The Rice Haptic Rocker: skin stretch haptic feedback with the Pisa/IIT SoftHand

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Abstract— Myoelectric prostheses have seen increased application in clinical practice and research, due to their potential for good functionality and versatility. Yet, myoelectric prostheses still suffer from a lack of intuitive control and haptic feedback, which can frustrate users and lead to abandonment. To address this problem, we propose to convey proprioceptive information for a prosthetic hand with skin stretch using the Rice Haptic Rocker. This device was integrated with the myo-controlled version of Pisa/IIT SoftHand and a size discrimination test with 18 able bodied subjects was performed to evaluate the effectiveness of the proposed approach. Results show that the Rice Haptic Rocker can be successfully used to convey proprioceptive information. A Likert survey was also presented to the experiment participants, who evaluated the integrated setup as easy to use and effective in conveying proprioception.

I. INTRODUCTION

Restoring hand functionality in upper limb amputees is a very challenging task, with the high dexterity, versatility, sensitivity, and ease of use of a natural human hand being extremely difficult to reproduce in artificial hands. In the past, most artificial hands used in clinical practice were either purely cosmetic or body powered [1], with the actuation of the end effector realized typically through cables pulled by the shoulder. Body powered prostheses have the advantage of being simple and intrinsically able to partially convey haptic feedback to the user through the actuation; however they can also suffer from lack of comfort and smaller grip forces compared to healthy hands [2].

More recently, myoelectric prostheses, where the actuation obtained through motors is controlled by electro-myographic (EMG) signals generated by the user's muscles, are becoming increasingly popular. This approach has a high potential for better hand functionality, while also retaining a good cosmetic value, but is often difficult to control for the user [2], [3]. Moreover, when compared to body powered prostheses, myoelectric prostheses lack inherent haptic feedback, which is a highly desired feature amongst users [4]–[6] and has

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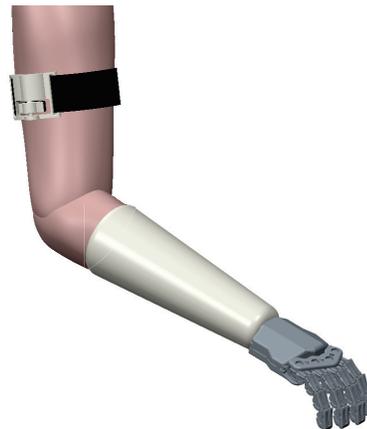
Fig. 1: Envisioned integration of the Rocker and the SoftHand.

been shown to increase embodiment of the prosthesis [7]. This critical absence can generate frustration for the user and cause abandonment of the prosthesis, which is still observed in many cases and represents a serious issue [8].

To address this deficiency, researchers have been trying to devise ways to convey haptic feedback to prosthetic users, with different methods being proposed, both invasive and non invasive [9]. Non-invasive solutions traditionally rely on sensory substitution techniques, with vibrotactile [10], electrotactile [11], force feedback [9], [12] and skin stretch [13] feedback being conveyed to the user by external devices. While different types of feedback devices are useful to convey information on different measurements, simultaneous display of different types of haptic information can also be confusing for the user [14]. For this reason it is important to focus on conveying information which is most important for task execution.

A common requirement from amputees is to be able to operate prostheses without constant visual attention [4], [15], and proprioceptive feedback has been shown to improve targeting accuracy under non-sighted conditions [16]. Because of this, in this work we choose to focus on proprioceptive feedback, and in particular on conveying it through skin stretch. In the following sections we will first describe the motivation and background behind our work, discussing some solutions that have been used in the past for proprioceptive feedback. We will then present the integration of a skin stretch haptic feedback device, the Rice Haptic Rocker, with a myo-controlled version of the Pisa/IIT SoftHand, an under-

actuated and adaptable artificial hand which has recently been adapted for prosthetic use [17]. Finally, an experimental evaluation will be presented where we test the effectiveness of the setup at conveying proprioceptive information on hand opening with able bodied subjects in a size discrimination task. The methods used for the evaluation procedure are inspired by [18]. It is worth noting that the main focus of this work is to show that the Rice Haptic Rocker is a valuable means for proprioceptive feedback, and that the effectiveness of the device has not been ever tested before in a systematic manner. This paper aims at bridging this gap presenting the device and discussing results from a set of experiments performed with able bodied subjects.

II. MOTIVATION AND BACKGROUND

From retrieving something out of a pocket to reaching to turn off an alarm clock, we encounter a multitude of tasks where we depend on our sense of proprioception. This natural mechanism is missing for myoelectric prosthetic users, who have to rely heavily on vision to know the pose of their artificial hand.

Previous work has shown that artificial introduction of proprioceptive feedback in artificial hands could be beneficial to the user. Blank et al. [16] found in a study with able-bodied subjects that proprioceptive feedback improves targeting accuracy in nonsighted and, for some tasks, also sighted conditions. More recently, in [19] an experiment was performed where participants controlled a cursor though EMG signals, with and without proprioceptive feedback, and results showed that proprioceptive feedback significantly improved myoelectric control in nonsighted conditions.

Proprioceptive feedback can be conveyed both in an invasive and non invasive fashion. Invasive approaches include Peripheral Nerve Stimulation (PNS), which uses neural electrodes to directly stimulate nerves, and can successfully deliver proprioceptive sensations [20] but is still challenging from a technological point of view [21], and its feasibility as a long term solution has yet to be proven [22]. A non-invasive option to relay proprioception is offered by sensory substitution by means of wearable haptic displays. Vibrotactile displays are the traditional approach, often evaluated in EMG control of virtual hands [23], and due to their small size and low cost of the actuators this type of feedback is often used as a baseline to evaluate other solutions [21]. However, not all of the studies conducted on vibrotactile as a feedback method for proprioception have shown promising results [24], and other solutions such as electrotactile feedback [11], [25] and skin stretch have been tested [26], [27].

III. DEVICES AND INTEGRATION

In this study we follow the skin stretch approach by focusing on a rocker design. Chinello et al. studied combining multiple rockers interacting in a bracelet about the forearm [28] to direct able bodied subjects in more complex wrist movements, but did not consider prosthetic applications. Our group has previously explored this mode of skin stretch mapped to a gripper aperture, [29]–[31], with prototype versions of a rocker design for providing feedback. Here,

(a) CAD model and parts. The offset d is used to apply pressure of the user's arm.

(b) Physical prototype on the upper arm of a subject.
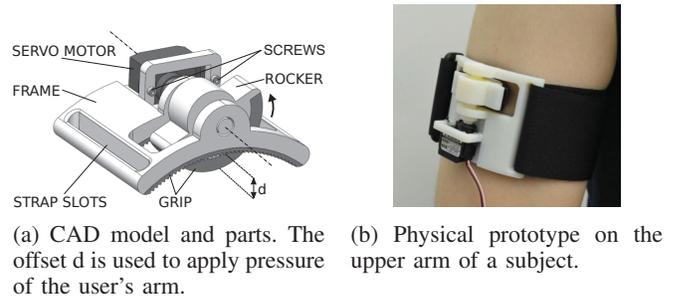
Fig. 2: The Rice Haptic Rocker.

we propose a refined rocker solution featuring a frictional interface, which can be used without adhering the contact interface to the skin, with some advantages compared to the adhesive elements used in other studies (e.g. [27]): namely, the frictional contact interface allows easier donning when integrated with a prosthetic socket, and the rocking motion provides an intuitive cue when mapped to the hand aperture. To the best of the authors' knowledge, this is the first paper to present a skin stretch rocking device to convey information on the opening of a prosthetic hand.

The Pisa/IIT Softhand was chosen to be used as a prosthetic hand, building upon previous work on its adaptation to myoelectric control [32], [33] and use with haptic feedback devices [32], [34]–[36]. Because of its adaptability and ease of control, and because the encoder reading from the motor can be used directly to control the Rice Haptic Rocker, integration of the two devices was natural and has the potential of being profitably used in prosthetics, as we will show in the following sections.

A. The Rocker

The Rice Haptic Rocker is a wearable device that uses the sense of touch in the upper arm as a surrogate for proprioception in the prosthetic hand grasp position. The Haptic Rocker has a simple design consisting of a frame, strap, rocker, and servo, as shown in Figure 2a, with a total weight of only 60 g. The frame, 3D printed on a Connex Objet 260, houses the rocker and servo, and is attached to the arm with a 2 inch Velcro strap. It has a curved bottom to rest comfortably on the arm, with a 3D printed rubber grip to keep it in place during use. The rocker has a radius of curvature of 20 mm with a 3/16 inch (5 mm) neoprene foam strip to avoid slipping and increase comfort.

The axis of rotation for the rocker is set so the contact point of the rocker has a 10 mm offset, d, from the bottom of the frame. This offset serves to create a normal force while reducing the tightness of the strap. The rocker is held in the frame by two shaft supports, and is driven by a digital servo (Futaba S3154), which is secured to the frame with 2 socket head screws and nuts (M1.6 x 0.35 mm). Figure 2b shows an image of the device on a subjects upper arm. The rocker rests in the neutral position shown in Figure 2b when the hand is completely open, and rotates up to 60 degrees when the hand is closed as shown in Figure 2a, stretching the skin as the rocker rotates (for a maximum displacement of about 10.5

mm). This maximum value of the angle is chosen to avoid slipping on the skin and is kept constant for all subjects.

B. The Pisa/IIT SoftHand

The Pisa/IIT Softhand design [37] takes inspiration from neuroscience. It is known that humans control their hands not merely by acting on each of the numerous degrees of freedom, but rather by coordinating and co-activating them in organized motions called synergies [38], [39]. In more recent work [40], *soft synergies* were introduced, where the synergy serves as a reference position for a virtual hand, and the interaction forces between the hand and a grasped object depend on the stiffness matrix connecting the virtual and real hand position.

The Pisa/IIT SoftHand combines compliance and synergy inspiration into an artificial hand with 19 DoFs, 4 on each of 4 fingers, and 3 on the thumb. The fingers are capable of flexion/extension as well as ab/adduction. Traditional revolute joints were employed for ab/adduction of the fingers and at the equivalent of the carpometacarpal joint of the thumb. The rest of the joints incorporate rolling contact joints with elastic ligaments, which ensure physiologically correct motions when actuated, but easily disengage on impact to allow safe interaction with humans without compromising the hand. The elastic ligaments also allow deformation while ensuring the hand returns to its original configuration. A single tendon runs though all joints to simultaneously flex and adduct the fingers upon actuation.

The hand is actuated by a single DC motor which moves the fingers on the path of the first synergy as described in [38]. However, due its compliant design, it can conform around a large variety of objects. The motor employed in the current release is a 15 Watt Maxon DCX 22S with a GPX22 (86:1) gearhead and a 12 bit magnetic encoder, resolution of $0.0875°$ (Austrian Microsystems). With this setup the hand has a maximum force of 130 N perpendicular to the palm. The CAD model of the Pisa/IIT SoftHand, as well as the design of the electronic board that is used to control it are open source and available at the Natural Machine Motion Initiative Website (http://www.naturalmachinemotioninitiative.com/).

C. Integration

Due to the simple design of the Rocker and synergistic actuation of the SoftHand, haptic feedback can be conveyed directly by mapping the encoder reading of the SoftHand to the commanded motor position of the servo. An Arduino Uno control board is used to actuate the servo motor, and integration with the SoftHand is done in Matlab through Simulink. The servo position is controlled between 0 and 60 degrees, with the flat side of the rocker being parallel to the upper face of the servo in the zero position.

Commanded angles for the servo are obtained by linearly mapping the hand encoder reading, which assumes values inside a certain range. These values were estimated from a preliminary test observing encoder readings during a series of ten close-open cycles of the hand from the resting open position (Figure 3).
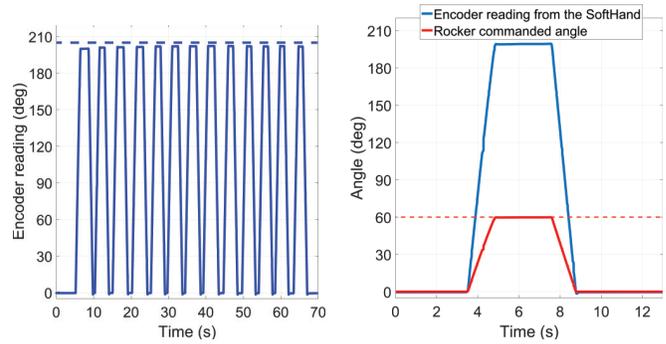
(a) Test with the SoftHand to evaluate encoder range.

(b) Rocker angle command for a single close-open cycle.

Fig. 3: Integration of the Rice Haptic Rocker with the Pisa/IIT SoftHand. The blue dashed line in Figure 3a is the estimated maximum threshold for the encoder reading ($205 \deg$), while the red dashed line in Figure 3b is the maximum commanded angle for the Rocker ($60 \deg$).

IV. EXPERIMENTAL PROTOCOL

Eighteen healthy subjects (age 22 ± 0.5 years, 6 female) took part in the experiment. Two subjects were left handed, while the remaining participants were right handed. The participants did not suffer from any physical or cognitive impairment, which could interfere with their ability to follow the instructions of the study, nor any pathology that could affect tactile sensibility or muscular activity of the forearm. The methods and procedures described in this paper were carried out in accordance with the recommendations of the Institutional Review Board of Rice University with written informed consent obtained from all subjects.

The experiment was designed to evaluate the effectiveness of the proprioceptive feedback provided by the Rocker when using the SoftHand for an object size discrimination task, and was inspired by the procedure presented in [18]. Subjects were seated comfortably in front of a table. The Rocker was fastened around the right upper arm with Velcro bands for 9 subjects under the Haptic Feedback (HF) condition, while the remaining nine in the No Haptick Feedback (NHF) condition did not wear the device. The two left handed subjects were randomly assigned to each group, and female and male participants were equally distributed. The SoftHand was secured to the right hand and forearm using a handle structure with Velcro bands, and the EMG electrodes were positioned on the Flexor Digitorum Superficialis (FDS) and on the Extensor Digitorum Communis (EDC) and held in place with medical tape [9]. Before the experiment began, subjects were guided through a calibration procedure for the EMG electrodes to ensure that each person could control the opening and closure of the hand easily [33]. Participants who were under the HF condition were also instructed through some preliminary training with the Rocker, which included closing the SoftHand to a certain posture, opening it and then taking it back to the previous closure with their eyes closed.

The experiment was divided in three phases, all taking place in the same session. First was a *training* phase, where
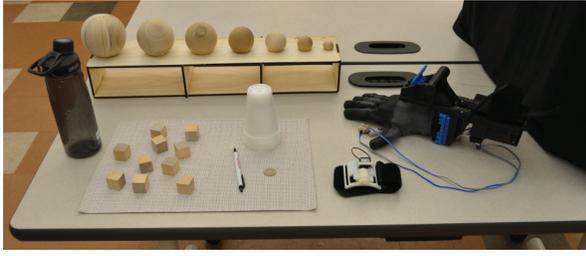
Fig. 4: From right to left: the SoftHand together with the EMG electrodes used to control it, the Rice Haptic Rocker and the objects used during the training session.

subjects learned how to use the SoftHand to interact with object of various sizes. In particular the subjects were asked to complete tasks such as building a pyramid with blocks, grasping a bottle as if they were drinking from it, grabbing a set of nested ridged cups with the SoftHand and removing them from the stack one by one using their left hand, picking up a pen and a coin from the table, and placing spheres of different sizes on a stand. An overview of the objects used in the experiment can be seen in Figure 4. Preliminary setup and training took on average about 35 minutes.

During the *testing* phase, which lasted on average around 20 minutes, the subjects wore noise canceling headphones, and their right arm, laying next to the SoftHand, was occluded from view by a black curtain. Pink noise was played through the headphones in order to cover possible auditory cues produced by the actuators of the SoftHand and the Rocker. Figure 5 shows the experimental setup. Subjects were presented ten different pairs of spheres and asked to tell whether the second sphere was bigger, smaller or of equal size with respect to the first sphere. Three spheres were used in this experiment with a diameter of 1.5, 2.5 and 3 inches (i.e. 38.1, 63.5 and 76.2 mm), as well as a fourth grasping condition where the hand was empty. To avoid artifacts in the results due to time error, each pair of spheres was presented two times, in opposite, for a total of twenty trials in random order. During each trial, the subject had to voluntarily close the SoftHand to grasp each sphere and, depending on their group assignment, relied on the feedback from the Rocker to infer the size of the sphere.
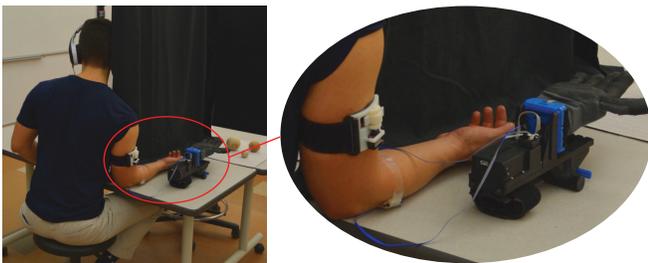
Fig. 5: Experimental setup for the object size discrimination task.

In the final *evaluation* phase, the participant took off the headphones and moved the SoftHand back to the other side of the curtain, where they had the possibility to use it for an

additional ten minutes in a reduced version of the training procedure (limited to building a pyramid with blocks and placing spheres on the stand). Members of the HF group had the Rocker taken off for this phase, while members of the the NHF group had it placed on their upper arm. At the end of the session, the subjects took off the devices and completed a Likert-type seven point survey. The questionnaire considered the comfort and usability of the proposed experimental setup (four questions), the perceived performance (eight questions), the experimental conditions (four questions) and the level of engagement of the subjects (two questions). To each question the subject had to answer by choosing a value between 1 ("strongly disagree") and 7 ("strongly agree"), with 4 as a neutral term corresponding to "undecided". The statements were presented in pairs where one had an opposite meaning with respect to the other to check consistency and prevent bias effects from the wording.

V. RESULTS

The experiment required subjects to discriminate between different sphere sizes. Proprioceptive haptic feedback was conveyed by the Rocker for the HF group, while subjects under the NHF condition served as the control group. Figure 6 shows discrimination accuracy for each subject, with blue bars showing the accuracy for subjects under the HF condition and red bars showing accuracy for subjects under the NHF condition. Subject 15, despite showing an unusually high accuracy for being under the NHF condition, reported being under sound experimental conditions, which lead us to treat this result as a statistical outlier. The average accuracy for subjects under the HF condition was $73.3 \pm 11.2\%$, well above the 33.33% $(1/3)$ chance level, while for subjects under the NHF condition it was $33.3 \pm 12.7\%$. Overall accuracy for each pair presented was also considered, with better results for the HF condition as shown in Figure 7.

Statistical analysis was performed to test for significance in the differences found. Normality of the data was tested with the Shapiro-Wilk test, from which the assumption of normality is met for Group I (p = .82). However, Group II had a significant result (p = .006) prompting us to utilize nonparametric statistical tests for further analysis. The Kruskal-Wallis test shows a highly significant difference in discrimination accuracy (p < .001) between the two groups. We can thus conclude that the Haptic Rocker enables the subject to detect a difference in objects size with better accuracy than chance.

Table I shows an overview of scores for the Likert scale survey. Results were analyzed with the Kruskal-Wallis test, comparing the HF and NHF groups. According to these results, the integration of SoftHand and Rocker was deemed easy to use (Q1), able to convey information on the opening of the hand (Q9,Q10) and improve performance overall (Q5,Q6). Participants under the HF condition seemed to find the object size discrimination task somewhat challenging, while subjects under the NHF condition found it understandably very difficult (Q7 - p = 0.051 close to significance, Q8 - p < 0.001), since they were not wearing the Rocker

	Questions	HF	NHF	p-value
Q1	It has been easy to use the SoftHand together with the Rocker.	5.00(5.00; 6.00)	6.00(5.00; 6.00)	0.647
Q2	I was feeling uncomfortable while using the SoftHand together with the Rocker.	2.00(2.00; 2.5)	2.00(1.00; 5.00)	0.85
Q3	The sensation provided by the Rocker on the arm felt pleasant.	4.00(3.00; 4.50)	5.00(3.50; 5.50)	0.111
Q4	The sensation provided by the Rocker on the arm felt unpleasant.	4.00(3.00; 4.50)	2.00(2.00; 4.50)	0.085
Q5	I had the feeling of performing better while receiving position feedback by the Rocker.	6.00(4.50; 6.50)	5.00(4.00; 6.50)	0.651
Q6	I had the feeling of performing better when I was not receiving any feedback by the Rocker.	3.00(1.50; 3.50)	3.00(1.00; 3.00)	0.645
Q7	It has been easy to discriminate the spheres.	**3.00(3.00; 5.00)**	**1.00(1.00; 2.50)**	**0.051**
Q8	Discriminating the spheres without looking at them was very difficult.	**3.00(3.00; 5.00)**	**7.00(7.00; 7.00)**	**< 0.001**
Q9	When I was using the Rocker, I was able to tell how open the SoftHand was without looking at it.	5.00(5.00; 6.00)	5.00(4.50; 5.50)	0.36
Q10	When I was using the Rocker, I had no clue about the opening of the SoftHand.	2.00(2.00; 3.00)	2.00(1.50; 2.00)	0.246
Q11	It was easy to feel the rotation of the Rocker.	**6.00(5.00; 7.00)**	**5.00(3.00; 5.00)**	**0.063**
Q12	It was not easy to feel the rotation of the Rocker.	**2.00(1.00; 3.00)**	**3.00(2.50; 5.00)**	**0.061**
Q13	During the discrimination task, I was not able to see the SoftHand, the Rocker or the spheres.	7.00(7.00; 7.00)	7.00(7.00; 7.00)	0.317
Q14	During the discrimination task, I was able to see the spheres or the devices.	1.00(1.00; 1.00)	1.00(1.00; 1.00)	0.317
Q15	During the discrimination task, I was well isolated from external noises.	7.00(6.00; 7.00)	7.00(7.00; 7.00)	0.27
Q16	During the discrimination task, I was able to hear the sounds made by the motors of the devices.	1.00(1.00; 1.50)	1.00(1.00; 1.00)	0.539
Q17	I would have been happy to continue the experiment for longer.	6.00(4.50; 6.00)	6.00(5.00; 6.50)	0.612
Q18	At the end of the experiment I felt tired.	2.00(1.50; 5.00)	3.00(1.00; 5.00)	0.784

TABLE I: Results of the Likert scale survey. The central tendency of responses is summarized by using median with dispersion measured by IQR ($25° \sim 75°$). Scores with significant or close to significant differences in bold.
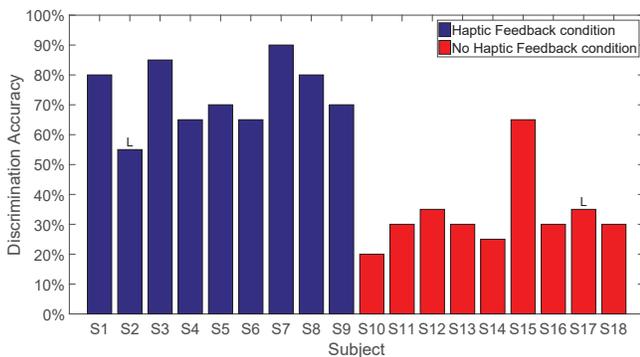
Fig. 6: Discrimination accuracy during the sphere size discrimination test. Left handed subjects marked with "L".
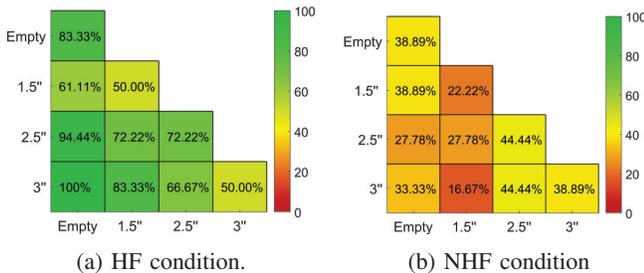
(a) HF condition.

(b) NHF condition

Fig. 7: Pairwise accuracy for the two groups.

during the size discrimination test. Q11 and Q12 show that subjects had good perception of the rotation of the Rocker. Participants who began in the HF condition showed a tendency close to significance to find the Rocker movement easier to detect respect to the NHF subjects (Q11 - p = 0.063, Q12 - p = 0.061), which could be ascribed to the extra training they received. Finally, results for questions Q13 to Q16 show that the experimental conditions were sound, and Q17-18 provide indication that the load on the subjects from the experiment was not excessive.

VI. CONCLUSIONS

In this work we introduce the Rice Haptic Rocker, a skin stretch haptic feedback device that can be used to convey proprioceptive information during opening and closure of a prosthetic hand, moving the skin through an eccentric rocker with frictional contact. We present its integration with the Pisa/IIT SoftHand, which due to its adaptability and simple control is well suited for use with this type of haptic feedback, presenting a setup that, for the first time, integrates skin stretch with a prosthetic device for proprioceptive feedback. We also present an experimental evaluation of the effectiveness of the proposed approach at conveying proprioception, through a size discrimination test performed with 18 able bodied subject, as well as subjective evaluation of the setup obtained by participants through a Likert-scale survey.

Subjects who performed the size discrimination test with the Rice Haptic Rocker were able to successfully discriminate between different sized spheres with an average accuracy of $73.3\pm11.2\%$, well above the $1/3$ chance level which was observed in the control group($33.3 \pm 12.7\%$). Results of the survey showed that the setup was considered easy to use and effective by the participants. Because of these results, we believe the proposed solution to be viable in real prosthetic applications: future work will focus on further experimentation to evaluate performance when a distraction task is present, tests with amputees subjects, evaluation of different locations on the arm to convey the haptic feedback (e.g. forearm) and and grasping conditions closer to a real life situation (subjects grasping objects actively instead of them being offered to them).

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