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Electro-prosthetic E-skin Successfully Delivers Finger Aperture Distance by Electro-Prosthetic Proprioception (EPP)

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***Abstract*— Electronic skin (E-skin) is an emerging wearable device typically used to mimic the function of the human skin, mainly by replicating the role of tactile sensory receptors in the skin. This study showed an interesting modification of the E-skin, called an electro-prosthetic E-skin, which adds the functionality of distance sensing and stimulation of the palmar digital nerve. The electro-prosthetic E-skin operates as a closed loop to deliver the finger aperture distance information to the nervous system. This E-skin was implemented as an additional layer mounted to the original human skin, to be worn on the fingertip with a thin silicone substrate. The E-skin was designed to be mounted onto the index fingertip, to deliver the distance information between the fingertips and to enhance the finger aperture distance control. In this study, we demonstrated that electro-prosthetic proprioception (EPP), implemented with the electro-prosthetic E-skin, successfully delivered the distance information between the fingertips and enhanced the finger aperture distance control accuracy.**

***Clinical Relevance*— Presented electro-prosthetic E-skin delivering finger aperture distance, via electro-prosthetic proprioception (EPP), will enhance accuracy of the finger aperture distance control. This technology can be applied to the neurosurgery to minimize unforced errors caused by the limited human control accuracy over the fingertip.**

I. Introduction

Electronic skin (E-skin) is an emerging wearable device, which replicates the function of the human skin. E-skin incorporates advanced sensors in soft and flexible material, so that it detects important physical and physiological changes on and around the skin [1],[2]. Since artificial sensors can detect novel changes beyond the human sensing capability, the functionality of the E-skin does not need to be limited to the original utility of the human skin. For example, E-skin devices sense breathing rate or magnetic force, which are not intrinsic sensations measured by the human skin [2],[3]. However, in spite of the manifold benefits expected from detecting the proximity around the human skin, the capability of proximity sensing has not been integrated into the E-skin yet.

Further, conventional E-skins limitedly replicated the function of the human skin, as they focused on replicating tactile sensory receptors. Those E-skins delivered the sensor data by indirect translation to processors instead of direct translation to the human nervous system. Indeed, the closed-loop operation of the E-skin, including the delivery of superimposed sensory information to the nervous system as well as the natural sensing function, has been understudied. The delivery of sensory information to the nervous system has been better investigated in the field of sensory neuroprosthesis. Multiple studies of sensory neuroprosthesis with amputee subjects demonstrated that electrical stimulation onto the residual cutaneous nerves successfully replicates the tactile feedback from the fingertip or the foot sole [4]-[6]. It is important for E-skin to have the function of delivering sensory information to the nervous system as well as monitoring sensory changes, as a closed-loop operation [7].

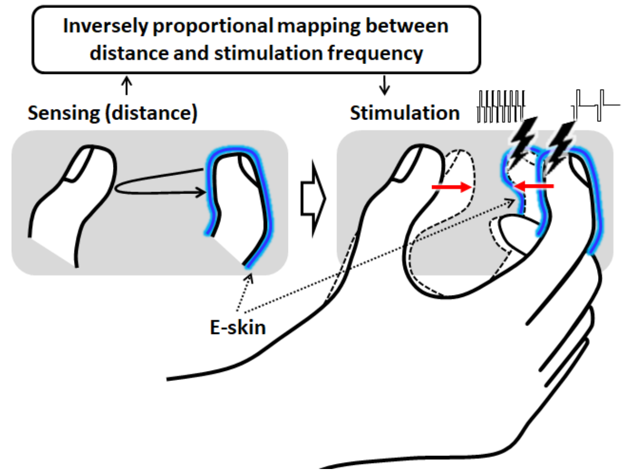

Figure 1. Concept of the electro-prosthetic E-skin delivering finger aperture distance via frequency-modulated electrical stimulation applied onto the palmar digital nerve (sensory nerve innervating the fingertip).

In our prior works, we demonstrated that frequency-modulated electrotactile feedback successfully delivered the information of distance between the fingertips or between the fingertip and the target object [8]. Frequency-modulated electrotactile feedback also enhanced the lateral balance when it was applied to the foot sole, even with cognitive tasks like the n-back counting task [9]. Experimental results suggested that the frequency-modulated electrotactile feedback was intuitive enough to deliver the distance information between the distal part of the body and the target object with minimal cognitive load.

In this study, we present the novel electro-prosthetic E-skin delivering the finger aperture distance by using frequency-modulated electrotactile feedback. In the rest of the paper, we

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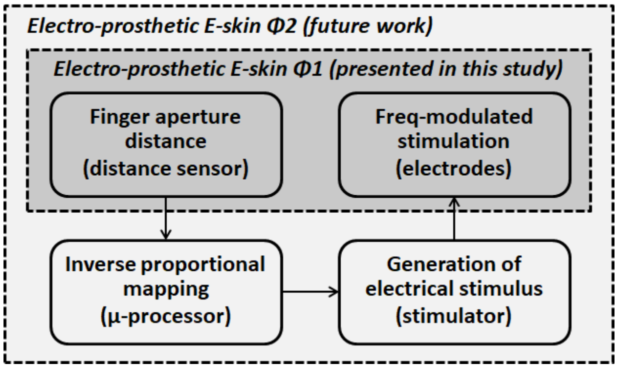
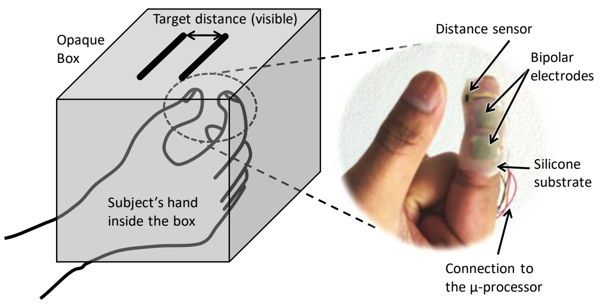


(a)



(b)

Figure 2. System implementation of the electro-prosthetic E-skin providing electro-prosthetic proprioception (EPP): (a) block diagram and (b) actual test setup with electro-prosthetic E-skin installed on the index finger.

refer to this novel sensation as electro-prosthetic proprioception (EPP), since it delivers proprioceptive information by a form of electrotactile feedback. We tested the effect of the electro-prosthetic E-skin with the task of finger aperture distance control. Finger aperture distance control is critical in gripping small objects by fingers with precision, for instance in the case of neurosurgery, while handling delicate tissues and nerves. However, intrinsic visual-proprioceptive mismatch fundamentally limits the accuracy of the finger aperture distance control [10]. In this study, we tested the effect of the E-skin delivering the finger aperture distance on the accuracy of finger aperture distance control. In the following paragraphs, we have presented system implementation, experimental results, discussion, and conclusion.

II. System Implementation

A. Electro-prosthetic E-skin

Electro-prosthetic E-skin was composed of a sensing unit which measured finger aperture distance and a pair of stimulating electrodes which delivered the distance information by EPP (see Fig. 2a). The sensing unit consisted of an infrared proximity sensor (GP2S700HCP, Sharp, Japan), and measured the distance between the fingertips of the index finger and the thumb. Hydrogel electrodes were used as the transcutaneous stimulation electrodes, which were custom fabricated using two 4mm × 4mm conductive hydrogel pads for skin interface and conductive Cu-Ni alloy-plated polyester fabric for hydrogel-wire connection. For the electronics and electrodes to be consistently positioned on the fingertip, all electronics and electrodes were integrated into the thin layer of silicone substrate (see Fig. 2b). Distance sensor was carefully positioned to see the front side of the fingertip and electrodes were carefully positioned to be mounted onto the palmar digital nerve of the index finger.

B. Sensor Signal Processing and Generating Electrical Stimuli

We also employed μ-controller and stimulator, which processed the proximity sensor output and generated corresponding electrical stimuli (see Fig. 2a). We mapped the measured finger aperture distance ($d_{measured}$) to the stimulation frequency (f_{stim}) based on (1), where f_{max} and f_{min} were set as 70 Hz and 10 Hz and d_{max} and d_{min} was set as 25 and 10 mm.

$$f_{stim} = f_{max} - \frac{f_{max} - f_{min}}{d_{max} - d_{min}} \times (d_{measured} - d_{min}) \qquad (1)$$

III. Experimental Procedure

A. Human Subject Recruitment

All experiments were performed adhering to relevant guidelines and regulations, in accordance with the procedure described in the protocol approved by Institutional Review Board, Texas A&M University (IRB2018-0893D). Two healthy human subjects in age 25–28 (with average age of 26.5), one male subject and one female subject participated in the study. All subjects were right-handed. Subjects with neurological disorder, cognitive impairment, upper limb deformity, and any known allergic problem to skin adhesive were excluded from the study. All subjects provided their informed consent for the experimentation according to the approved IRB protocol.

B. Establishing the Parameters to evoke EPP

First, the parameters to evoke EPP were identified prior to the experiments. Stimulation amplitude was determined by measuring both perception threshold (*i.e.,* minimum amplitude evoking any perception) and discomfort threshold (*i.e.,* minimum amplitude evoking any discomfort) at 70 Hz and averaging the two threshold values. With the constant amplitude, the stimulation frequency was then swept from 70 Hz down to 10 Hz, to sufficiently oversample the fingertip movement over the Nyquist rate. After sweeping over 10-70 Hz frequency range, subjects were then asked to confirm consistent change in electrotactile feedback regarding its pulsing frequency.

C. Finger Aperture Distance Matching Test

Finger aperture distance matching test was designed to determine the effect of EPP on the accuracy of the finger aperture distance control. Under various conditions described below, subjects were asked to replicate the distance between the lines, provided by either visual or tactile feedback. Throughout this experiment, the object used was a pair of embossed parallel lines with a fixed width (see Fig. 2b), which didn't obstruct the proximity sensor, yet provided sufficient tactile and visual feedback to approximate the distance between the lines.

First, the baseline data was measured for all subjects before any training based on the testing protocol described below.

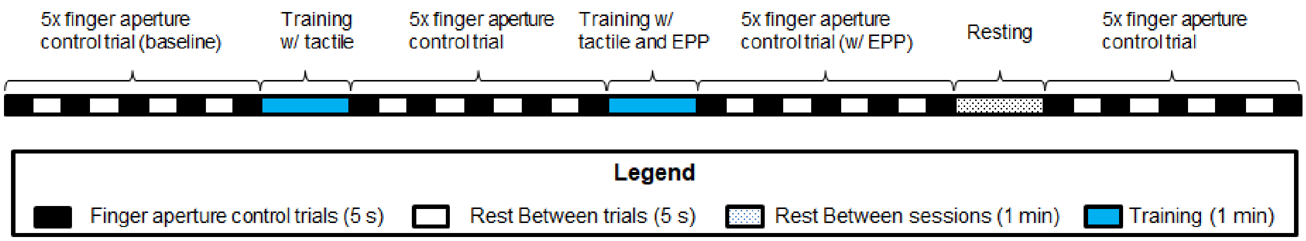


Figure 3. Experimental procedure of the presented study: 1) Baseline finger aperture control accuracy was measured before any training, 2) finger aperture control accuracy was measured again after the tactile training, 3) finger aperture control accuracy was measured again after the tactile+EPP training (with EPP), and 4) finger aperture control accuracy was measured again (without EPP), as an aftereffect of the training. Five trials were performed for each condition with 5s rest in between.

Subjects were asked to replicate the distance between the lines in their line of sight (*i.e.,* visual reference) using the finger aperture distance, while their own fingers were concealed directly underneath the object, inside an opaque supporting platform. The error between the visual reference (*i.e.,* distance between the lines) and the subject's finger aperture distance (*i.e.,* visual-proprioceptive mismatch) was observed over five trials with 5s rest in between trials.

Second, subjects were trained by the tactile feedback. In this case, both the object and subject's fingers were concealed inside the platform. Subjects were instructed to physically touch the lines by the fingertips of index finger and thumb, and internalize proprioceptive and tactile feedback of the finger aperture distance in order to better replicate the distance between the lines. This instruction was given the course of 10 repetitions during a 1 minute interval. After the training, subjects were asked to go through the same testing protocol described in the baseline test, to evaluate the error between the distance between the lines and the subject's finger aperture distance (*i.e.,* visual-proprioceptive mismatch).

Third, subjects were then trained through the tactile+EPP training session, where EPP was given along with the tactile feedback, while the object and the subject's fingers were concealed inside the platform. Subjects were instructed to physically touch the object by their fingertips and internalize proprioceptive, tactile, and EPP feedback of the finger aperture distance in order to better replicate the distance between the lines. After the training, subjects were asked to go through the same testing protocol described in the baseline test, while delivering EPP according to the mapping described in (1).

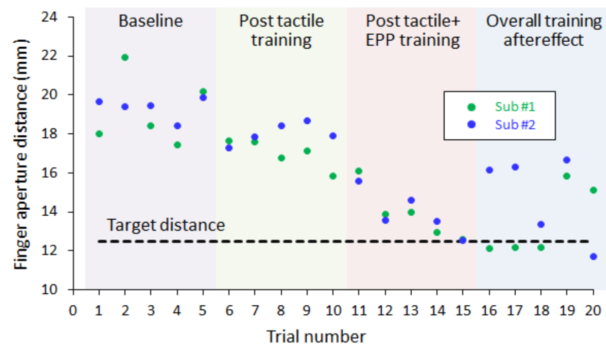
Finally, EPP was deactivated, and subjects underwent the same testing protocol as the baseline test, to identify any aftereffect of the tactile and tactile+EPP trainings on finger aperture distance control and visual-proprioceptive mismatch.

IV. Experimental Results

Experimental results suggest that electro-prosthetic E-skin delivering finger aperture distance information significantly enhanced the control accuracy of the finger aperture distance. The tactile+EPP training enhanced the control accuracy of the finger aperture distance by 42.74%, while the tactile training enhanced the control accuracy by 14.13%.

A. Selected Parameters of EPP

Frequency range was selected as 10 to 70 Hz, based on the prior success of using pulsing-type electrotactile feedback on the fingertip [8]. Stimulation voltage thresholds for perception



(a)

		Baseline	Post tactile training	Post tactile+ EPP training (with EPP)	Overall training aftereffect
Sub #1	Distance (mm)	19.19±1.83	16.99±0.74	13.89±1.36	13.48±1.85
	Error (%)	53.69±14.66	35.93±5.94	11.15±10.89	7.87±14.83
Sub #2	Distance (mm)	19.36±0.54	18.02±0.55	13.96±1.18	14.83±2.19
	Error (%)	54.85±4.35	44.15±4.38	11.71±9.41	18.64±17.50
Total	Error (%)	54.17±10.22	40.04±6.56	11.43±9.60	13.26±16.31

(b)

Figure 4. Experimental result of the finger aperture distance measured at four different conditions for two subjects: 1) baseline before any training, 2) post tactile training, 3) post tactile+EPP training, with EPP applied to subjects, and 4) training aftereffect after all the trainings, without EPP. Raw data is depicted in graph (a) and average and standard deviations are summarized in table (b).

and discomfort were measured as 7 V and 18.2 V for subject #1 and 19 V and 38 V for subject #2. As a result, stimulation voltages for subjects #1 and #2 were selected as 11.6 V and 28 V, respectively for the following experiments with EPP, as the median value between perception and discomfort thresholds.

B. EPP Enhanced Accuracy of Finger Aperture Distance Control

Both subjects showed consistent results of enhanced accuracy in controlling the finger aperture distance, after both tactile and tactile+EPP trainings. Raw finger aperture distance data from both subjects are shown in Fig. 4a. Fig. 4b showed summarized measurements and calculated errors in replicating the distance. Error in the finger aperture distance control was measured as 54.17±10.22% at the baseline test before any training. The error was decreased to 40.04±6.56% on average after the tactile training. The error was further decreased to 11.43±9.60% on average after the tactile+EPP training, where subjects received EPP based on the finger aperture distance. The error measured as an aftereffect of all training sessions, without EPP, was 13.26±16.31% on average.

V. Discussion

Electro-prosthetic E-skin successfully delivered the distance information between the fingertips via EPP, a novel sensory modality presented in this paper, based on frequency-modulated electrotactile feedback. The proximity sensing function, which does not exist in intact human skin, can provide useful information for the sophisticated motor tasks. Addition of this novel EPP via electro-prosthetic E-skin significantly improved the accuracy of the finger aperture distance control for the two healthy subjects. Further, training with EPP along with tactile feedback left significant lasting effect in enhancing the accuracy of the finger aperture distance control, which might be used to train people doing precision tasks like neurosurgeon.

A. Visual-proprioceptive error critically limits the accuracy of the finger aperture distance control

The experimental results confirm the prior knowledge of the visual-proprioceptive mismatch [10],[11]. As subjects replicated the target distance given by visual feedback based on their proprioceptive feedback, the error in the baseline measure (54.17±10.22%) indicates the visual-proprioceptive mismatch of the finger aperture distance control. This result suggests that the visual-proprioceptive mismatch significantly degrades the finger aperture distance control accuracy.

B. EPP significantly enhanced the accuracy of the finger aperture distance control

Tactile+EPP training enhanced the finger aperture distance control accuracy significantly by the amount of 42.74% on average (compared to the baseline), while tactile training enhanced the control accuracy by 14.13% on average. This result suggests that the addition of EPP using electro-prosthetic E-skin has a potential to significantly improve the control accuracy of the finger aperture distance.

C. Tactile+EPP training has a potential lasting effect

The aftereffect measure of the tactile+EPP training showed that the tactile+EPP training has a potential lasting effect [12]. The error was measured as 13.26±16.31% on average, which is not much different from the 11.43±9.60% error with EPP. Considering the baseline error was 54.17±10.22%, the tactile+EPP training left a significant lasting effect. This result suggests that the tactile+EPP training may recalibrate the visual-proprioceptive mapping for the finger aperture distance control. This lasting effect might be useful for training the novice surgeons for better finger control.

D. Limitations and Future Direction

This study has been conducted as a pilot study, with a critical limitation in the number of subjects. Also, the aftereffect of the tactile training was not well considered when measuring the effect of the tactile+EPP training. Note that we cannot exclude the possibility of accumulation effect of training, as the tactile+EPP training was done right after the tactile training. In the follow-up study, we will confirm the effect of electro-prosthetic E-skin delivering finger aperture distance information, with larger number of subjects and separated experimental groups per the training method. Further, E-skin will be implemented as more compact form and size, to minimize intrusiveness and maximize the user acceptance.

VI. Conclusion

In this study, we presented a novel electro-prosthetic E-skin, which will provide EPP and add the novel functionality of distance sensing to the human skin. With the electro-prosthetic E-skin providing EPP, control accuracy of the finger aperture distance was significantly enhanced. The experimental results suggest that electro-prosthetic E-skin providing EPP can be a promising candidate to address the limited control accuracy of the finger aperture distance.

References

[1] Sanderson K. Electronic skin: from flexibility to a sense of touch. Nature. 2021 Mar 1;591(7851):685-7.

[2] Yang JC, Mun J, Kwon SY, Park S, Bao Z, Park S. Electronic skin: recent progress and future prospects for skin-attachable devices for health monitoring, robotics, and prosthetics. Advanced Materials. 2019 Nov;31(48):1904765.

[3] Shih B, Shah D, Li J, Thuruthel TG, Park YL, Iida F, Bao Z, Kramer-Bottiglio R, Tolley MT. Electronic skins and machine learning for intelligent soft robots. Science Robotics. 2020 Apr 22;5(41).

[4] Tan DW, Schiefer MA, Keith MW, Anderson JR, Tyler J, Tyler DJ. A neural interface provides long-term stable natural touch perception. Science translational medicine. 2014 Oct 8;6(257):257ra138-.

[5] Charkhkar H, Shell CE, Marasco PD, Pinault GJ, Tyler DJ, Triolo RJ. High-density peripheral nerve cuffs restore natural sensation to individuals with lower-limb amputations. Journal of Neural Engineering. 2018 Jul 2;15(5):056002.

[6] Pitkin M, Cassidy C, Shevtsov MA, Jarrell JR, Park H, Farrell BJ, Dalton JF, Childers WL, Kistenberg RS, Oh K, Klishko AN. Recent Progress in Animal Studies of the Skin-and Bone-integrated Pylon With Deep Porosity for Bone-Anchored Limb Prosthetics With and Without Neural Interface. Military Medicine. 2021 Jan;186(Supplement_1):688-95.

[7] Shon A, Brakel K, Hook M, Park H. Fully implantable plantar cutaneous augmentation system for rats using closed-loop electrical nerve stimulation. IEEE Transactions on Biomedical Circuits and Systems. 2021 Apr 16;15(2):326-38.

[8] Zhao Z, Yeo M, Manoharan S, Ryu SC, Park H. electrically-evoked proximity Sensation can enhance fine finger control in telerobotic pinch. Scientific reports. 2020 Jan 13;10(1):1-2.

[9] Azbell J, Park J, Chang SH, Engelen MP, Park H. Plantar or Palmar Tactile Augmentation Improves Lateral Postural Balance With Significant Influence from Cognitive Load. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2020 Nov 10;29:113-22.

[10] Smeets JB, van den Dobbelsteen JJ, de Grave DD, van Beers RJ, Brenner E. Sensory integration does not lead to sensory calibration. Proceedings of the National Academy of Sciences. 2006 Dec 5;103(49):18781-6.

[11] Fuentes CT, Bastian AJ. Where is your arm? Variations in proprioception across space and tasks. Journal of neurophysiology. 2010 Jan;103(1):164-71.

[12] Jiang B, Kim J, Park H. Palatal Electrotactile Display Outperforms Visual Display in Tongue Motor learning. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2022 Mar 4.