A Novel Skin-Stretch Haptic Device for Intuitive Control of Robotic Prostheses and Avatars

Nicoletta Colella, Matteo Bianchi, Giorgio Grioli, Antonio Bicchi, and Manuel G. Catalano

***Abstract*—Without proprioception, i.e., the intrinsic capability of a body to perceive its own limb position, completing daily life activities would require constant visual attention and it would be challenging or even impossible. This situation is similar to the one experienced after limb amputation and in robotic tele-operation, where the natural sensory-motor loop is broken. While some promising solutions based on skin stretch sensory substitution have been proposed to restore tactile properties in these conditions, there is still room for enhancing the intuitiveness of stimulus delivery and integration of haptic feedback devices within user's body. To contribute to this goal, here, we propose a wearable device based on skin stretch stimulation, the Stretch-Pro, which can provide proprioceptive information on artificial hand aperture. This system can be suitably integrated in a prosthetic socket or can be easily worn by a user controlling remote robots. The system can imitate the stretching of the skin that would naturally occur on the intact limb, when it is used to accomplish motor tasks. Two versions of the system are presented, with one and two actuators, respectively, which deliver the stretch stimulus in different ways. Experiments with able-bodied participants and a preliminary test with one prosthesis user are reported. Results suggest that Stretch-Pro could be a viable solution to convey proprioceptive cues to upper limb prosthesis users, opening promising perspectives for tele-robotics applications.**

***Index Terms*—Haptics and haptic interfaces, prosthetics and exoskeletons, human-centered robotics.**

Manuscript received September 10, 2018; accepted January 8, 2019. Date of publication January 30, 2019; date of current version February 19, 2019. This letter was recommended for publication by Associate Editor V. Levesque and Editor A. M. Okamura upon evaluation of the reviewers' comments. This work was supported in part by the European Union's Horizon 2020 Research and Innovation Programme under Grant 688857 (SoftPro). The content of this publication is the sole responsibility of the authors. The European Commission or its services cannot be held responsible for any use that may be made of the information it contains. This work was also supported in part by the Italian Ministry of Education and Research (MIUR) in the framework of the CrossLab project (Departments of Excellence). *(Corresponding author: Nicoletta Colella.)*

N. Colella is with the Centro di ricerca E. Piaggio, University of Pisa, 56122 Pisa, Italy (e-mail: nicoletta.colella@gmail.com).

M. Bianchi is with the Centro di ricerca E. Piaggio and the Information Engineering Department, University of Pisa, 56122 Pisa, Italy (e-mail: matteobianchi23@gmail.com).

G. Grioli and M. G. Catalano are with Soft Robotics for Human Cooperation and Rehabilitation, Fondazione Istituto Italiano di Tecnologia, 16163 Genova, Italy (e-mail: giorgio.grioli@gmail.com; manuel.catalano@iit.it).

A. Bicchi is with the Centro di ricerca E. Piaggio and the Information Engineering Department, University of Pisa, 56122, Pisa, Italy, and also with Soft Robotics for Human Cooperation and Rehabilitation, Fondazione Istituto Italiano di Tecnologia, 16163 Genova, Italy (e-mail: antonio.bicchi@unipi.it).

This letter has supplementary downloadable multimedia material available at http://ieeexplore.ieee.org provided by the authors. This includes a video, which shows how the skin stretch is induced on the user's forearm by the three modalities discussed in the letter: Stretch-Pro 1M, Stretch-Pro 2M SD, and Stretch-Pro 2M OD. This material is 4.0 MB in size.

Digital Object Identifier 10.1109/LRA.2019.2896484

Fig. 1. Picture shows the two envisioned applications of the Stretch Pro: Tele-operation of robot avatars (top panels) and prosthetics (bottom panel). Picture reported in the top-left panel shows the robot Walk-Man during a tele-operated activity in the Amatrice (Italy) village after an earthquake [10].

I. Introduction

The sense of touch is one of the fundamental sensory channels for humans to interact and explore the external environment [1]–[3]. The correct delivery of haptic information is crucial in many application fields such as prosthetics [4] and tele-robotics [5]. Indeed, in both these cases, the natural action-perception loop is hindered because of the limb loss, or the distance between the tele-operated robot and the human operator. It is hence not surprising that there is a clear demand in prosthesis users for an effective restoration of tactile perception [6], [7]. This *restoration* is of paramount importance in tele-robotics too, where the inclusion of haptic information (delivered according to the temporal constraints of the haptic loop [8]) was proven to be useful to increase transparency and immersiveness [9].

Recently, the development of wearable haptic systems (WHS) that can be easily worn at different body locations has opened promising scenarios for natural stimulus delivery in both prosthetics [4], and tele-robotics [11]. In the latter case the usage of wearable devices has also enabled to overcome classic stability issues that affect bilateral tele-operation, which are related to latencies in the communication channel between the master and the slave robot [11]. WHS can convey touch-related information on different object properties, relying on skin stimulation and sensory substitution [12]. For a complete review on these devices, see [2], [11].

Among the different types of haptic information, proprioception, i.e. the inner ability of a body to perceive its own position and movement, plays a crucial role to accomplish everyday life motor tasks, even the simplest ones. This is especially true if we consider hand motions and interactions with the external world. Indeed, humans can "perceive" hand location and grip aperture as well as finger motions, without the need of any visual cue. This information is then used to successfully perform grasping and manipulation tasks, with minimal cognitive burden [13]. This explains why prosthesis users are demanding prostheses that can be operated without constant visual attention [14]. An analogous issue affects the operators of robotic avatars. Indeed, as discussed in [10], the remote control of the opening/closing of a robotic hand in telemanipulation tasks is possible only by strongly relying on visual information. The latter which is prone to signal degradation and occlusions of the slave robot vision system. Under this regard, the inclusion of haptics could overcome these limitations and decrease users' cognitive effort arisen from constant visual attention.

As of today, the correct restoration of the somatosensory cues through wearable haptic devices still represents a challenge for haptics engineers, in terms of the intuitiveness of tactile stimulation. i.e. the correct association between artificial and natural tactile elicitation [15]. Focusing on grip aperture information delivery, classic WHS usually rely on vibrotactile feedback (e.g. [16]) and electrocutaneous stimulation [17]. Although the low cost and compactness of the electrodes would make electrocutaneous stimulation the ideal choice for this application, it has been shown that these stimuli may elicit a range of unpleasant sensations [18]. Furthermore, electrocutaneous devices usually provide worst performance if compared to vibrotactile stimulation [17]. However, not all the studies on vibrotactile feedback for proprioceptive cue delivery have reported positive results [19]. For these reasons, skin stretch has emerged as an alternative and promising approach for proprioceptive information restoration (see Sec. II), as e.g. in [20].

With this as motivation, we propose a new skin stretch modality system, which uses fixed actuated rollers that can move the user skin to induce unidirectional or "pinch" like stretch stimulation. This solution exhibits a layout with reduced dimensions and compact design. This will likely enable an easy and effective integration with the body of the user performing teleoperation tasks or within the prosthetic system. The proposed WHS is here preliminarily validated and tested in combination with an anthropomorphic, heavily under-actuated, artificial hand, the Pisa/IIT SoftHand, [21], and with its prosthetic counterpart [22]. Taking inspiration from [23], we implemented an intuitive mapping between the information collected on the robotic side (on the level of hand aperture) and its translation in terms of haptic feedback. The fully integrated system was tested with able bodied participants and with one prosthesis user. Experimental outcomes show excellent performance for a sphere discrimination task (90% accuracy with able bodied subjects, 85% with the prosthesis user). Positive comments on the device were expressed by all participants, who underwent a subjective quantitative evaluation.

This letter is organized as it follows. In Sec. II the principle of skin stretch modality is presented. The description of the design of the device and its characterization are reported in Secs. III and IV, respectively. Sec. V discusses the experimental tests performed with abled-bodied subjects, and one prosthesis user. Finally, conclusions are drawn in Sec. VI.

II. The Principle

Human proprioception is provided by a combination of sensors, such as muscle spindles, Golgi organs, and skin mechanoreceptors [24]. The latter have been proven to effectively contribute to the kinesthetic perception of fingers [25] and joints [26], eventually inducing the illusory idea of joint movements, after skin stimulation.

Previous works reported that the best direction to convey skin stretch stimuli in an informative way is along the main axis of the limb (i.e. longitudinal direction) [27]. In [23], authors presented the Hap-Pro, a wearable haptic device used to convey proprioceptive information on the level of aperture of a prosthetic hand actuated using only one degree of actuation. Hap-Pro uses a moving wheel on the user's forearm, which maps the encoder-measured hand aperture to the position of the wheel. A similar mapping was used in [28], where a wearable device was employed to elicit skin stretch through an eccentric rocker with frictional contact. Despite the good results obtained with these implementations, e.g. in [23] the Hap-Pro obtained a 76.7% overall accuracy for a sphere size discrimination task, there is still room for both in terms of achievable performance and system design. For instance, one of the main limitation of the Hap-Pro device is the need for a considerable space to allow the wheel to move along the user's arm, making its use problematic, especially in prosthetic. To overcome these limitations and achieve a lightweight and simple design – which is fundamental also in tele-robotics applications – in this work we investigate the use of two skin stretch strategies, to deliver information on the level of aperture of an artificial hand, namely *unidirectional skin stretch*, Fig. 2(a), and *"pinch" stretch*, Fig. 2(b). In the former strategy, the user's skin undergoes a unidirectional stimulation, while in the latter the user's skin is pinched.

To implement the two strategies, we follow a minimalist approach using a set of active rollers (see Sec. III for details), which are placed in continuous contact with the user's skin. Thanks to this approach, both stimulation strategies shown in Fig. 2 can be implemented, by simply changing the number of rollers and the way they are controlled. The *unidirectional skin stretch* strategy can be implemented, as depicted in Fig. 2(c), using one single active roller, here in after referred to as Stretch-Pro 1M [SP-1M]. The *"pinch" stretch* strategy can be implemented, as depicted in Fig. 2(d), with two active rollers, Stretch-Pro 2M [SP-2M]. These can be properly controlled to rotate in opposite direction, thereafter defined as Stretch-Pro 2M OD [SP-2M-OD].

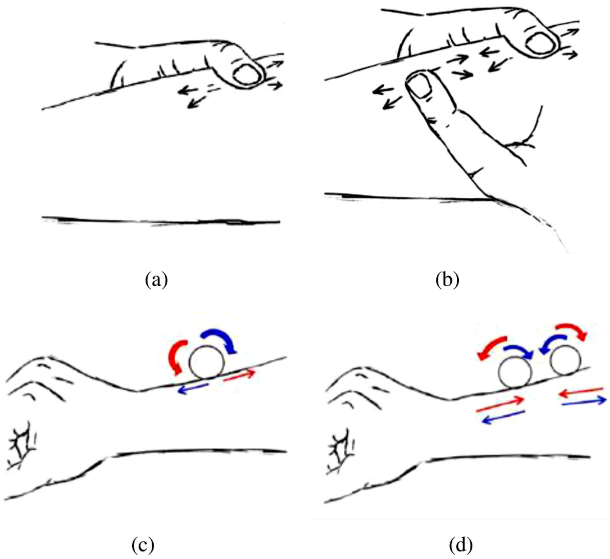


Fig. 2. (a) Representation of the *unidirectional skin stretch* strategy and its implementation with (c) one and (d) two active rollers (same rotation direction, SD). (b) Representation of the *"pinch" stretch* strategy, and its implementation with (d) two active rollers (opposite rotation direction, OD).

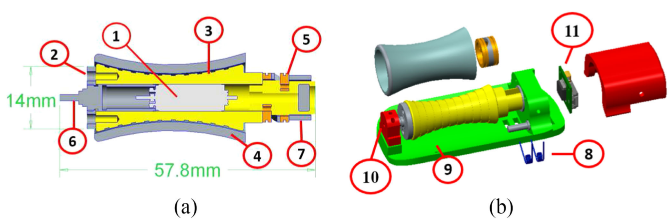


Fig. 3. (a) 2-D section of the active roller, and (b) 3-D CAD representation. The numbers indicate the components described in Section III.

It is worth to note that the latter configuration can also be used to implement the *unidirectional skin stretch* strategy, by simply controlling the rollers to rotate in a coherent mode (same direction of rotation), hereinafter referred to as Stretch-Pro 2M SD [SP-2M-SD]. This allows to multiply the skin stretch effect achievable with the Stretch-Pro 1M. The curved arrows in Fig. 2(c) and 2(d) illustrate the rotation commanded to the active rollers, while the straight arrows show the consequent stretch generated on the users skin.

III. Device Description

To obtain a modular system, reduce encumbrance and simplify the hardware/software complexity, we adopted a technological solution for the active rollers that can be used to implement the feedback strategies discussed in Sec. II.

To this aim, we developed an active roller with a gear motor, whose output shaft is attached to a fixed frame. In this manner, the stator acts as the active rotational part in contact with the user's skin. Fig. 3 shows the mechanical parts of the system. The main subassembly of the feedback device is the active roller depicted in Fig. 3(a). This is composed of a geared-motor[1](1), whose frame is connected to a rigid cylinder (3) through a rigid flange (2). The cylinder (3) has an external hyperboloid shape (min radius = 5.2 mm, max radius = 7.7 mm), which was chosen to conveniently fit with the shape of the arm. The hyperboloid surface is covered with a silicone[2] layer (4) to increase the friction between the skin and the device. The active roller is mounted on a frame (9), in Fig. 3(b). The motor shaft (6) is connected to (9), through the flange (10). The back side of the roller is connected to (9) through a bushing (7) to allow the roller to rotate and support the external load.[3] A magnetic encoder (11) (AS5045, by Austriamicrosystem) measures the motor frame rotation. With this architecture, the active roller can be controlled to rotate clockwise or counter-clockwise. It is worth noticing that the proposed design architecture was inspired by the technical solution adopted in [29]. However, the specific approach described above allows for a sensible reduction of the device dimensions and weight. Indeed, locking the output shaft (instead of locking the gear motor housing) enables to reduce the number of bearings and custom components needed. However this solution comes with the possible drawback that the motor wires can entangle when the cylinder rotates. To overcome this problem, we designed a customized power supply system with sliding contacts. This consists of two copper rings with a groove (5) integrated within the rotating cylinder (3), in contact with the two power supply wires of the gear motor so to keep electrical connector. Two torsional springs (8), with a stiffness of $k = 120.1834$ Nmm/°, are fixed to the frame (9) and placed in contact with the grooves of the copper rings (5). The springs are soldered to wires connected to the electronic board. In this manner, we ensure power supply to the motor, while avoiding wire entanglement.

The active roller system can be used to implement the two stimulation strategies described in Sec. II. Fig. 4, shows a tridimensional representation and the real implementation of the Stretch-Pro 1M, Figs. 4(a) and 4(c), and of the Stretch-Pro 2M (OD and SD), Figs. 4(b) and 4(d) respectively. In the SP-2M the distance between the motors was chosen as a trade-off between the space constraints and the requirements for enabling two-point discrimination on the forearm [30]. Two custom electronic boards ((14) and (15) in Fig. 4) based on a Cypress PSoC (Programmable System-on-Chip) micro-controller are used to control the system. The two boards present similar features but of controlling one or two active rollers, respectively. The design of the electronic boards is open source and more information can be found on the Natural Machine Motion Initiative website, and in [21].

The modularity of the design and the dimensions of the Stretch-Pro represent a clear advantage with respect to other analogous state of the art solutions, which makes it more easily wearable on the user's body and/or integrable within the prosthetic socket. Looking at the dimensions of both the Stretch-Pro 1 M, 70 × 32 × 18 mm, and Stretch-Pro 2 M, 73 × 68 ×

[1]Maxon RE 6 equipped with a gearbox GP6A (gear ratio of 221:1)

[2]To apply the silicone (biphasic, bio-compatible, C-MOL AK8) layer we designed an ABS hyperboloid mold, with a diameter 2 mm larger than the one of the hyperboloid. The polymerization occurred at room temperature.

[3]Most of the components are 3D printed in ABS, except for the parts used to fix the motor shaft, which are built in aluminium alloy.

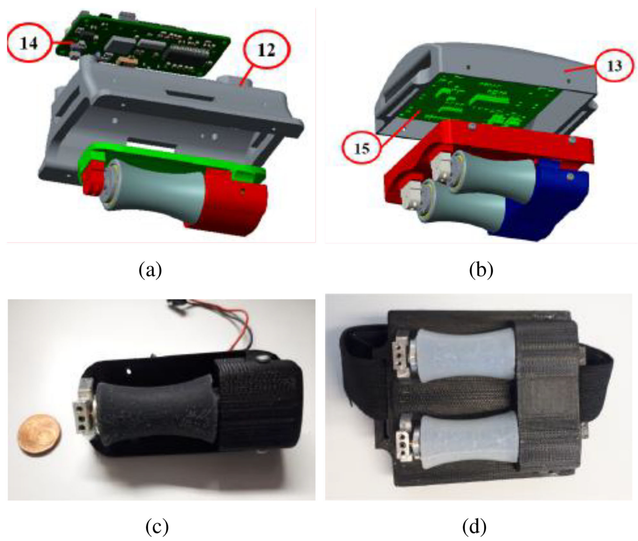


Fig. 4. Tridimensional CAD representation of the (a) Stretch-Pro 1M and (b) Stretch-Pro 2M. An ABS case is used to cover the active roller(s), and the electronic board [(12) and (13), respectively]. (c) Stretch-Pro 1M prototype, weight 80 g, and (d) Stretch-Pro 2M prototype, weight 103 g.

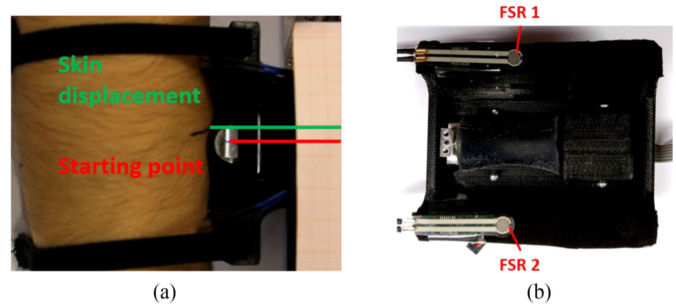


Fig. 5. Experimental setup adopted for the skin stretch characterization. (a) Configuration for the measurement of the skin displacement, the red line refers to the starting point of the marker, while the green line points to the position of the marker after the skin stretch elicitation; (b) placement of force sensors (FSR1 and FSR2).

26 mm, it is worth noticing that these are smaller if compared to the Hap-Pro in [23], 90 × 65 × 30 mm. The dimension of [28] are comparable to the Stretch-Pro 1M: however if we would like to duplicate its architecture to provide different tactile elicitations, the dimensions would significantly grow, as reported in [31].

IV. Device Characterization

Based on previous literature on delivery of hand proprioceptive information [23], [31], the Stretch-Pro system is intended to be placed on the user's arm, preferably on the forearm.

A. Skin Stretch Characterization

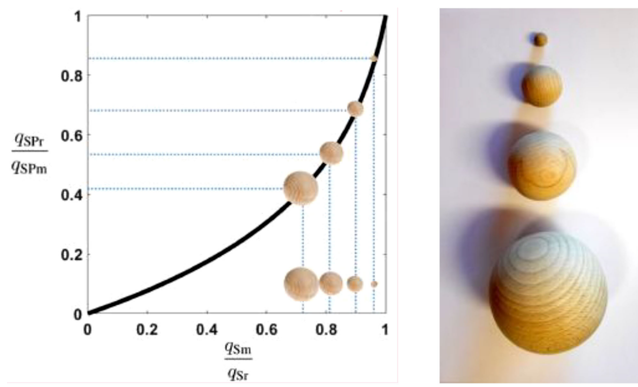
To identify the relationship between the active roller rotation and the maximum skin displacement induced on the user, we performed a first set of experiments. Six subjects took part in the experiment (2 female, 4 male, mean age 27). The displacement is related to the body mass index (BMI) of the users. For these reasons, we chose participants with a BMI within the average values of the standard biometric tables (range BMI = 20-24,9)[32]. The range of skin displacement was identified both when the active roller (mounted on a suitable case printed in ABS, see Fig. 5) was placed on the ventral and dorsal side of the user's forearm. To do that, we drew, on the user skin, a marker aligned with the motor axis, as in Fig. 5(a). The movements of the marker induced by skin stretch was recorded through a camera that was placed to avoid misalignments and parallax errors. Moreover, to double check the measure and correctly determine the amount of skin displacement, we placed the graph paper aligned with the device and close to the forearm. To ensure a reliable characterization, we chose to perform the experiment under controlled force condition. For this reason, we used two FSR (Force Sensing Resistors, by Interlink Electronics) placed on the face of the ABS structure in contact with the forearm (see Fig. 5(b)).[4] We commanded motor rotation with an increasing step of 10 degrees and identified the maximum skin displacement as the condition where the markers reached a steady condition, which is the point beyond which the roller starts to slip. During the characterization experiment we monitored that the range of forces applied on the skin was between 1.5 N and 2.5 N.[5] We chose these values of force since they are completely contained within the range of pleasant perceived stimulation (see [33]). Values of the skin displacement obtained prior to roller slip had a mean value of 4.5 mm, standard deviation 1.02, in the ventral case, and a mean value of 5 mm, standard deviation 1.41, in the dorsal positioning. We noted no significant statistical differences between the ventral and dorsal side, in terms of maximum skin stretch (Mann-Whitney $p > 0.05$). To be conservative, we chose a maximum skin displacement range of 4.5 mm.

B. Mapping

As briefly mentioned in Sec. I, to validate the system we connected the Stretch-Pro to the Pisa/IIT SoftHand, an underactuated and adaptable artificial hand, which was recently adapted for myoelectric prosthetic usage [22]. It was also used in tele-robotics tasks, still relying on surface electromyographic (sEMG) control [10], [29]. This hand was designed to move according to the most common pattern of grasping in humans, or first synergy, using a single motor and a suitable routing of the tendon, which constrains the movement of the fingers in a coordinated fashion. The information conveyed to the user through the Stretch-Pro motor control is proportional to the hand aperture read from the motor hand encoder. We chose a logarithmic mapping between the rotation of the Stretch-Pro motor(s) and the reading of the encoder of the SoftHand motor, capitalizing on previous results, [23], [28]. The mapping can be

[4] The sensor adopted in this test had a force sensitivity range of [0.1 - 10.0 N], with a continuous (analog) resolution.

[5] When the force is out of this range, a visual LED alarm is activated, and the experiment is stopped.



(a) (b)

Fig. 6. (a) Graphical representation of the logarithmic mapping between the normalized values of q_{Sm} and the normalized values of q_{SPr}. (b) Wooden spheres of different sizes adopted in the *size discrimination* task.

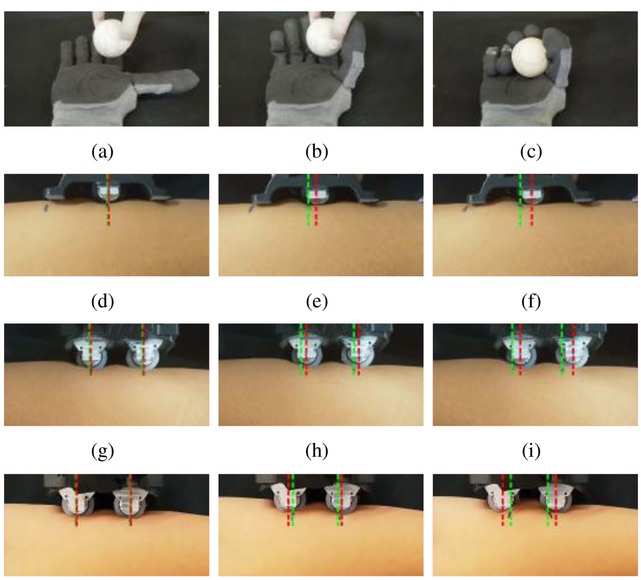
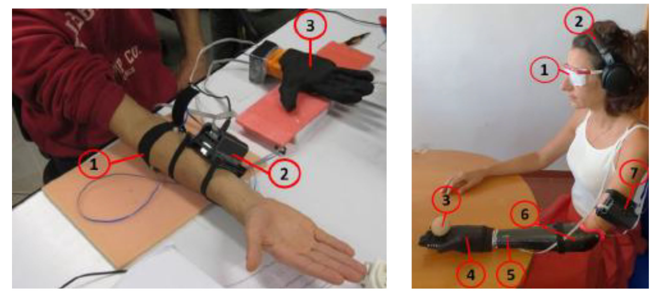


Fig. 7. (a)–(c) SoftHand grasping a sphere and the skin stretch induced on the user's forearm by the three modalities discussed in this work: (d)–(f) Stretch-Pro 1M; (g)–(i) Stretch-Pro 2M SD; and (j)–(l) Stretch-Pro 2M OD.

described as:

$$q_{\mathrm{SPr}} = b \quad \log\left(1 - a\frac{q_{\mathrm{Sm}}}{q_{\mathrm{Sr}}}\right) \quad q_{\mathrm{SPm}}, \tag{1}$$

where q_{SPr} is the commanded position of the active roller, q_{Sm} is the value measured by the hand motor encoder; q_{Sr} is the maximum value that can be acquired by the hand encoder, corresponding to the complete closure of the hand; q_{SPm} is the maximum value of the active roller encoder, found in the previous experiment, which corresponds to the maximum skin displacement allowed. a and b values are 0.9510 and -0.3317, respectively. Graphical representation of the logarithmic mapping is shown in Fig. 6(a). Fig. 7 shows how the proposed characterisation and mapping works. Figs. 7(a-c) show the Pisa/IIT SoftHand grasping a sphere, Figs. 7(d-l) show how the skin stretch is induced on the user's forearm by the three modalities



(a) (b)

Fig. 8. Experimental setup used with able bodied subjects: 1(a) sEMG sensors; 2(a) haptic device; and 3(a) Pisa/IIT SoftHand. Experimental setup used with the prosthesis user: 1(b) blackout glasses; 2(b) headphones; 3(b) sphere; 4(b) SoftHand Pro; 5(b) socket; 6(b) EMG sensor; 7(b) haptic device.

discussed in this work: Stretch-Pro 1M (d-f), Stretch-Pro 2M SD (g-i), Stretch-Pro 2M OD (j-l). The red dotted lines highlight the starting contact point of the motor(s), the green dotted line the induced skin displacement. Please refer to the attached video for further information.

V. Experimental Results

We designed and performed a set of experiments to compare the effectiveness of the stretch modalities proposed in this work. The final goal was to determine if these feedback modalities and the Stretch Pro device could be successfully employed in prosthetics and towards robotic tele-operation. We defined a protocol based on an object size discrimination task to evaluate quantitatively and objectively the system. Furthermore, we delivered the participants a questionnaire to collect subjective information. We performed the tests with able bodied subjects and with one prosthesis user.

1) Experimental Setup: We used a myoelectrically controlled version of the Pisa/IIT SoftHand [34] with able bodied subjects, Fig. 8(a), and the prosthetic release of the hand, SoftHand Pro [22], Fig. 8(b), with the prosthesis user. In both cases, two sEMG sensors were applied on the user forearm, one on the flexor digitorum superficial (FDS) muscle and one on the extensor digitorum communis (EDC) muscle. The signals from these two electrodes allow controlling the opening and closing of the robotic hand. Fig. 8(a) and Fig. 8(b) show the experimental setup used to perform the object pair recognition task with able bodied subjects, and with the prosthesis user. For able-bodied subjects the haptic feedback device was placed on the ventral side of the forearm - for its higher sensitivity [23], while for the prosthesis user on the upper arm. We chose this positioning to enable the user to use the inner socket, she usually wears in daily life.

2) Study Protocol: For the size discrimination test, we selected as experimental stimuli 4 wooden spheres S1, S2, S3, S4 diameter of (10 mm, 30 mm, 50 mm, 80 mm; see Fig. 6) and the total hand closure (identified as sphere 0). In each trial, we provided participants with two stimuli, sequentially, and we asked them to report which one was the larger, relying on the feedback provided by the Stretch-Pro. Each stimulus (i.e. sphere)

TABLE I
CORRECT ANSWERS % FOR 1M TEST OVER TEN SUBJECTS

Spheres	0	1	2	3	4
0	-	100%	100%	90%	80%
1	100%	-	60%	90%	100%
2	100%	70%	-	80%	100%
3	80%	100%	70%	-	100%
4	90%	100%	90%	90%	-

TABLE II
CORRECT ANSWERS % FOR 2M SD TEST OVER TEN SUBJECTS

Spheres	0	1	2	3	4
0	-	100%	100%	100%	90%
1	100%	-	60%	100%	100%
2	90%	80%	-	80%	100%
3	90%	90%	100%	-	100%
4	90%	100%	90%	100%	-

TABLE III
CORRECT ANSWERS % FOR 2M OD TEST OVER TEN SUBJECTS

Spheres	0	1	2	3	4
0	-	60%	70%	100%	100%
1	90%	-	60%	100%	100%
2	80%	50%	-	90%	100%
3	90%	80%	90%	-	90%
4	90%	100%	100%	100%	-

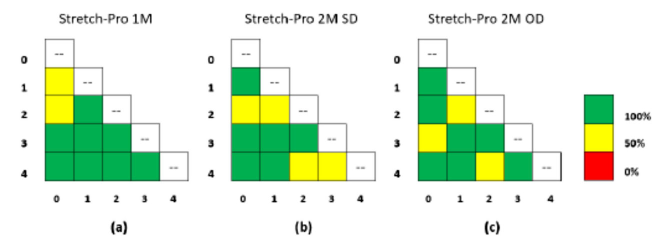


Fig. 9. Overall accuracy from the prosthesis user during the sphere-size discrimination task with the three devices: (a) SP-1M, (b) SP-2M-SD and (c) SP-2M-OD. Each square represents the overall accuracy obtained for a particular pair of spheres. As two trials are executed for each pair of spheres, the possible accuracy values are 0% (red), 50% (yellow) or 100% (green).

was positioned on the palm of the SoftHand and the subject had to voluntarily close the SoftHand to grasp it. Each pair was presented twice, i.e. the participants experienced both the couple (S1, S2) and (S2, S1). The test was performed using the Strecth-Pro 1M, Stretch-Pro 2M OD, Stretch-Pro 2M SD. All participants underwent through all three modalities, whose order in the experiment execution was randomized as the order of the experimental pairs presented to the subject. The experiment lasted roughly 100 minutes and consisted of two phases. During the training phase, which lasted approximately 35 minutes, the subjects learned how to use the SoftHand to grasp and manipulate objects of various sizes and became familiar with the feedback device. At the end of the experiment, subjects were asked to report their impressions about comfort, intuitiveness and usability of the devices through a Likert scale.

3) Participants: We tested both able bodied right-handed subjects (7 male and 3 female, mean age 27) and one prosthesis user (F, age 37 with agenesis of left forearm). The subjects were blindfolded and wore headphones with pink noise to cover any possible auditory cue produced by the actuators of the SoftHand and of the Stretch-Pro. The participants did not suffer from any cognitive impairment that could have affected their ability to follow the instructions of the study. The methods and procedures described in this letter were approved by the Ethical Committee of the University of Pisa and the volunteers signed an informed consent before participating. Subjects were allowed to take self-timed breaks and were encouraged to rest if they were experiencing fatigue, and to leave the experiment whenever they wanted.

A. Object Pair Recognition: Results With Able Bodied Users

In Tab. I, II and III we reported the results for the discrimination accuracies observed with all three versions of the device for each discrimination pair. The total overall accuracy was 89.5% with Stretch-Pro 1M, 93% with Stretch-Pro 2M SD and 87% with Stretch-Pro 2M OD. Results are comparable and even superior with respect to other state of the art proprioceptive devices: for istance, the Hap-Pro [23] obtains 76.7% overall accuracy for the same discrimination experiment. We performed a chi-squared non-parametric statistical test considering the relative frequency of succeeding trials between the three different versions. The contingency table of observed frequencies is associated with a p > 0.05, suggesting that there is no significant statistical difference between the two modalities and the three implementations.

B. Object Pair Recognition: Results With Prosthesis User

The results of the test with the prosthesis user are represented in the Fig. 9 for the three devices tested. Only a few errors were reported and the best performance was obtained with the Stretch-Pro 1M. In particular, the average accuracy is 90% with Stretch-Pro 1M (Fig. 9(a)), 80% Stretch-Pro 2M SD (Fig. 9(b)), while it is 85% with Stretch-Pro 2M OD (Fig. 9(c)). Of note, although the device was placed on the upper limb, which represents a placement different from the envisioned one, results are positive and further encourage us to push the integration of the system with the socket.

C. Subjective Quantitative Evaluation: Results

At the end of the experiments, the participants (both able-bodied and the prosthesis user) underwent through a subjective quantitative evaluation using a 7-point *Likert Scale*, with scores ranging from 1 (*totally disagree*) to 7 (*totally agree*). Participants had to answer questions concerning usability, intuitiveness, comfort, performance and experimental conditions. Results of the experiments with able-bodied participants are reported in Table IV, with the Confidence Interval 95% (C.I) and the Interquartile Range (IQR). The devices were all evaluated as easy to use with the SoftHand (Q1) and comfortable (Q2). The stimulation they provided was perceived as pleasant (Q3), intuitive and effective for task accomplishment. We performed a statistical analysis on the scores obtained in each question with the three devices, using the Wilcoxon signed rank test with

TABLE IV
QUESTIONS LIKERT SCALE RELATIVE TO ABLE BODIED USERS

	Questions	Median 1M	Median 2M SD	Median 2M OD	IQR 1M	IQR 2M SD	IQR 2M OD	CI m. 95% 1M	CI m. 95% 2M SD	CI m. 95% 2M OD	Median & IQR WF I
Q1	It has been easy to use the SoftHand together with the Stretch-Pro	6	6	6	0.75	0.75	2	(5.5,6.3)	(4.7,6.3)	(5.1,6.5)	/
Q2	I was feeling uncomfortable while using the SH together with the Stretch-Pro	2	2	2	0.75	1	1.75	(1.5,2.3)	(1.7,3.5)	(1.4,2.6)	/
Q3	The sensation provided by the Stretch-Pro on the forearm felt pleasant	5	5	5	1	2	1.75	(4.7,5.9)	(3.5,5.5)	(4.2,5.8)	/
Q4	I had the feeling of performing better when I was not receiving any feedback by the SP	1	1	1	0	0	0	(1.0,1.4)	(0.9,1.3)	(0.9,1.3)	/
Q5	When I was using the Stretch-Pro, I was able to tell how open the SoftHand was without looking at it	5.5	5.5	5.5	1.75	2.5	1	(4.1,5.9)	(4.4,6.2)	(4.2,6.1)	/
Q6	It was easy to feel the displacement/stretch of the skin induced by the Stretch-Pro	5.5	6	6	2	1.5	0	(4.9,6.5)	(5.5,6.5)	(5.3,6.4)	/
Q7	It was not easy to feel the displacement/stretch of the skin induced by the SP	1.5	1.5	2	1	1	1	(1.2,2.6)	(1.2,3.0)	(1.3,1.9)	/
Q8	It has been easy to discriminate the spheres using the Stretch-Pro	5.5	5.5	6	1	1	2	(4.8,6.2)	(4.9,6.1)	(4.1,6.1)	/
Q9	Discriminating the spheres without looking at them was very difficult using the SP	2.5	2.5	2	2	1.75	0.75	(1.6,3.2)	(1.7,2.9)	(1.4,3.2)	/
Q10 II	It has been easy to discriminate the spheres without any feedback (WF)	/	/	/	/	/	/	/	/	/	1 0
Q11 II	Discriminating the spheres w/o looking at them was difficult w/o any feedback (WF)	/	/	/	/	/	/	/	/	/	7 0

I WF stands for Without Feedback ;
II The symbol / means that this question does not apply to the without feedback condition;

TABLE V
QUESTIONS LIKERT SCALE RELATIVE TO PROSTHESIS USER

	Questions	1M	2M SD	2M OD	WF I
Q1	It has been easy to use the SoftHand together with the Stretch-Pro	3	4	5	/
Q2	I was feeling uncomfortable while using the SoftHand together with the Stretch-Pro	3	2	1	/
Q3	The sensation provided by the Stretch-Pro on the forearm felt pleasant	6	5	4	/
Q4	I had the feeling of performing better when I was not receiving any feedback by the Stretch-Pro	3	3	3	/
Q5	When I was using the SP, I was able to tell how open the SoftHand was without looking at it	1	1	1	/
Q6	It was easy to feel the displacement/stretch of the skin induced by the Stretch-Pro	4	5	6	/
Q7	It was not easy to feel the displacement/stretch of the skin induced by the Stretch-Pro	4	3	2	/
Q8	It has been easy to discriminate the spheres using the Stretch-Pro	3	4	5	/
Q9	Discriminating the spheres without looking at them was very difficult using the Stretch-Pro	4	5	6	/
Q10 II	It has been easy to discriminate the spheres without any feedback (WF)	/	/	/	1
Q11 II	Discriminating the spheres without looking at them was very difficult without any feedback (WF)	/	/	/	7

I WF stands for Without Feedback ;
II The symbol / means that this question does not apply to the without feedback condition;

Bonferroni post-hoc correction for each pair of conditions. Results show that there is no statistical significant difference between the devices, except for (Q5) where the Stretch-Pro 2M OD was evaluated as more effective than Stretch-Pro 1M for task accomplishment, $p = 0.02$. This pushes us to investigate the opposite motor control configuration as a viable solution for proprioceptive feedback. These outcomes were also confirmed in the prosthesis user's answers (see Table V), where a clear trend in favour of Stretch-Pro 2M OD is observable, despite the fact that the comfort, intuitiveness and effectiveness of all three versions were perceived as good, in a comparable fashion. Pleasantness of the stimuli, although positive, could be further improved e.g. trying different mapping or re-scaling the workspace for skin displacement.

VI. CONCLUSIONS

In this letter, we presented the design, development and testing of a novel wearable device, the Stretch-Pro, which can provide proprioceptive information on artificial hand aperture through sensory substitution and, in particular, through longitudinal skin stretch stimulation. We described and tested three modalities and implementations of the system. The Stretch-Pro 1M and Stretch-Pro 2M SD capable of delivering a skin stretch along the direction of the main arm axis, and the Stretch-Pro 2M OD capable of simulating a pinch-stretch stimulation. We reported the characterization of the skin displacement induced on the users' forearm using the Stretch-Pro. We also discuss the performance obtained during object pair discrimination tasks using the three versions of the devices, with able bodied subjects and one prosthesis user. The experimental outcomes reveal that all three configurations present similar results in terms of discrimination accuracy. The accuracy is comparable with, or even better, with respect to some of the state of the art solutions. Furthermore, all devices were well received by users in terms of comfort, intuitiveness of usage and effectiveness for object discrimination, although there is a trend in favour of the Stretch-Pro 2M OD that will be investigated in future studies. Future works will aim at further increasing the usability of the device and evaluate it with more potential end-users, during the execution of activities that imply active movements of the user's arms. An in depth psychophysical characterization to compute Just Noticeable Difference will be performed. We will also move towards an effective integration of the Stretch-Pro within the prosthesis socket (thanks to the reduced layout of the system). Finally, we will test Stretch-Pro capabilities in increasing user's immersiveness and transparency in remote bilateral tele-operation. Applications to other fields such as entertainment and assistive robotics, e.g. blind people guidance, as well as other body location for stimulus delivery will be also investigated.

Acknowledgment

The authors would like to thank F. Barontini, A. Di Lallo, M. Poggiani, and S. Casini for their useful help in setting up the experiments.

References

[1] M. A. Heller, *The Psychology of Touch*. Hove, U.K.: Psychology Press, 2013.

[2] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics: The present and future of artificial touch sensation," *Annu. Rev. Control, Robot. Auton. Syst.*, vol. 1, no. 1, pp. 385–409, 2018. [Online]. Available: https://doi.org/10.1146/annurev-control-060117-105043

[3] G. Robles-De-La-Torre, "The importance of the sense of touch in virtual and real environments," *IEEE MultiMedia*, vol. 13, no. 3, pp. 24–30, Jul. 2006.

[4] C. Antfolk, M. D'Alonzo, B. Rosn, G. Lundborg, F. Sebelius, and C. Cipriani, "Sensory feedback in upper limb prosthetics," *Expert Rev. Med. Devices*, vol. 10, pp. 45–54, 2013.

[5] A. M. Okamura, "Methods for haptic feedback in teleoperated robot-assisted surgery," *Ind. Robot, Int. J.*, vol. 31, no. 6, pp. 499–508, 2004.

[6] E. A. Biddiss and T. T. Chau, "Upper limb prosthesis use and abandonment: A survey of the last 25 years," *Prosthetics Orthotics Int.*, vol. 31, no. 3, pp. 236–257, 2007.

[7] S. Lewis, M. F. Russold, H. Dietl, and E. Kaniusas, "User demands for sensory feedback in upper extremity prostheses," in *Proc. IEEE Int. Symp. Med. Meas. Appl.*, 2012, pp. 1–4.

[8] B. Hannaford and A. M. Okamura, *Haptics*. Berlin, Germany: Springer, 2008, pp. 719–739.

[9] W. McMahan *et al.*, "Tool contact acceleration feedback for telerobotic surgery," *IEEE Trans. Haptics*, vol. 4, no. 3, pp. 210–220, Jul./Sep. 2011.

[10] F. Negrello *et al.*, "Walk-man humanoid robot: Field experiments in a post-earthquake scenario," *IEEE Robot. Autom. Mag.*, vol. 25, no. 3, pp. 8–22, Sep. 2018.

[11] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 580–600, Oct. 2017.

[12] P. Bach-Y-Rita and C. Collins, "Sensory substitution and limb prosthesis," in *Proc. 3rd Int. Symp. Adv. External Control Human Extremities*, 1970, pp. 9–21.

[13] A. Blank, A. M. Okamura, and K. J. Kuchenbecker, "Identifying the role of proprioception in upper-limb prosthesis control: Studies on targeted motion," *ACM Trans. Appl. Perception*, vol. 7, no. 3, 2010, Art. no. 15.

[14] C. Pylatiuk, S. Schulz, and L. Döderlein, "Results of an internet survey of myoelectric prosthetic hand users," *Prosthetics Orthotics Int.*, vol. 31, no. 4, pp. 362–370, 2007.

[15] K. Kim and J. E. Colgate, "Haptic feedback enhances grip force control of sEMG-controlled prosthetic hands in targeted reinnervation amputees," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 20, no. 6, pp. 798–805, Nov. 2012.

[16] A. Ninu, S. Dosen, S. Muceli, F. Rattay, H. Dietl, and D. Farina, "Closed-loop control of grasping with a myoelectric hand prosthesis: Which are the relevant feedback variables for force control?," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 22, no. 5, pp. 1041–1052, Sep. 2014.

[17] H. J. Witteveen, E. A. Droog, J. S. Rietman, and P. H. Veltink, "Vibro- and electrotactile user feedback on hand opening for myoelectric forearm prostheses," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 8, pp. 2219–2226, Aug. 2012.

[18] K. A. Kaczmarek, J. G. Webster, P. Bach-y Rita, and W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 1, pp. 1–16, Jan. 1991.

[19] C. J. Hasson and J. Manczurowsky, "Effects of kinematic vibrotactile feedback on learning to control a virtual prosthetic arm," *J. Neuroeng. Rehabil.*, vol. 12, no. 1, 2015, Art. no. 31.

[20] K. Bark, J. Wheeler, P. Shull, J. Savall, and M. Cutkosky, "Rotational skin stretch feedback: A wearable haptic display for motion," *IEEE Trans. Haptics*, vol. 3, no. 3, pp. 166–176, Jul./Sep. 2010.

[21] C. D. Santina *et al.*, "The quest for natural machine motion: An open platform to fast-prototyping articulated soft robots," *IEEE Robot. Autom. Mag.*, vol. 24, no. 1, pp. 48–56, Mar. 2017.

[22] S. B. Godfrey *et al.*, "The softhand pro: Functional evaluation of a novel, flexible, and robust myoelectric prosthesis," *PLoS ONE*, vol. 13, no. 10, pp. 1–20, Oct. 2018. [Online]. Available: https://doi.org/10.1371/journal.pone.0205653

[23] M. Rossi, M. Bianchi, E. Battaglia, M. G. Catalano, and A. Bicchi, "Happro: A wearable haptic device for proprioceptive feedback," *IEEE Trans. Biomed. Eng.*, vol. 66, no. 1, pp. 138–149, Jan. 2019.

[24] D. I. McCloskey, "Kinesthetic sensibility," *Physiol. Rev.*, vol. 58, no. 4, pp. 763–820, 1978.

[25] B. B. Edin and N. Johansson, "Skin strain patterns provide kinaesthetic information to the human central nervous system," *J. Physiol.*, vol. 487, no. 1, pp. 243–251, 1995.

[26] D. F. Collins, K. M. Refshauge, G. Todd, and S. C. Gandevia, "Cutaneous receptors contribute to kinesthesia at the index finger, elbow, and knee," *J. Neurophysiol.*, vol. 94, no. 3, pp. 1699–1706, 2005.

[27] J. P. Clark, S. Y. Kim, and M. O'Malley, *The Rice Haptic Rocker: Comparing Longitudinal and Lateral Upper-Limb Skin Stretch Perception*. New York, NY, USA: Springer, 2018.

[28] E. Battaglia, J. P. Clark, M. Bianchi, M. G. Catalano, A. Bicchi, and M. K. O'Malley, "The rice haptic rocker: Skin stretch haptic feedback with the Pisa/IIT softhand," in *Proc. World Haptics Conf.*, 2017, pp. 7–12.

[29] S. Fani *et al.*, "Simplifying telerobotics: Wearability and teleimpedance improves human-robot interactions in teleoperation," *IEEE Robot. Autom. Mag.*, vol. 25, no. 1, pp. 77–88, Mar. 2018.

[30] J. Tong, O. Mao, and D. Goldreich, "Two-point orientation discrimination versus the traditional two-point test for tactile spatial acuity assessment," *Frontiers Human Neurosci.*, vol. 7, 2013, Art. no. 579.

[31] N. Dunkelberger *et al.*, "Improving perception accuracy with multi-sensory haptic cue delivery," in *Haptics: Science, Technology, and Applications*, D. Prattichizzo, H. Shinoda, H. Tan, E. Ruffaldi, A. Frisoli, Eds., Cham, Switzerland: Springer, 2018, pp. 289–301.

[32] F. Q. Nuttall, "Body mass index: Obesity, BMI, and health: A critical review," *Nutrition Today*, vol. 50, no. 3, pp. 117–128, 2015.

[33] M. Bianchi *et al.*, "On the role of affective properties in hedonic and discriminant haptic systems," *Int. J. Social Robot.*, pp. 1–9, 2016.

[34] A. Ajoudani, S. B. Godfrey, M. Catalano, G. Grioli, N. G. Tsagarakis, and A. Bicchi, "Teleimpedance control of a synergy-driven anthropomorphic hand," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Nov. 2013, pp. 1985–1991.