simulate accidental slippery from the hand (Fig. 5). Each measurement was repeated three times and the $F_{pull,max}$ registered was averaged ($F_{pull,avgmax}$) and taken as the SR value.

As it happened with the SHAP, the grasping posture intended with the cylinders was the *power* grasp. With the plate, the intended grasping postures (*extension*, *lateral*, or *pinch*) were sometimes mutually exclusive because of the architecture of the hand.

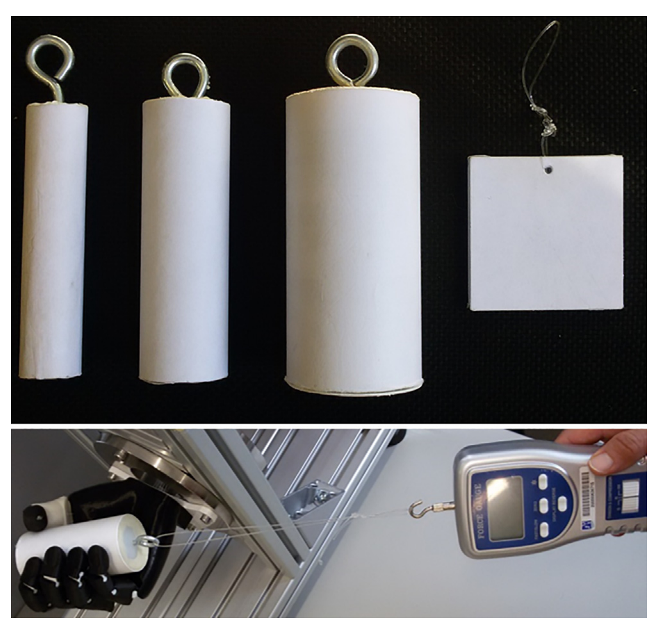

Fig. 5. Plate (60x60x5 mm, 49 g) and cylinders S, M, and L (100 mm length, from left to right: diam. 22/32/50 mm, 28/48/48 g) used for the slip resistance test.

3. Results

3.1. SHAP results

Fig. 6 resumes the averaged SHAP scores, for the three subjects, with both Light's and Burgerhof's proposals. Due to the high rate of failure with the HAO and ADL tasks, and to get a better insight of the SHAP, the additional scores LIF_{LAO}, LIF_{HAO}, and LIF_{ADL}, defined by the Equations (2), (3) and (4), are also shown.

Aside from the mean scores, the minimum times observed for each device across the three subjects do highlight the best performances achieved (*best-case scenario)* under the boundaries of this research. It also leaves aside the possible subject-effect. It should be noted that all the tasks with LAO could be possible in less than 30 s. In practice, the *Lateral L* task showed to be the most cumbersome because the subject had to grasp the object's handle, which is away from the object's centre of mass. Most HAO tasks were not completed because the objects turned out to be too slippery and/or too heavy and, if achieved, it was through an unconventional grasp pattern such as by pressing against the dorsum of the thumb, being it flexed.

Regarding the ADL tasks [53], all hands failed the tasks needing fine manipulation, such as the *Pick-up Coins*, *Button Board*, *Open/Close Zip*, *Simulated Food Cutting*, and *Rotate A Screw*. The last two were not accomplished even with the tool (knife or screwdriver) being offered by the abled hand. If achieved, *Page Turning* was done by first dragging the sheet up to the edge of the table, yet the lack of wrist mobility made awkward the act itself. For *Glass Jug Pouring* task, all hands transported the jug tilted and with critical instability as the handle did not fit properly any of the hands. What is more, with the Ada and Dextrus hands, the fingers warped due to their rubberized constitution. That said, *Page Turning* or *Glass Jug Pouring*, may not point out the true usefulness of the prostheses but the stubbornness of the user. The main reason for failure in the task of *Removing a Jar Lid* was that the jar slid into the prosthetic hand when the lid was turned with the healthy hand. It was successful only with the Ada hand. In the *Lifting a Heavy Object* task, at least one of the attempts was successful with the Ada, Limbitless-45, or InMoov models, but no trial could be completed with any of the other two hands as the jar easily slid out of them. In the *Lifting a Light Object* task, the object (an empty tin) was instinctively grasped from the top. For the *Rotate a Key* task with InMoov and Limbitless models, the key was rotated after fitting it between the proximal phalanges of the fully flexed index and middle fingers but, with Dextrus and Ada models, the fingers warped in every way to attempt this task. None of the prosthesis could use the lateral grasp with the thumb to rotate the key. The merit of the *Lifting a Tray* task, which can be performed with both hands, was that of the healthy hand. About the *Door Handle* task, it did not involve a real grasp but a push following the handle rotation, which could be performed even with the palm. Only *Lifting a Tray*, and *Door Handle* tasks were achieved in less than 10 s by all hands.

Results from the aforementioned *best-case scenario* are coherent with those averaged amongst subjects: InMoov hand obtained the highest *LIF* score (24.5), closely followed by Limbitless-0 (23.9). Besides, InMoov hand was the one that took the shortest *minimum times* with LAO thus getting the best LIF_{LAO} (40.3), followed again by the Limbitless-0 hand (31.2). On the other hand, the Limbitless-45 obtained the worst overall *LIF* score (11.5) and LIF_{LAO} (15.9). Oddly enough, Limbitless-45 was the only device that managed to perform both *Power H* and *Lateral H* tasks, but with critical instability and not fast enough to score according to the protocol.

3.2. Mechanical advantage results

AMAP values are shown in Table 3. In this table, the hands have been ordered from highest to lowest values of the averaged LIF_{LAO}.

In the case of the index finger, no major differences were observed in the proximal phalanx that articulates with the palm through the MCP joint: with an averaged AMAP close to 0.53 for all hands, both Limbitless versions, Ada and InMoov showed the greatest AMAP. The middle and distal phalanges offered unequal results: the middle phalanx showed the greatest AMAP for the Dextrus and both Limbitless versions, whereas both Limbitless versions and the InMoov demonstrated the greatest AMAP for the distal phalanx. Regarding the thumb, none of the Limbitless versions emulates the CMC joint, and the other three models exhibited AMAP values of the same order in the metacarpal phalanx (mean of 0.58). All hands emulate the MCP joint, and the AMAP in the proximal phalanx approached a mean value of 0.57 for all the hands except the Ada, which exhibited a very low value (0.14). Finally, in the distal phalanx, Dextrus offered a low AMAP compared to the InMoov and both Limbitless versions, with an AMAP close to the unit. Like in the index finger, Ada does not contemplate the existence of an IP joint in the thumb. Generally, for both versions of the Limbitless, AMAP values are alike, as the finger architecture is the same.

3.3. Slip resistance results

Fig. 7 shows the mean ($F_{pull,avgmax}$) and standard deviation intervals for the three acquisitions of $F_{pull,max}$, for all hands and across all the objects and taxonomies tested.

By comparing the SR of the two versions of Limbitless, it seems to be clear that an opposed thumb helps with grasping bigger diameters. On the contrary, Limbitless-0 got better results with cylinders of the sizes S and M.

4. Discussion

The present research focused on affordable prosthetic devices, mainly devoted to amputees with basic needs to be covered first in low-resource sceneries. User expectations are subjective and the ultimate usefulness of a hand depend on various factors that can compensate each other without making clear their particular relevance. This poses the need to be pragmatic when considering the set of tests for a possible benchmarking. The ultimate interest is to discern practical information for the designers regarding the utility of these kinds of devices.

The SHAP is a well-known protocol, simple, replicable, and assumes the evaluation of the global performance by focusing on the achievement of a set of tasks. However, the SHAP and its primary focalization onto certain patterns of prehension (*spherical*, *power*, *tip*, *tripod*, *lateral*, and *extension*) may be criticized. SHAP protocol deals firstly with abstract objects aiming to enforce the aforementioned patterns of prehension. However, the correctness of the pattern is not observed in the SHAP score but only the *time-to-accomplishment*. It is also important to note that various tasks, from both sections of the procedure, contribute to the final scores for each prehension with either Light's [10] or Burgerhof's [24] method (all tasks in case of calculating any of the global IoF or LIF). This mixture to score each pattern of prehension seems unsustainable in terms of both their *veracity* and *relevance* to the user. Schweitzer [56] documented some profound reflections on the inadequate *relevance* of the tasks proposed as ADL (e.g. L*ifting a Tray*, R*otate a Key*, or *Door Handle*, deviate from the logic of a prosthetic wearer). Regarding their *veracity*, the evaluation on the

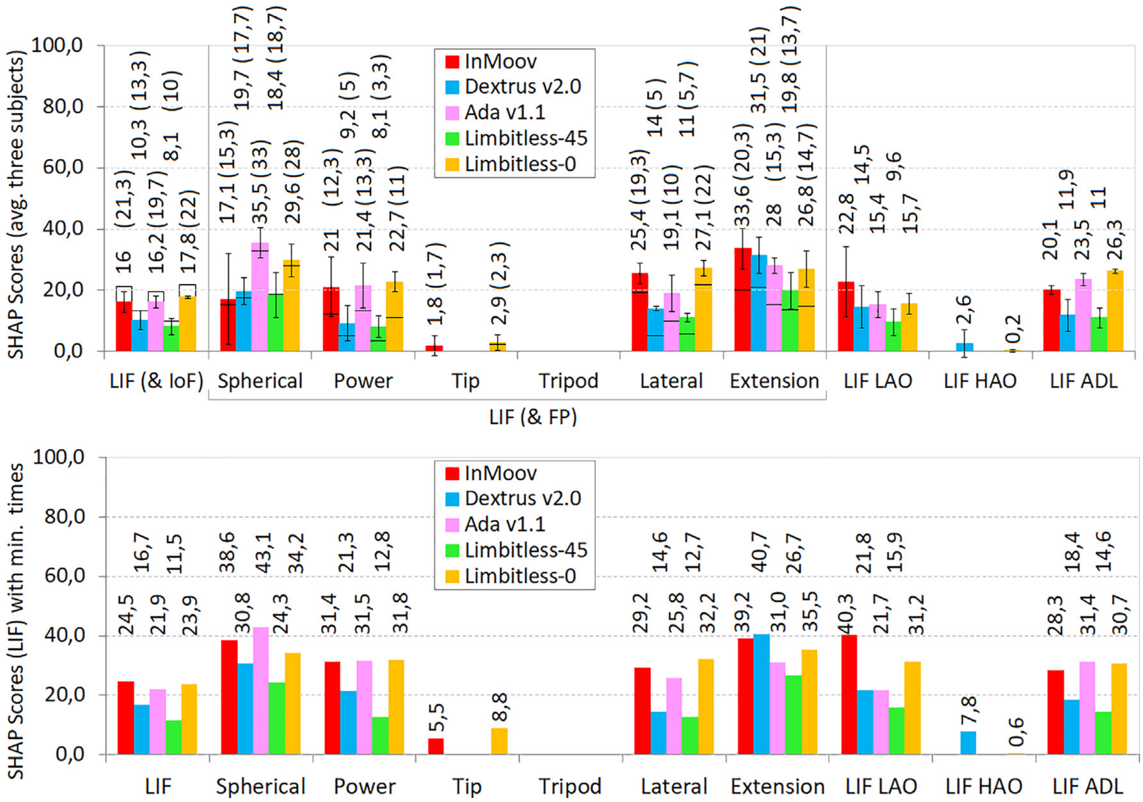

Fig. 6. Above, SHAP mean scores and standard deviation amongst the three users, using Burgerhof's LIF [24]. The mean scores using Light's IoF and FPs [10] are indicated with horizontal lines over the corresponding bars (value in brackets). Below, LIF for the best-case scenario (i.e. minimum time) registered across the three subjects. LIF LAO, LIF HAO, and LIF ADL are also depicted.

Table 3
AMAP in each of the phalanges of the index finger and the thumb.

Prosthesis	LIF_{LAO}	Index phalanges			Thumb phalanges		
		Prox.	Mid.	Dist.	Metac.	Prox.	Dist.
InMoov	22.8	0.46	0.64	0.98	0.56	0.51	0.94
Limbitless-0	15.7	0.53	0.8	1.21	N/A	0.64	0.91
Ada v1.1	15.4	0.60	0.63	N/A	0.55	0.14	N/A
Dextrus v2.0	14.5	0.42	1.03	0.62	0.64	0.50	0.48
Limbitless-45	9.6	0.63	0.98	1.16	N/A	0.64	1.15

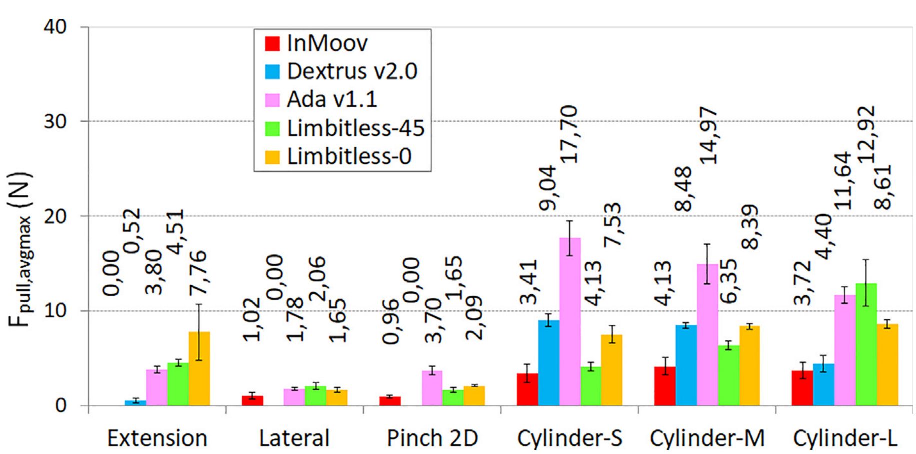

Fig. 7. Mean maximum pull force and standard deviation, supported by each hand across four intended taxonomies on the set of objects used.

basis of *time-to-accomplishment* finds a ground in the fact that the success of a prosthetic device may be more related to what each individual considers to be a useful grasp or supportive device to get the task done than to a precise pattern of prehension [57,58]. On the whole, given the pliancy to score by simply achieving the task (even with a non-conventional grasp), the specific scores for patterns devoted to using the whole set of fingers (*spherical*, *power*, and *extension*) and for the *lateral* grasp were greater than those for the precision grasps (*tripod* and *tip*). It indicates the greater service of these affordable devices to simply manipulate larger objects.

At first glance, the results of the SHAP for the hands tested may seem discouraging. InMoov, Limbitless-0, and Ada got the best global scores. However, their scores are far from those documented for commercial DMC (IoF of 74) and i-Limb (IoF of 52) hands [15]. Overall, SHAP results seem to point out that these kinds of affordable prosthetic devices are not still prepared to deal with small objects. Regarding the bigger objects (requiring *spherical*, *power*, or even *lateral* grasps), these hands perform better but the scored times and the observed grasp patterns encourage us to think of them as an assistant for the healthy hand.

The benchmarks for evaluating the *functionality* should consider focusing on the success or failure of the tasks to be performed. It should be noted that all hands managed to perform the part of the SHAP with LAO. With the aim of having a set of replicable trials providing useful information, this part of the SHAP, *LAO-relocations* for the sake of brevity, could be proposed as part of a benchmarking to evaluate the performance since:

- *LAO-relocations* contemplate a wide range of grasps and, without loss of generality, abstract shapes and volumes are representative of many of the objects handled in ADL. It may be representative of what is expected for an assistive device.
- The results are not influenced by the excessive weight or different friction coefficients of the surfaces of the objects. They merely observe the ability to handle those basic shapes.
- The scoring differences between hands are sufficient to discern the best performance of one or another.
- The duration of the procedure is considerably reduced.
- The shapes and weights are easily replicable, with little investment in materials (less than $100, much less than the budget to buy the entire SHAP [53]).
- *LAO-relocations* involve very short distances that can be set at 35 mm for the plate, tripod, and extension objects, and 80 mm for the spherical, power, and lateral objects. It avoids problems related to the manipulability allowed by the geometry of the ABA and the lack of wrist, and simply focuses on the performance of the palm and the digits.
- The results are not in confrontation with either the global IoF or LIF previously exposed.

It should be noted the great sensitivity of SHAP to the effects of the design on the final performance: it is demonstrated with the results of the two versions of the Limbitless hand, where thumb placement was critical to performance measured as it influences the manipulability with objects of different sizes.

Besides the *LAO-relocations* suggested, and regarding more analytical ways to explore the closure force and the grip of the hands, two more tests have been proposed: the *evaluation of the MA* of the phalanges of the index finger and the thumb, and the *evaluation of the SR*. The slippage is directly affected by the MA as the friction forces are proportional to the contact forces between the hand and the object. Better performance is expected if both characteristics are improved.

Regarding the *evaluation of the SR*, the use of cylinders has been the prominent choice in the literature [26,28,55,59] possibly because (i) it is one of the most required basic grasps [60], (ii) it is one of the basic grasps easily learned by users of prostheses, or the only option in BP hands with all fingers bending together, (iii) cylinders avoid peculiar problems such as the lack of contact with thin plates (see Fig. 8), (iv) cylindrical shapes guarantee a straightforward slippage without being blocked by the fingers, as it would occur with other shapes, e.g. with the plate, (v) cylindrical objects are easy for parameterization, aiming for more complex metrics [61]. It should be noted that there is no consensus on the object size. Recommendations from the NIST [55] comprehend 25.4 mm, 50.8 mm, 76.2 mm, and 101.6 mm in diameter, standard values for PVC pipes in the Imperial and US customary measurement systems. For the scope of having a criterion to perform a benchmarking, the three diameters here considered are close to those (M and L, i.e. 32 and 50 mm standard PVC pipes in the metric system) and are common values of many small objects and handles used in ADL. 50 mm is also the diameter of the cylindrical LAO. One smaller diameter (S, 22 mm, common broom handle) has been included. Bigger diameters have been discarded as they are not common in assistive tasks to the healthy hand. The use of a plate for benchmarking is to be avoided since it does not meet points (iii) and (iv) of the above-mentioned.

Concerning the *evaluation of the MA*, it is remarkable that some other tests found in literature measuring the force transmission from the actuator did not take thumb into account. They only studied one finger in the extended posture [33,62,63]. The thumb is particularly important as it represents up to 40% of all human hand functionality [64,65]. As for the *evaluation of the SR*, a pulling force of 20 N proved to be sufficient.

It is interesting to seek a relationship between the *LAO-relocations* results and those of the SR and MA evaluations:

- The evaluation of the SR with cylinders revealed Ada as the model with the best properties, probably due to its rubberized material. Remarkably, both rubberized models (Ada and Dextrus) offered greater SR with the narrower cylinders (cylinders S and M), possibly due to the existence of a larger number of contact points, although the early flexion of the DIP joints of the Dextrus made it difficult the grasp of the biggest cylinder. In general, there is no correlation between the *LAO-relocations* and the SR results across the different hands, meaning that both tests give complementary information. In fact, after getting the best *LAO-relocations* results, InMoov gave the worst scores in the SR evaluation, denoting that contact is to be improved.
- Regarding the evaluation of the MA, the most outstanding outcome is the great influence of the shape of the whole hand on its capability. For example, after ranking the hands by their LIF_{LAO} scores (see Table 3), both Limbitless versions ranked very differently while having AMAP values of the same order, which were not the smallest. Ada was in the middle of Table 3, having the lowest AMAP at both the middle phalanx of the index and the proximal phalanx of the thumb. However, its rubberized surface and the rigidity of the DIP joint may have helped to succeed in some grasps. It should be noted that (i) generally the better AMAP was found in the distal phalanx, possibly due to the short distance between the contact point and the joint, and (ii) as for the evaluation of the SR, there was no direct correlation between *LAO-relocations* scores and AMAP values. Designers should think about improving MA as a goal to boost the performance of a prosthetic hand with the HAO tasks, after having a geometry enabling the basic LAO tasks.

To end the discussion, we may think of some possible improvements for the InMoov, Ada, and Limbitless-0 hands, which got the best functionality scores. The InMoov hand may benefit from using rubberized material at the palm side so that it would rank better in the SR test. The Ada hand would benefit from improved force

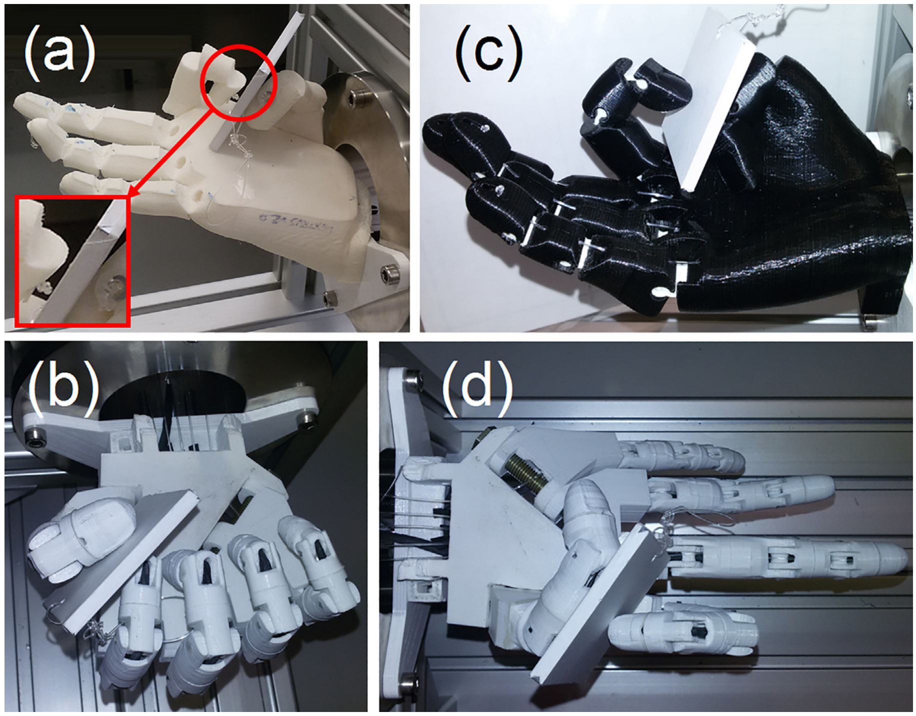

Fig. 8. (a) Dextrus could not make contact with the plate in the precision pinch nor the lateral grasp; (b) InMoov could not oppose the thumb against all fingers for an extension grasp; (c, d) Some other grasps with the plate were done against the dorsum of the thumb.

transmission through the tendon. Reducing internal friction by embedding a rigid cannula in each phalange could be a cheap and affordable solution. A possible improvement for the Limbitless-0 and Limbitless-45 hands would be the addition of a degree of freedom for abduction of the thumb allowing a switch between both configurations, which gave complementary results in the SR test.

5. Conclusion

The comparison of some of the trending affordable prostheses confirms that current mechanical designs are very limited in their functional ranges. Actually, they may be thought of as a supplemental elective tool to particular activities, without assessing the grasp correctness. In this sense, bringing the results related to certain grasp patterns could be left on a second plane.

However, this increasing tendency of printing affordable devices is unstoppable and needs for simple and replicable tests to guide the paths chosen by designers. The tests here proposed adopt procedures from the *Rehabilitation* and the *Robotics* in order to evaluate three decisive factors affecting the quality of a grasp: the closure force, the anti-slippage properties, and the functionality.

For the functionality, it is assumed a reduced part of the SHAP, that one with LAO, as it can provide valuable insight into the usability and limitations in many different tasks or even ADL. Also, a simple and open scoring formulation has been proposed. Together with the evaluation of the mechanical advantage of the index finger and the thumb, and the evaluation of the slip resistance with cylinders as described, they represent a replicable benchmark to evaluate key factors affecting the performance of a prosthetic hand. Such a benchmarking would provide a realistic point of view to stakeholders: designers, regulatory authorities, and users.

From amongst the hands evaluated in this research, the InMoov and Limbitless-0 models can be considered the most functional, followed closely by the Ada hand. The evaluation of the mechanical advantage of the index finger and the thumb showed alike results for the proximal joints, yet the closure force is to be optimized for the furthest phalanges of the Dextrus (distal one) and the Ada (noting that Ada has the medial and distal phalanges fused). The evaluation of the slip resistance showed the importance of the rubberized material for the contact areas of the hand, with the Ada hand getting the best results. It also showed the ultimate importance of the thumb geometry as the results between the Limbitless-45 and Limbitless-0 changed with the diameter of the cylinder: the Limbitless-45 hand, with greater adduction of the thumb, better grasped the cylinder of the size L.

Supplemental online material

The 3D shapes of the abstract objects proposed for the benchmarking of affordable prosthetic hands are openly available at https://doi.org/10.5281/zenodo.4059311. The CAD file of the test-bench assembly used in this research is openly available for its replication or adaptation at https://doi.org/10.5281/zenodo.4718017.

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.

Acknowledgements

This work was supported by the Spanish MINECO, AEI, and ERDF under Grant DPI2017-89910-R; the Generalitat Valenciana under Grant GV/2018/125; and the Universitat Jaume I under Grant UJI-B2017-70. The authors would like to thank prof. J. Fuentes-Ballesteros for his contribution to 3D printing and assembly.

References

[1] B. Phillips, G. Zingalis, S. Ritter, K. Mehta, A review of current upper-limb prostheses for resource constrained settings, Proc. 5th IEEE Glob. Humanit. Technol. Conf. GHTC 2015. (2015) 52–58. https://doi.org/10.1109/GHTC.2015.7343954.

[2] J. ten Kate, G. Smit, P. Breedveld, 3D-printed upper limb prostheses: a review, Disabil. Rehabil. Assist. Technol. 12 (3) (2017) 300–314, https://doi.org/10.1080/17483107.2016.1253117.

[3] R. Elmansy, Designing the 3D-printed prosthetic hand, Des. Manag. Rev. 26 (2015) 24–31, https://doi.org/10.1111/drev.10311.

[4] J. Gibbard, Open Hand Project, (n.d.). www.openhandproject.org (accessed 20 July 2019).

[5] J. Gibbard, Openbionics, (n.d.). https://www.openbionics.com (accessed 1 July 2019).

[6] e-NABLE, (n.d.). http://enablingthefuture.org/which-design/ (accessed 1 August 2019).

[7] K. Asanuma, Definition of the Terms 'Medical Device' and 'In Vitro Diagnostic (IVD) Medical Device', 2012. https://doi.org/GHTF/SG1/N071:2012.

[8] M.B. Burn, A. Ta, G.R. Gogola, Three-dimensional printing of prosthetic hands for children, J. Hand Surg. (ISSN 0363-5023). 41 (2016) e103–e109. https://doi.org/10.1016/j.jhsa.2016.02.008.

[9] K.S. Tanaka, N. Lightdale-Miric, Advances in 3D-printed pediatric prostheses for upper extremity differences, J. Bone Jt. Surg. 98 (15) (2016) 1320–1326, https://doi.org/10.2106/JBJS.15.01212.

[10] C.M. Light, P.H. Chappell, P.J. Kyberd, Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity, Arch. Phys. Med. Rehabil. 83 (6) (2002) 776–783, https://doi.org/10.1053/apmr.2002.32737.

[11] C. Dally, D. Johnson, M. Canon, S. Ritter, K. Mehta, Characteristics of a 3D-printed prosthetic hand for use in developing countries, in: Proc. 5th IEEE Glob. Humanit. Technol. Conf. GHTC 2015, 2015: pp. 66–70. https://doi.org/10.1109/GHTC.2015.7343956.

[12] B. Phillips, S. Ritter, K. Mehta, Printed prostheses not yet ready for developing countries, Mech. Eng. 138 (2016) 14–15. https://www.scopus.com/record/display.uri?eid=2-s2.0-85042066133&origin=inward&txGid=13011a5527375e400b739f7b2d5fe7e2.

[13] P.J. Kyberd, The influence of control format and hand design in single axis myoelectric hands: assessment of functionality of prosthetic hands using the Southampton Hand Assessment Procedure, Prosthet. Orthot. Int. 35 (2011) 285–293, https://doi.org/10.1177/0309364611418554.

[14] M. Yoshikawa, R. Sato, T. Higashihara, T. Ogasawara, N. Kawashima, Rehand: Realistic electric prosthetic hand created with a 3D printer, in: Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS, 2015: pp. 2470–2473. https://doi.org/10.1109/EMBC.2015.7318894.

[15] O. Van Der Niet Otr, H.A. Reinders-Messelink, R.M. Bongers, H. Bouwsema, C.K. Van Der Sluis, The i-LIMB hand and the DMC plus hand compared: a case report, Prosthet. Orthot. Int. 34 (2010) 216–220, https://doi.org/10.3109/03093641003767207.

[16] H. Bouwsema, P.J. Kyberd, W. Hill, C.K. van der Sluis, R.M. Bongers, Determining skill level in myoelectric prosthesis use with multiple outcome measures, J. Rehabil. Res. Dev. 49 (9) (2012) 1331, https://doi.org/10.1682/JRRD.2011.09.0179.

[17] E. Vasluian, R. Bongers, H. Reinders-Messelink, J. Burgerhof, P. Dijkstra, C. Sluis, Learning effects of repetitive administration of the southampton hand assessment procedure in novice prosthetic users, J. Rehabil. Med. 46 (8) (2014) 788–797, https://doi.org/10.2340/16501977-1827.

[18] H. Bouwsema, C.K. van der Sluis, R.M. Bongers, Changes in performance over time while learning to use a myoelectric prosthesis, J. Neuroeng. Rehabil. 11 (1) (2014) 16, https://doi.org/10.1186/1743-0003-11-16.

[19] A.L. Fougner, Ø. Stavdahl, P.J. Kyberd, System training and assessment in simultaneous proportional myoelectric prosthesis control, J. Neuroeng. Rehabil. 11 (1) (2014) 75, https://doi.org/10.1186/1743-0003-11-75.

[20] P.J. Kyberd, A. Murgia, M. Gasson, T. Tjerks, C. Metcalf, P.H. Chappell, K. Warwick, S.E.M. Lawson, T. Barnhill, Case studies to demonstrate the range of applications of the Southampton Hand Assessment Procedure, Br. J. Occup. Ther. 72 (5) (2009) 212–218, https://doi.org/10.1177/030802260907200506.

[21] M. Luchetti, A.G. Cutti, G. Verni, R. Sacchetti, N. Rossi, Impact of Michelangelo prosthetic hand: Findings from a crossover longitudinal study, J. Rehabil. Res. Dev. 52 (5) (2015) 605–618, https://doi.org/10.1682/JRRD.2014.11.0283.

[22] S.A. Dalley, D.A. Bennett, M. Goldfarb, Preliminary functional assessment of a multigrasp myoelectric prosthesis, in: 2012 Annu. Int. Conf. IEEE Eng. Med. Biol. Soc., IEEE, 2012: pp. 4172–4175. https://doi.org/10.1109/EMBC.2012.6346886.

[23] S.A. Dalley, D.A. Bennett, M. Goldfarb, Functional assessment of a Multigrasp Myoelectric prosthesis: An amputee case study, in: 2013 IEEE Int. Conf. Robot. Autom., IEEE, 2013: pp. 2640–2644. https://doi.org/10.1109/ICRA.2013.6630939.

[24] J.G.M. Burgerhof, E. Vasluian, P.U. Dijkstra, R.M. Bongers, C.K. van der Sluis, The Southampton Hand Assessment Procedure revisited: a transparent linear scoring system, applied to data of experienced prosthetic users, J. Hand Ther. 30 (1) (2017) 49–57, https://doi.org/10.1016/j.jht.2016.05.001.

[25] E. Vasluian, R.M. Bongers, H.A. Reinders-Messelink, P.U. Dijkstra, C.K. van der Sluis, Preliminary study of the Southampton Hand Assessment Procedure for Children and its reliability, BMC Musculoskelet. Disord. 15 (2014) 199, https://doi.org/10.1186/1471-2474-15-199.

[26] J. Falco, K. Van Wyk, S. Liu, S. Carpin, Grasping the performance, IEEE Robot. Autom. Mag. 22 (2015) 125–136, https://doi.org/10.1109/MRA.2015.2460891.

[27] R. Mio, M. Sánchez, Q. Valverde, Mechanical Testing Methods for Body-Powered Upper-Limb Prostheses, in: 18th IEEE Int. Conf. Bioinforma. Bioeng., 2018.

[28] J.T. Belter, M.T. Leddy, K.D. Gemmell, A.M. Dollar, Comparative clinical evaluation of the Yale Multigrasp Hand, in: 2016 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics, IEEE, Singapore, Singapore, 2016: pp. 528–535. https://doi.org/10.1109/BIOROB.2016.7523680.

[29] e-NABLE, E-NABLE prosthetic hand testing devices, (n.d.). http://buildinprogress.media.mit.edu/projects/2060/steps (accessed 4 October 2019).

[30] J.L. Segil, S.A. Huddle, R.F. ff. Weir, Functional assessment of a myoelectric postural controller and multi-functional prosthetic hand by persons with trans-radial limb loss, IEEE Trans. Neural Syst. Rehabil. Eng. 25 (6) (2017) 618–627, https://doi.org/10.1109/TNSRE.733310.1109/TNSRE.2016.2586846.

[31] L.H.B. Huinink, H. Bouwsema, D.H. Plettenburg, C.K. Van der Sluis, R.M. Bongers, Learning to use a body-powered prosthesis: changes in functionality and kinematics, J. Neuroeng. Rehabil. 13 (2016) 1–12, https://doi.org/10.1186/s12984-016-0197-7.

[32] I. Llop-Harillo, A. Pérez-González, J. Andrés-Esperanza, Grasping ability and motion synergies in affordable tendon-driven prosthetic hands controlled by able-bodied subjects, Front. Neurorobot. 14 (2020) 57, https://doi.org/10.3389/fnbot.2020.00057.

[33] N.E. Krausz, R.A.L. Rorrer, R.F.F. Weir, Design and fabrication of a six degree-of-freedom open source hand, IEEE Trans. Neural Syst. Rehabil. Eng. 24 (5) (2016) 562–572, https://doi.org/10.1109/TNSRE.733310.1109/TNSRE.2015.2440177.

[34] M. Stoppa, J.C. Mendes, Kinematic Modeling of a Multifingered Hand Prosthesis for Manipulation Tasks, in: Blucher Mathematical (Ed.), Congr. Nac. Mat. Apl. a Ind., 2014 Nov 18-21, Caldas Novas, 2014. https://doi.org/10.5151/mathpro-cnmai-0140.

[35] S. Patrick, DIY Prosthetic Hand & Forearm, (n.d.). http://www.instructables.com/id/Voice-Controlled-Prosthetic-Hand-Forearm/.

[36] LeelaKrishna, Mind Controlled Robotic Arm, (n.d.). http://www.instructables.com/id/Mind-Controlled-Robotic-Arm/ (accessed 1 September 2017).

[37] G. Langevin, Inmoov Hand and Forearm, (n.d.). http://inmoov.fr/hand-and-forarm/.

[38] N. Huchet, Bionicohand: Open Source Myohand, (n.d.). https://bionico.org/.

[39] P. Slade, A. Akhtar, M. Nguyen, T. Bretl, Tact : Design and Performance of an Open-Source , Affordable , Myoelectric Prosthetic Hand, in: IEEE Int. Conf. Robot. Autom., Washington, 2015: pp. 6451–6456. https://doi.org/10.1109/ICRA.2015.7140105.

[40] J. Gibbard, Open Hand Project: Downloads, (n.d.). http://www.openhandproject.org/downloads.php (accessed 1 September 2019).

[41] A.- 3ders.org, Wounded war hero gets a 3D printed Dextrus bionic hand, (2015). https://www.3ders.org/articles/20150411-wounded-war-hero-has-been-provided-with-a-3d-printed-dextrus-bionic-hand.html.

[42] J. Gibbard, Openbionics (downloads), (n.d.). https://www.openbionics.com/downloads/ (accessed 20 July 2019).

[43] S. Griffiths, The cheap robotic hand set to revolutionise prosthetics: 3D-printed device performs advanced tasks for a fraction of the cost, Dailymail (Mailonline) (2015). http://www.dailymail.co.uk/sciencetech/article-3211347/The-cheap-robotic-hand-set-revolutionise-prosthetics-3D-printed-device-performs-advanced-tasks-fraction-cost.html.

[44] Limbitless solutions, (n.d.). https://limbitless-solutions.org/ (accessed 1 June 2019).

[45] UCFArmory, Enablingthefuture, Limbitless arm, (n.d.). https://www.thingiverse.com/thing:408641.

[46] J. Owen, Limbitless Solutions Begin Clinical Trials For 3D Printed Arms, (n.d.). https://enablingthefuture.org/2018/05/30/limbitless-solutions-begin-clinical-trials-for-3d-printed-arms/ (accessed 30 July 2019).

[47] M. Controzzi, C. Cipriani, M. Carrozza, Design of Artificial Hands: A Review, in: R. Balasubramanian, V. Santos (Eds.), Hum. Hand as an Inspir. Robot Hand Dev., Springer, Cham, 2014: pp. 219–246. https://doi.org/10.1007/978-3-319-03017-3_11.

[48] C.L. Ventola, Medical Applications for 3D Printing: Current and Projected Uses, Pharm. Ther. 39 (2014) 704–711. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4189697/.

[49] F.J. Andrés, A. Pérez-González, C. Rubert, J. Fuentes, B. Sospedra, Comparison of grasping performance of tendon and linkage transmission systems in an electric-powered low-cost hand prosthesis, J. Mech. Robot. 11 (2018) 1–14, https://doi.org/10.1115/1.4040491.

[50] Steve Wood, The Flexy Hand and Flexy Hand 2, (2014). http://enablingthefuture.org/upper-limb-prosthetics/the-flexy-hand/ (accessed 20 November 2018).

[51] I. Llop-Harillo, A. Pérez-González, System for the experimental evaluation of anthropomorphic hands. Application to a new 3D-printed prosthetic hand prototype, Int. Biomech. 4 (2) (2017) 50–59, https://doi.org/10.1080/23335432.2017.1364666.

[52] García-Ortiz, Mora, Pérez-González, Cantero-Ramis, Plataforma automática de control de manos Antropomórficas y Robóticas, in: VIII Reun. Del Capítulo

Español La Soc. Eur. Biomecánica, Universitat Jaume I, Castellón de la Plana, 2018: pp. 83–84.

[53] C. Metcalf, Southampton hand assessment procedure (SHAP), (2017). http://www.shap.ecs.soton.ac.uk (accessed 22 October 2018).

[54] N. Kamakura, M. Matsuo, H. Ishii, F. Mitsuboshi, Y. Miura, Patterns of static prehension in normal hands, Am. J. Occup. Ther. Off. Publ. Am. Occup. Ther. Assoc. 34 (7) (1980) 437–445, https://doi.org/10.5014/ajot.34.7.437.

[55] NIST (National Institute of Standards and Technology), Grasping Performance Metrics and Test Methods, (2018). https://www.nist.gov/el/intelligent-systems-division-73500/robotic-grasping-and-manipulation-assembly/grasping.

[56] W. Schweitzer, Ripping through the Southampton Hand Assessment Procedure, (2014). https://www.swisswuff.ch/tech/?p=3043. (accessed 29 August 2019).

[57] I. Vujaklija, A.D. Roche, T. Hasenoehrl, A. Sturma, S. Amsuess, D. Farina, O.C. Aszmann, Translating research on myoelectric control into clinics—are the performance assessment methods adequate?, Front Neurorobot. 11 (2017), https://doi.org/10.3389/fnbot.2017.00007.

[58] A. Spiers, J. Cochran, L. Resnik, A. Dollar, Quantifying prosthetic and intact limb use in upper limb amputees via egocentric video: an unsupervised, at-home study, IEEE Trans. Med. Robot. Bionics. 3 (2) (2021) 463–484, https://doi.org/10.1109/TMRB10.1109/TMRB.2021.3072253.

[59] M. Controzzi, C. Cipriani, M.C. Carrozza, Miniaturized non-back-drivable mechanism for robotic applications, Mech. Mach. Theory 45 (10) (2010) 1395–1406, https://doi.org/10.1016/j.mechmachtheory.2010.05.008.

[60] M. Vergara, J.L. Sancho-Bru, V. Gracia-Ibáñez, A. Pérez-González, An introductory study of common grasps used by adults during performance of activities of daily living, J. Hand Ther. 27 (3) (2014) 225–234, https://doi.org/10.1016/j.jht.2014.04.002.

[61] G.A. Kragten, C. Meijneke, J.L. Herder, A proposal for benchmark tests for underactuated or compliant hands, Mech. Sci. 1 (2010) 13–18, https://doi.org/10.5194/ms-1-13-2010.

[62] J. Koprnicky, J. Šafka, M. Ackermann, Using of 3D printing technology in low cost prosthetics, Mater. Sci. Forum 919 (2018) 199–206, https://doi.org/10.4028/www.scientific.net/msf.919.199.

[63] S. Tenim, Design of an Affordable Anthropomorphic Mechanical Prosthetic Hand, University of Cape Town, South Africa, 2014. https://open.uct.ac.za/handle/11427/13280.

[64] J.T. Belter, A.M. Dollar, Performance characteristics of anthropomorphic prosthetic hands., in: IEEE Int. Conf. Rehabil. Robot., 2011: p. 5975476. https://doi.org/10.1109/ICORR.2011.5975476.

[65] M. Chalon, M. Grebenstein, T. Wimböck, G. Hirzinger, The thumb: Guidelines for a robotic design, IEEE/RSJ 2010 Int. Conf. Intell. Robot. Syst. IROS 2010 - Conf. Proc. (2010) 5886–5893. https://doi.org/10.1109/IROS.2010.5650454.