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Design and Experimental Evaluation of a Skin-Stretch Haptic Device for Improved Control of Brain-Computer Interfaces

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Abstract— **Robotic systems, such as prosthetics and exoskeletons, offer people suffering from motor impairments a chance to regain lost physical functionality. However, the neural control that individuals are able to exert over these robots is currently limited. This is due to both lack of control authority in many degrees of freedom and insufficient sensory feedback through the human-robot interface. We propose that haptic feedback is paramount for accurate and efficient control of robots via brain-computer interfaces (BCIs). Skin stretch at the fingertip is a novel form of haptic feedback for improving BCI-based robot control. In this paper, we describe the design of a BCI-driven skin-stretch device, assess several control paradigms for this device, and evaluate its effectiveness in a small user study. We show that BCI-based movement-intent classification improved in the presence of skin-stretch feedback for 3 of 4 healthy individuals controlling a computer cursor via an inexpensive, commercial electroencephalography-based (EEG) BCI.**

I. INTRODUCTION

Over 50 million Americans suffer from mobility or dexterity impairments. Recent research in robotics and neuroscience has resulted in novel brain-controlled assistive devices for this population. In bypassing the impaired motor system, these brain-computer interfaces (BCIs) and their connected robots have enhanced individuals' ability to interact with the world. For example, those "locked-in" by late-stage amyotrophic lateral sclerosis (ALS) can type messages on virtual keyboards, quadriplegics can power and steer their own wheelchairs, and amputees can accomplish dexterous manipulation tasks. Currently, such interactions come without the rich haptic feedback that allows for accurate, efficient, and intuitive neuromotor control [1]. To allow BCI-based control to reach levels of accuracy, efficiency, and intuitiveness similar to innate motor control, we propose that haptics should be integrated with the human-robot interface. Appropriately applied haptic feedback has the potential to decrease BCI training time, reduce cognitive workload during operation, and ultimately improve users' quality of life. For those with mobility or dexterity impairments, this approach leverages their intact sensory system, whether colocated with the location of motor deficit (e.g., for ALS patients) or elsewhere on the body (e.g., for amputees). In this paper, we describe a BCI-driven robotic manipulator that applies tangential skin stretch at the fingertip, a novel form of haptic feedback for BCI control. We then assess whether this skin-stretch feedback improves the ability of electroencephalography-based (EEG) BCI users to control a computer cursor in one dimension. Our results have implications for BCI control of higher-degree-of-freedom (DOF) robotic systems, such as powered wheelchairs or prosthetic limbs, because skin-stretch haptic feedback has previously been shown effective for multi-DOF haptic interfaces [2].

II. BACKGROUND

Haptic feedback can provide BCI users with information about their brain activity without taxing the auditory and visual systems on which they rely to monitor the environment [3]. To date, however, only vibrotactile feedback (vibrations applied to the skin) and kinesthetic feedback (forces applied to the limbs) have been proposed for BCIs. Neither form of feedback is ideal for a neurally connected assistive device. Vibrotactors can be small and unobtrusive, but vibration feedback is unnatural, difficult to interpret, and no more reliable than visual feedback (seeing the cursor or prosthesis move) for BCI control [4]. Kinesthetic feedback, which can communicate trajectory information (e.g., the path of a computer cursor), is natural and has been shown to improve BCI control [5], but kinesthetic devices such as robotic exoskeletons can encounter feedback stability issues. An ideal haptic device for BCIs should combine the best features of vibrotactile and kinesthetic feedback, communicating natural trajectories in a safe, portable, and possibly wearable package. We propose that a tangential skin-stretch (cutaneous shear force) display is well suited for BCI control because it encodes amplitude and direction (i.e., trajectory information) without stability concerns or the need for large actuators.

Cutaneous shear force, which tangentially stretches the skin, is a naturally occurring phenomenon to which humans are especially attuned. It is a compelling substitute for kinesthetic feedback [6] and can even communicate proprioceptive information [7]. Skin stretch has been most often applied at the fingertip because of its high density of mechanoreceptors, the biological sensors that detect tactile stimuli [6]. Moreover, it is known that humans can "path integrate" — use local motion cues to infer trajectory information — from tactile feedback at the fingertip [8]. This is relevant given

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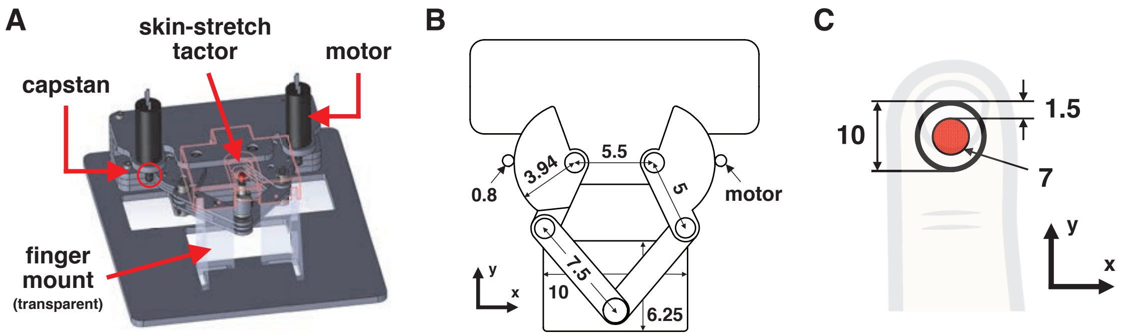

Fig. 1. Skin-stretch haptic device: (A) A CAD rendering of the device, with transparent finger mount to display the five-bar linkage below. (B) A top-down schematic of the five-bar linkage. The skin-stretch tactor is mounted at the joint of the two outermost links. Units are in centimeters. (C) A top-view schematic of the fingertip aperture (black circle) and skin-stretch tactor (red circle), displaying the radial workspace. Units are in millimeters.

that BCI users often want to communicate a trajectory to the device they are controlling.

This paper presents skin stretch at the fingertip as a novel form of haptic feedback for improving BCI control. In the paper, we describe the design of a BCI-driven skin-stretch device, the results of a user poll on the "intuitiveness" of four control paradigms for the device, and the use of a one-dimensional cursor-movement task to evaluate the efficacy of the most intuitive of these paradigms for improving BCI control. The work can be extended to multi-DOF brain-controlled assistive devices, including communication interfaces for ALS patients, mobility solutions for quadriplegics and paraplegics, and prosthetics for amputees.

III. SYSTEM DESIGN

This section describes the mechatronic design of the skin-stretch haptic device and how it is integrated with a BCI and graphical display.

A. Skin-Stretch Haptic Device

To provide shear forces on the pad of the fingertip, we developed a two-degree-of-freedom robotic manipulator inspired by the five-bar linkage in [9], [10] (Fig. 1). A rough tactor (similar to those found on the keyboards of some laptop computers) mounted at the linkage end-effector provides the friction necessary to maintain contact with and gently stretch the fingertip's skin. As shown in Fig. 1A, the end-effector and tactor are straddled by an elevated finger mount. The mount includes a channel to cradle the finger and a 10-mm circular aperture (slightly smaller than average fingerpad width) to ground the skin when stretched from below. Two Velcro straps running overtop the channel prevent excessive motion of the finger relative to the tactor; both the straps and aperture help to guarantee precise stimulation.

The overall device dimensions are shown in Fig. 1B. The base is 25×30 cm and all links are between 5 and 10 centimeters. Thus, the device is desktop-sized and portable. The device's body is constructed of acrylic (0.125 inches and 0.25 inches thick), 3D-printed ABS plastic, and joint hardware.

The aperture in the finger mount allows for 1.5-mm radial movement of the skin-stretch tactor (Fig. 1C), sufficient displacement (by an order of magnitude) for directional discrimination by the user [11]. To fully travel this workspace while the tactor is in contact with the fingerpad (assuming skin stiffness of 1.4 N/mm [12]), the five-bar linkage produces just over 2 N at its end effector. Two encoded Maxon RE 25 motors are geared down through capstan drives by a factor of 10:1. While the device was designed to enable 2-DOF skin stretch, only horizontal movement was used in this work.

B. Integrated BCI Haptic System

The integrated system consists of three components: an input device controlling movement of an on-screen computer cursor, a graphical user interface (GUI) displaying the cursor, and the skin-stretch device providing haptic feedback in accordance with the cursor state.

1) Input Device: The system allows for three input modes: autonomous, BCI, and manual. The user can switch between the modes by pressing a key.

Autonomous mode: The cursor moves along the horizontal dimension (left/right) with a sinusoidal trajectory spanning the width of the graphics window; frequency can be adjusted by the user in steps of 0.02 Hz.

BCI mode: The user controls the cursor with EEG signals from an Emotiv EPOC neuroheadset. These EEG signals are recorded at 14 locations across the scalp: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4, based on the International 10-20 locations [13]. The recorded signals are translated to gross cognitive powers associated with thinking "right" (P_{right}), "left" (P_{left}), and "neutral" (P_{neutral}). These cognitive powers are given decimal values between 0 and 1 as decoded by the proprietary machine-learning algorithms in the Cognitiv Suite of the Emotiv Control Panel. Although the EPOC records additional biosignals, including electrooculography (EOG), electromyography (EMG), and inertial head movements, the Cognitiv Suite only processes EEG. The three cognitive states are converted to a "force" F_c on the cursor:

$$F_c = P_{\text{right}} - P_{\text{left}}$$

Finally, this force is scaled to acceleration using an arbitrary cursor "mass", and acceleration is Euler-integrated to update velocity and position. Because the Emotiv headset is designed for use by subjects without motor impairments, none of the recording electrodes are positioned over the sensorimotor cortex. Sensorimotor signals in healthy, mobile individuals could interfere with the device's decoding algorithms. As a result, the cursor movement is not based on actual motor activity (as would be the case for a BCI implanted in the motor cortex) but rather on an amalgamation of activity from the 14 locations sensed by the device. This leverages machine learning instead of knowledge about neurophysiology.

Manual mode: A SensAble PHANTOM Omni haptic device (now marketed as a Geomagic Touch) acts as a joystick; cursor position and velocity are scalings of the device's position and velocity in one degree of freedom (the horizontal direction).

In both BCI and manual modes, cursor movement is limited to the graphics window to provide the participant with information regarding the traversable area of the cursor. The cursor stops just before the edges of the window, regardless of additional input.

2) Graphics: Graphics are rendered using CHAI 3D (http://www.chai3d.org). In the graphics window, a user sees a spherical cursor moving left and right, current system settings (e.g., the selected input device), and messages/instructions (e.g., when to take a break during the study). The graphical environment is updated at a frequency of 50 Hz.

3) Skin-Stretch Haptic Feedback: The skin stretch displayed to the user via the haptic device depends on the state of the on-screen cursor and the current control paradigm. As displayed in Fig. 2, we programmed four paradigms:

- **Position-Based, Cursor-Aligned** ($p+$): Force commanded to the skin-stretch tactor, F_{p+}, is directly proportional to the position of the cursor in the graphics window, x_c. The constant of proportionality (position gain) is denoted K_p.
- **Position-Based, Cursor-Anti-Aligned** ($p-$): Force F_{p-} is inversely proportional to the position of the cursor.
- **Velocity-Based, Cursor-Aligned** ($v+$): Force F_{v+} is directly proportional to the velocity of the cursor, v_c. The constant of proportionality (velocity gain) is denoted K_v.
- **Velocity-Based, Cursor-Anti-Aligned** ($v-$): Force F_{v-} is inversely proportional to the velocity of the cursor.

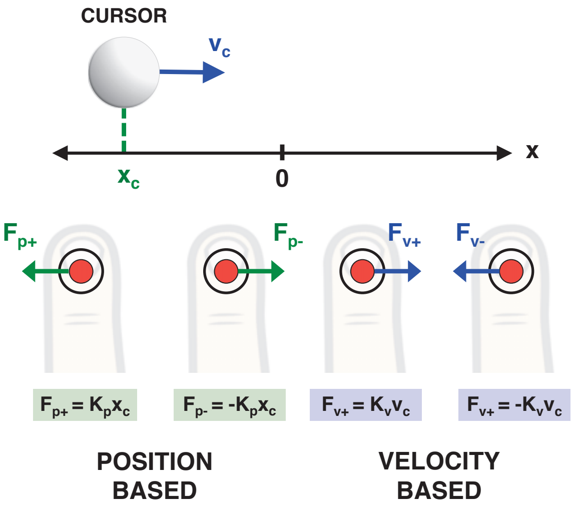

Fig. 2. Skin stretch is a function of the on-screen cursor's position or velocity. There are four different paradigms.

Gains K_p (2.5 N/mm) and K_v (1.5 Ns/mm) were selected so that a maximum force of 0.56 N would elicit a skin stretch approximately twice the just-noticeable skin-stretch displacement of 0.2 mm [11], assuming fingertip skin stiffness of 1.4 N/mm [12]. The user can switch between the control paradigms by pressing a key.

IV. SYSTEM EVALUATION

This section describes the user studies for assessment of our device's skin-stretch feedback for BCI control.

A. Methods

1) Pre-Study Poll: We conducted a pre-study poll to assess how users interpret the skin-stretch device's haptic feedback. While watching the cursor autonomously move on the screen (at a self-selected frequency between 0.25 and 1 Hz), 19 users (mainly engineering students and professors) put their index fingers over the tactor and switched between control paradigms, numbered 1 through 4. They were asked, "*Which of the skin-stretch controllers most intuitively represents the on-screen cursor movement?*" Users spent approximately 5 minutes testing the different controllers before verbally indicating their selection to the experimenter.

2) Human User Study: Four volunteers participated in a user study with the Emotiv EPOC headset and skin-stretch device. The study was approved by the Stanford University Institutional Review Board and all participants gave informed consent. Participants were healthy, right-handed males with no sensory deficits and no history of neurodegenerative disease, between 22 and 29 years of age. Participants were given a 15-minute training period with the Cognitiv Suite of the Emotiv Control Panel. Based on the Cognitiv Suite's underlying evaluation of user proficiency following the training period, Participant 1 was reported to display expert-level control, and Participants 2, 3, and 4 exhibited novice-level control.

During the study, participants used the Emotiv headset to move the on-screen cursor (small sphere) to a target (large sphere) in one dimension (Fig. 3). They were free to use whatever "cognitive strategies" they found most effective. Each session of the study consisted of 4 blocks of 20 cursor-movement trials. Each trial began with the target appearing on either the right or left side of the screen, a fixed distance away from the center. Starting from the center, participants were given 20 seconds to move the cursor to the target. Success was signaled if they reached the target within the time limit; otherwise, the trial ended. Performance metrics were defined as follows:

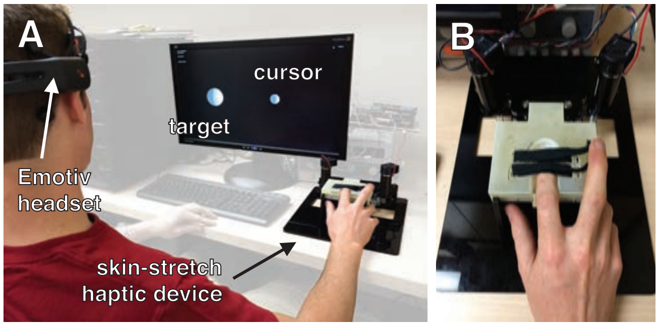

Fig. 3. (A) A participant performing the one-dimensional cursor-movement task using the Emotiv EPOC neuroheadset. (B) Close-up of the participant's finger secured in the finger mount.

- **Number of Successful Trials**: The number of trials during which the subject commanded the cursor to the target within the allotted time.
- **Time-To-Acquisition**: The amount of time elapsed during a trial, where the end was marked by the small cursor being fully enveloped in the target.
- **Cognitive Percentage**: The percentage of time during a trial when the BCI classified a participant's thoughts as being directed towards the target. This captures the accuracy of BCI-based movement-intent classification. For example, if a participant thought "right" for 750 of 1000 samples during a trial with the target on the right, his *Cognitive Percentage* would be 75%.

During blocks 1 and 3, participants experienced no haptic feedback. During blocks 2 and 4, participants experienced position-based, cursor-aligned ($p+$) skin-stretch feedback at the index fingertip. Visual feedback of the cursor and target was provided in all blocks. The participants alternated between haptic conditions to compensate for any order effects. Regardless of haptic feedback, participants' right index finger remained secured in the skin-stretch device. Each block lasted 6-8 minutes and was followed by a 3-minute break. Due to the stark difference in baseline BCI control capabilities between Participant 1 and Participants 2-4, Participants 2-4 were tested for twice the number sessions as Participant 1 (4 versus 2 sessions total); all sessions were conducted over the course of two weeks. The first session was preceded by a 15-minute training session with the Emotiv Control Panel (to build the EPOC's neural-activity mapping) and a 10-minute maximum period of experiencing the four skin-stretch control paradigms. No training was provided at the beginning of the subsequent sessions. Each participant devoted 4-5 hours to the study. This significant time committment limited the size of the participant pool.

B. Results

1) Pre-Study Poll: Fig. 4 shows the results from the poll on skin-stretch "intuitiveness". More than 80% of users found the cursor-aligned control paradigms to be more intuitive than their anti-aligned counterparts. Of these users, over 65% preferred position-based over velocity-based control. Thus, the $p+$ condition was used in the main study.

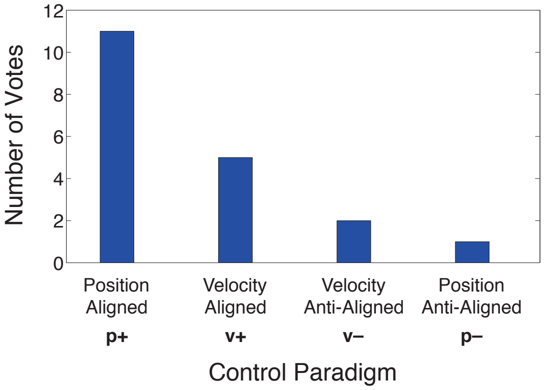

Fig. 4. Votes for intuitiveness of the four skin-stretch control paradigms, collected during the pre-study poll.

2) Human User Study: For the *Number of Successful Trials* metric, all participants displayed no significant difference between haptic conditions (with versus without skin-stretch feedback) in a two-sided Wilcoxon rank-sum test; data not shown. For the *Time-To-Acquisition* metric, the low *Number of Successful Trials* performed by Participants 2, 3, and 4 meant that *Time-To-Acquisition* was undefined for many of their trials; this made it an unacceptable statistical measure of performance for all participants. For the *Cognitive Percentage* metric, all participants displayed a significant difference between haptic conditions. The details are presented in Figs. 5 and 6. The "haptics" label indicates the fingertip skin-stretch feedback.

Fig. 5, which combines blocks of the same haptic condition, presents our primary finding: *Cognitive Percentage* was statistically significantly (*) higher for all but Participant 3 when operating the BCI with skin-stretch haptic feedback than without the skin-stretch feedback (two-sided Wilcoxon rank-sum test, $p < 0.05$). Participant 3 exhibited the opposite trend, a statistically significant (**) decrease in *Cognitive Percentage* in the presence of skin-stretch feedback (two-sided Wilcoxon rank-sum test, $p < 0.05$). Significance was evaluated using the nonparametric Wilcoxon rank-sum test because histograms of cognitive-percentage data did not meet normality conditions. Looking at the blocks separately, Fig. 6 depicts the expected performance fluctuation for an A-B-A-B designed study. For Participants 1, 2, and 4, *Cognitive Percentage* increased when transitioning from trials without skin stretch to those with skin stretch and decreased upon the transition back. Participant 3 exhibited exactly the opposite trend.

V. DISCUSSION

A. User Interpretation of Haptic Feedback

Given the ubiquity of computer trackpads, which map finger position to cursor position and exert frictional forces on the finger opposite the direction of cursor movement, we originally hypothesized that the position-based, cursor-anti-aligned ($p-$) control paradigm would be most intuitive for participants. Although our poll did support a position-based

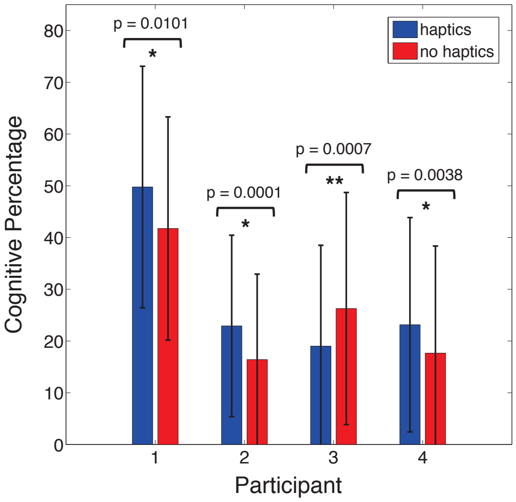

Fig. 5. *Cognitive Percentage* (percentage of time during a trial when the BCI classified a participant's thoughts as being directed towards the target) aggregated across sessions and combined for blocks of the same haptic condition. Bars are means, error bars are standard deviations. Asterisks indicate a significance difference at the $p = 0.05$ level based on a two-sided Wilcoxon rank-sum test.

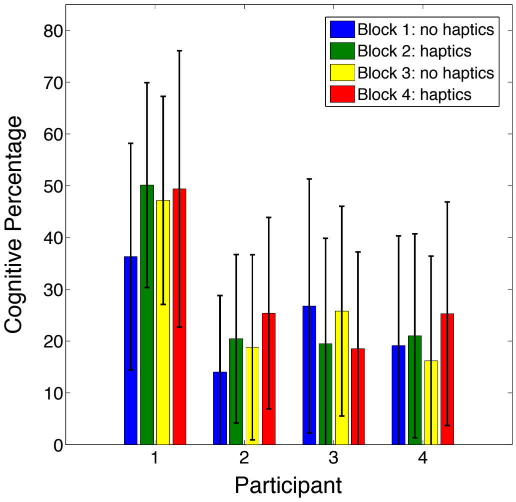

Fig. 6. *Cognitive Percentage* aggregated across sessions. Bars are means, error bars are standard deviations.

paradigm, it was the cursor-aligned ($p+$ and $v+$) feedback methods that were voted as most intuitive. This implies that most users interpret the feedback as a substitute for proprioception, not a re-creation of the trackpad experience. That said, the sample size for our poll was small and biased towards a population familiar with haptic devices. A larger and more diverse population would be necessary to fairly evaluate the four control paradigms.

Although the $p+$ control paradigm was voted as most intuitive by users, many of those who voted for $p+$ commented that $v+$ was also highly intuitive. Given humans' ability to path integrate from tactile cues at the fingertip, this is not surprising. It is also important to note that those who preferred $v+$ (or at least commented on its intuitiveness) had experienced the device under manual control. This suggests that a velocity-based mapping has some connection to kinesthesia and proprioception.

B. Effect of Haptic Feedback on BCI Control

Contrary to expectations, the skin-stretch feedback did not translate to a greater *Number of Successful Trials* in the cursor-control task. This is likely due to the nature of the task. The nearly perfect performance of Participant 1 indicated that the task was too "easy" for him; as noted above, he exhibited an expert level of baseline control over the Emotiv EPOC. His improvements were not reflected by such a gross metric as the *Number of Successful Trials*. Comparatively, the baseline control of Participants 2-4 was low and inconsistent. Their high variance meant that the success metric could not capture their improvements. Tailoring the task to each individual — for example, increasing the time allotted for target acquisition — could increase the *Number of Successful Trials* for Participants 2-4.

The data presented in Figs. 5 and 6 examine the short-term effects of skin-stretch feedback on BCI control. For all participants, skin stretch — specifically, that provided via the $p+$ controller — had a significant cognitive effect as they attempted to control the cursor. In line with expectations, it increased *Cognitive Percentage* for Participants 1, 2, and 4. Because *Cognitive Percentage* is a direct measure of the BCI's classification of movement intent, the skin-stretch feedback may have helped these participants to visualize left and right motor imagery, leading to more reliable decoding of their neural activity. For example, Participant 1 imagined "*physically dragging the cursor*" when controlling the BCI. Perhaps importantly, the Emotiv EPOC does not position any electrodes over the sensorimotor cortex. Therefore, motor imagery may not be synonymous with sensorimotor activity. To understand the effect of the skin-stretch feedback on actual sensorimotor activity, it would be necessary to either tilt the Emotiv EPOC back on the head (positioning as many as 8 sensors over the sensorimotor region) or use a more configurable and precise BCI, as we are doing in ongoing work with a g.tec EEG headset.

Surprisingly, the reportedly intuitive $p+$ feedback decreased *Cognitive Percentage* for Participant 3. This could be due to this individual's extensive experience with skin-stretch-based sensory substitution. He might have performed better with the $p-$ paradigm. Additional experimentation would be necessary to test this hypothesis.

The design of this study does not address long-term adaptation to the skin-stretch feedback. However, due to the nature of Emotiv's classification algorithms, performance in the cursor task should improve over time regardless of haptic feedback. So, it is reasonable to assume the presence of some learning period. While our data demonstrates that haptic feedback has an immediate effect on BCI control, a user would likely benefit from more experience with the fingertip skin stretch. Moreover, this could lead to "internalization" of the skin stretch, improving BCI control even when skin-stretch feedback is not physically present.

C. Future Work

We propose several future research directions for the project. With regard to the hardware, users reported needing to push down on the device to prevent the tactor from slipping on their fingertip. This increase in normal force masked some of the lateral skin stretch that they experienced. To remedy this, the device can be stiffened. In addition, we will modify the finger mount for interchangeable inserts, each rapid prototyped for an individual user's finger dimensions. Such inserts will better constrain the finger and allow for more effective skin-stretch stimulation.

The design of this device was motivated by ALS patients, for whom motor function progressively degrades while sensory pathways remain intact. However, we acknowledge that many BCI users (e.g., those suffering from spinal-cord injury) may not be able to sense skin stretch at the fingertip. The haptic device can be modified for skin-stretch stimulation on other sensate parts of the body, such as the skin of the face, scalp, or neck. Ultimately, we hope to make the device compact enough that it can be unobtrusively worn at all times when and in all places where the BCI is used. This miniaturized version of the device might take the form of a haptic glove or thimble, similar to the work in [14].

With regard to control, our device's skin-stretch feedback is currently based on the state of the BCI-driven cursor (i.e., a simple scaling of the actual position or velocity). Most feedback paradigms are instead rooted in the error between this actual state and some desired state, such as the cursor's target position. Based on the work of Wei et al. [15], such an error-based control paradigm has the potential to accelerate learning. Learning could be similarly accelerated by using machine-learning algorithms to adjust control gains in real time, tailoring feedback to individual users. It may also be possible to supplement the skin-stretch feedback with other forms of tactile haptic feedback. For example, carefully tuned vibration can render compelling stick-slip friction, viscosity, and inertia [16], or even enhance a user's tactile sensitivity [17].

The studies presented herein motivate increasing the number of participants and trials. Additionally, we should test how the less intuitive control paradigms affect BCI control because“intuitiveness” does not always map directly to performance. Moreover, how effective is skin-stretch feedback in two dimensions, or if the object controlled by the BCI is no longer a virtual cursor but a physical device? Ultimately, we plan to test the device with ALS patients having intracortical BCIs controlling in multiple DOFs. This work will be in collaboration with the Neural Prosthetics Translational Laboratory at Stanford, which is involved in the nationwide BrainGate2 project (http://www.braingate2.org).

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