Passive Mechanical Skin Stretch for Multiple Degree-of-Freedom Proprioception in a Hand Prosthesis

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Abstract. In this paper, we present a passive linear skin stretch device that can provide proprioceptive feedback for multiple degrees of freedom (DOF) in a prosthetic hand. In a 1-DOF virtual targeting task, subjects performed as well with our device as with a vibrotactile array, and significantly better ($p < 0.05$) than having no feedback at all. In a 3-DOF grip recognition task, subjects were able to classify six different grips with 88.0% accuracy. Training took 6 minutes and the average time to classification was 5.2 seconds. Subjects were also able to match a set of target grip apertures with 11.1% error on average.

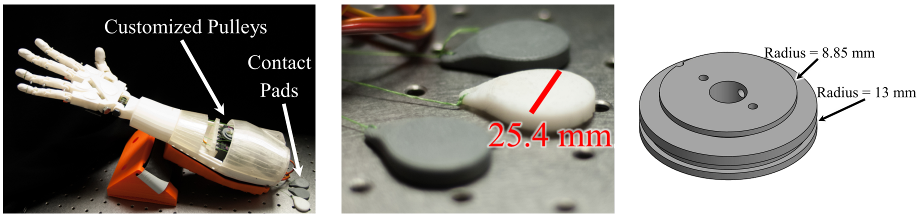
Keywords: Proprioception, Myoelectric Prostheses, Skin Stretch

1 Introduction

While major advancements have been made in the functionality of upper limb myoelectric prostheses, commercial devices still lack the ability to provide users with proprioceptive feedback. As a result, users have had to rely primarily on vision to know the position and orientation of their prosthesis. Surveys have reported that this over-dependence on vision is one of the largest contributors to prosthesis abandonment [1]. Various sensory substitution techniques have been used by research groups in order to provide proprioceptive feedback for use with upper limb myoelectric prostheses. Witteveen et al. used a vibrotactile array on the forearm to relay grip aperture to unimpaired subjects controlling a single degree-of-freedom (DOF) virtual hand with a mouse wheel [2]. Wheeler et al. developed a rotational skin stretch device that provided elbow angle feedback to unimpaired subjects controlling a single-DOF virtual arm with electromyography (EMG) [3]. While these devices were effective in improving accuracy when controlling a single-DOF virtual prosthesis, most users perform tasks which require controlling multiple DOFs on their prostheses, for example, in selecting between different grips for a specific task [4]. Furthermore, a large amount of surface area is required by both the vibrotactile array and the rotational skin stretch device. In addition, the rotational skin stretch device consumes a great deal of power and adds a considerable amount of weight (see Sec. 4.3).

Initial work to relay multiple DOF information was done by Cheng et al., who used vibrotactile patterns presented on a belt around the waist to convey the configuration of a virtual hand performing various grips [5]. While they achieved 79.7% accuracy in grip recognition, these results were marred by a long training time (30 min) and slow average time to classification (29.4 s).

To alleviate power, weight, and space issues, as well as easily provide multiple-DOF proprioceptive feedback for a prosthetic hand, we developed a passive mechanical linear skin stretch device (Fig. 1). The device cost less than $2 in raw materials. We compared our skin stretch device to a vibrotactile array and to a case where no feedback was given in a single-DOF virtual finger targeting task with myoelectric control. Our results show that the vibrotactile array and skin stretch device performed better than with no feedback given and that there was no statistical difference in performance between the two feedback methods.



(a) (b) (c)

Fig. 1. Passive linear skin stretch device attached to prosthesis. The InMoov hand used in our study (a) had custom pulleys pulling both the tendons driving the fingers and the lines to the contact pads (b). A schematic of one of the pulleys is shown in (c).

Extending our experiment to three DOFs, we assessed how well the user could recognize grips involving different configurations of the thumb, index, and middle fingers. Subjects identified six different grips with 88.0% accuracy. Training took 6 min per subject and the average classification time was 5.2 s. Finally, subjects also performed a task in which they were asked to match different levels of aperture for a pre-selected grip among the six used in the study. On average, the subjects were able to match the grip aperture (0-100%) with 11.1% error.

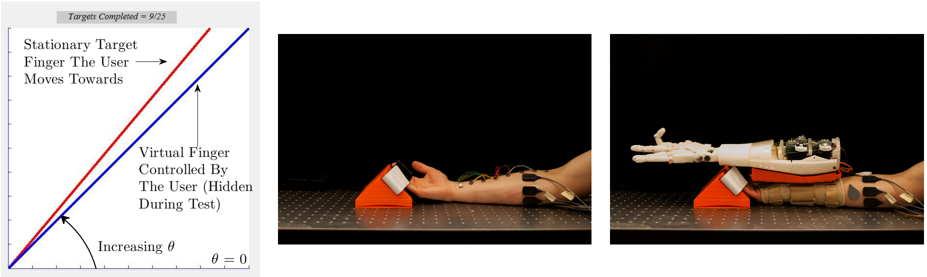
2 Methods

Five unimpaired subjects, four male, one female (ages: 19-27), volunteered for these experiments. The subjects were asked to participate in two experiments, one testing single-DOF proprioception, and the other testing multiple-DOF proprioception. During each experiment, six electrodes were placed over the finger flexor and extensor muscle groups located radially around the right forearm, with three electrodes being placed over each muscle group. A 16-channel Delsys

Bagnoli system (Delsys, Inc., Natick, MA) was used to record the EMG signals measured across these muscles. All data were collected and processed using the MATLAB DAQ Toolbox (Mathworks, Natick, MA).

2.1 Single-DOF Virtual Finger Task

In the first experiment, subjects were asked to move an onscreen virtual finger in a single-DOF task (Fig. 2a) based on [3] and [6]. The virtual finger was constrained to move between 0-90°. Meanwhile, the subject's metacarpophalangeal (MCP) joints on the right hand were restrained to 45° in order to remove any of the subject's own proprioceptive cues in controlling the arm. Flexing or extending the MCP joints against the restraint (Fig. 2b) would generate EMG signals. Linear discriminant analysis was used to classify these EMG signals to virtual finger movements every 0.1 s, following the procedure outlined in [7]. In order to have subjects rely more on feedback than timing-based open loop control strategies [2], the angular velocity was changed by a random walk bounded between 5-20°/s with a random initial velocity. Three feedback conditions were tested during the Virtual Finger Task: vibrotactile feedback, passive linear skin stretch feedback, and no feedback.



(a) (b) (c)

Fig. 2. (a) MATLAB GUI used for the single-DOF virtual finger task. (b) Vibrotactile array placement. (c) Passive linear skin stretch setup. A third contact pad was adhered to the skin on the radial side of the forearm. The orange triangular block restrained the subjects' hand in order to remove intrinsic proprioceptive cues.

Vibrotactile Array We used a vibrotactile array based on [2] to provide proprioceptive feedback of the angle of the virtual finger. It consisted of eight standard ERM motors placed longitudinally along the forearm, with each tactor spaced 29 mm apart (Fig. 2b). The joint angle range of the virtual finger was divided into eight intervals, each successively mapped to one of the vibrotactile motors.

Passive Linear Skin Stretch To use passive skin stretch to provide proprioceptive feedback, we constructed a prosthetic hand that pulled contact pads adhered to the forearm. The hand was modified from InMoov, an open source 3D-printed robotics project [8]. MG946R servo motors (TowerPro, Taiwan) mounted in the forearm of the prosthesis drove the tendon-actuated fingers. We seated the hand in a rigid plastic interface, which was then attached to a wrist brace. Guide holes at the proximal end of the interface kept the lines to the contact pads as horizontal as possible to maximize shear forces on the skin. For the single-DOF task, we adhered only the white contact pad to the skin (Fig. 2c).

We designed custom 3D-printed pulleys and mounted them onto the servos for the thumb, index, and middle fingers. A pulley had one channel to pull a tendon actuating a finger and a second to pull the line to a contact pad on the subject's arm. We set the ratio of the radii of these channels so that the displacement of the contact pad was 13 mm with respect to the finger's range of motion (Fig. 1c). In addition, we 3D-printed each contact pad to have a circular contact area of $507\,\mathrm{mm}^2$ and a hole to connect to the line from the pulley (Fig. 1b). Contact pads were adhered to the skin using BMTT-A adhesives (Garland Beauty Products, Hawthorne, CA) with roughly 1.5 N of initial tension.

Training and Evaluation A trial consisted of a training and evaluation phase for a particular feedback condition. During training, each subject used EMG to freely control the virtual finger for 60 s. Next, the subject was given five practice target angles from the evaluation phase. They were asked to move the virtual finger, now invisible, until it matched a series of displayed targets (Fig. 2a). Once the subject believed he was at the target angle, he would press a button and would be shown the actual angle to which he moved. Following the five practice angles, the subject was evaluated using 20 more targets. The mean absolute error between the target angle and the subject's estimate were recorded.

Subjects participated in two sessions consisting of a trial for each of the three feedback conditions, with each condition presented in a random order. Two sessions were conducted in order to evaluate whether performance improved over time. To help ensure subjects relied only on the feedback method under consideration, they wore headphones playing pink noise throughout the experiment. Additionally, when evaluating linear skin stretch, the prosthesis and contact pads were occluded from view.

2.2 Multiple-DOF Tasks

To extend the single-DOF skin stretch feedback to multiple-DOFs, we introduced two additional contact pads to either side of the right forearm. We placed a contact pad on the ulnar side for the middle finger, the middle for the index finger as before, and the radial side for the thumb (Fig. 2c). Two tasks were performed with skin stretch feedback: a grip recognition task and a grip aperture targeting task. For the grip aperture targeting task, subjects were also evaluated with no feedback. As before, subjects listened to pink noise through headphones and the prosthesis and contact pads were hidden from view during evaluation.

The multiple-DOF tasks involved six grips plus a starting reference configuration (open hand) (Fig. 3). To examine whether single-DOF grips could be distinguished from multiple-DOF grips, half of the grips chosen displaced a single

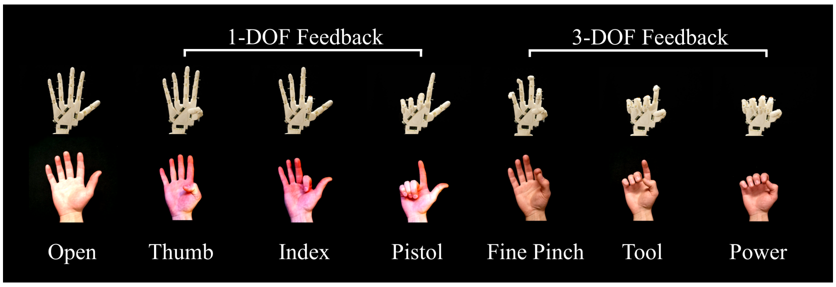


Fig. 3. Grips used for multiple-DOF experiments. The thumb, index, and pistol grips displace one contact pad; while the power, tool, and fine pinch grips displace multiple contact pads. The 1- and 3-DOF grips are shown at 100% grip aperture.

contact pad: the thumb, index, and pistol grips. The other three grips displaced multiple contact pads simultaneously: power, fine pinch, and tool grips. The amount of skin stretch per contact pad was proportional to each corresponding joint angle for each grip. These specific multiple-DOF grips were chosen because they are commonly implemented in upper limb myoelectric prostheses [4].

Grip Recognition Task This task was modified from [5]. In this task, grips were presented starting from the open hand reference configuration, transitioning over about 4 s to the completed grip. During the first of two training periods, subjects were shown an image of the grip while also being provided with the appropriate skin stretch feedback. Once the grip had completed moving, it was held for 3 s. The order of the grips were randomized and each grip occurred twice. In the second training period, subjects were asked to identify grips within 3 s after grip completion and were told the actual grip. Again, the order of the grips was randomized, except each grip occurred three times. The combined total training time across both periods took 6 min.

During evaluation, subjects had to identify a series of 30 grips, with each grip being presented five times in random order. This time, subjects were not told the correct grip after their selection. No time limit was imposed on the subjects when selecting a grip, and they were allowed to select a grip before the grip reached completion. The proportion of correct selections and the time from grip onset to selection was recorded.

Grip Aperture Targeting Task This task extended the single-DOF virtual finger task to incorporate the six grips from the grip recognition task. The aperture of each grip was normalized from 0% (open hand) to 100% (completed grip). Subjects had to match target apertures at 25%, 50%, and 75% grip completion using EMG control.

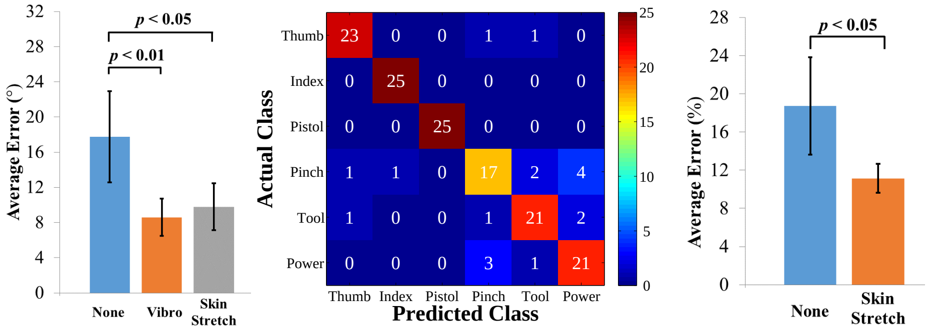
To decouple EMG pattern recognition from matching a percent aperture for a grip, the grips were pre-selected. Subjects flexed or extended the same muscles from the single-DOF task to control the aperture for all grips. During training, the subject was prompted to close a grip to within ±5% of a target percent aperture and stay in the zone for 2 s. This was repeated for each of the six grips at each of the three target apertures, presented in a randomized order.

Evaluation consisted of 30 random targets in which the subject tried to match percent aperture after starting from a random percentage between 0-100%. In order to reduce the completion time of the experiment, a random subset of all the combinations of grip and percent aperture were presented to each subject. Subjects repeated the task twice for both no feedback and skin stretch feedback conditions, with the order of conditions randomized. The mean absolute error between the target percent and subject's estimate was recorded.

3 Results

For the single-DOF virtual finger task, the no feedback, vibrotactile, and skin stretch conditions had (17.75 ± 5.17°), (8.58 ± 2.12°), and (9.79 ± 2.68°) of mean absolute error, respectively. We ran a two-way repeated measures ANOVA, where the within-subject factors were session number and feedback condition. We found a significant difference between the no feedback and vibrotactile conditions ($p < 0.01$) as well as the no feedback and skin stretch conditions ($p < 0.05$) (Fig. 4a). However, there were no significant differences between skin stretch and vibrotactile or between sessions for any feedback condition.

Over the course of the multiple-DOF grip recognition task, subjects correctly selected 88.0 ± 5.6% of the presented grips on average. Figure 4b shows the confusion matrix, which depicts the absolute number of correct and incorrect selections for a presented grip. The average time for grip selection was 5.2 ± 0.6 s, where time was measured from the start of when the reference began moving toward the closed grip. For the multiple-DOF grip aperture task, Fig. 4c shows that the error in percent aperture for the skin stretch condition (11.1 ± 1.5%) was significantly lower ($p < 0.05$) than the no feedback condition (18.7 ± 5.1%).



	Thumb	Index	Pistol	Pinch	Tool	Power
Thumb	23	0	0	1	1	0
Index	0	25	0	0	0	0
Pistol	0	0	25	0	0	0
Pinch	1	1	0	17	2	4
Tool	1	0	0	1	21	2
Power	0	0	0	3	1	21

(a) (b) (c)

Fig. 4. (a) Average mean absolute error for the single-DOF virtual finger task. (b) Confusion matrix for grip recognition task. (c) Average percent grip aperture error for the grip aperture targeting task.

4 Discussion

4.1 Single-DOF Virtual Finger Task

In the single-DOF virtual finger task, subjects had lower average error when given either linear skin stretch or vibrotactile feedback than when they were given no feedback. There was no significant difference between either form of feedback. However, users of prostheses have reported that vibrotactile feedback becomes distracting after prolonged periods of time [9], though constant proprioceptive feedback may be desired. Subjects in this study reported skin stretch remained comfortable throughout the experiments, which could make it more desirable than vibrotactile stimulation at providing proprioceptive feedback.

4.2 Multiple-DOF Tasks

Grip Recognition Task Subjects in this study distinguished between six different grips in an average of 5.2 s with 88.0% accuracy across subjects, while those in Cheng et al. distinguished between five different grips in an average of 29.4 s with 79.7% accuracy [5]. Though the grips used in this study differ from those used by Cheng et al., the similar success rates suggest that our passive linear skin stretch device is a viable system to use for multiple-DOF tasks.

Refinements will be made to the linear skin stretch system to further improve grip recognition accuracy. One possible improvement to the system would involve creating maximally distinct contact pad trajectories for each grip.

Grip Aperture Targeting Task In the grip aperture task, subjects performed better with skin stretch feedback than without, regardless of the grip. In later studies, we would like to determine whether subjects attend to all three contact pads or simply the one with the maximum range of stretch for a particular grip.

4.3 Power, Weight, and Surface Area Comparisons

During prosthesis design, power and weight must be considered. For feedback devices, the available skin area and size of the tactors are additional concerns, especially when competing for area with the prosthesis' sensors. First, for single-DOF, our device introduced a torque loss, decreasing the battery life of our hand by 1%. Our device would be even more efficient in prostheses that produce more torque. Assuming a 7.4 V, 2400 mA h battery, the vibrotactile array used in this study would decrease battery life by 2%, while the 3.2W motor for the rotational skin stretch device by Wheeler et al. [3] would decrease it by 9% if the device ran constantly. Second, our device, the vibrotactile array, and Wheeler et al.'s device would add 2g, 6g, and 82g to the prosthesis, respectively. Compared to the weight of commercially available prostheses, our device and the vibrotactile array were negligibly light. Finally, the area used by our device over the full range of stretch was 975 mm^2, while vibrotactile used 2380 mm^2, and Wheeler et al.'s device used 2800 mm^2. Thus, our passive skin stretch device used the least surface area of these three devices, drains little power, and is lightweight.

5 Conclusion

We have shown that for a single-DOF virtual finger targeting task, linear skin stretch is comparable to vibrotactile feedback and better than no feedback. In the multiple-DOF grip recognition task, our results are comparable to those attained in a previous study [5] that used a vibrotactile array. However, subjects in our study were able to achieve similar classification accuracy (88.0% vs. 79.7%) after a shorter training period (6 min vs. 30 min), requiring less time to make classifications (5.2 s vs. 30 s). In the grip aperture targeting task, subjects matched target grip apertures with 11.1% error on average. Finally, the simplicity, low cost, low power consumption, light weight, small contact area, and overall comfort make our passive linear skin stretch device well-suited for multiple-DOF proprioceptive tasks.

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