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PERIPHERAL NERVE STIMULATION AND AUDITORY SIMULATION CLOSED LOOP SYSTEM FOR SENSORY DECISION MAKING IN TRANSHUMERAL AMPUTEES

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ABSTRACT:
Peripheral nerve stimulation (PNS) is a key method for restoring sensory feedback in upper-limb prostheses, yet the necessity of invasive feedback for sensory decision-making remains uncertain. In this study, two transhumeral amputees underwent sensory restoration in their phantom limbs via PNS. They performed an active exploration task using a tablet and closed-loop feedback system to assess their sensory decision-making abilities. In the task patient needed to differentiate among three hidden objects using PNS-based tactile feedback or auditory feedback. Interestingly, one patient successfully completed the task only in PNS trials, while the other demonstrated improved speed and accuracy with auditory stimulation. These findings suggest varying responses to different feedback modalities in different subjects. They indicate the potential significance of personalized approaches in designing sensory feedback systems for prosthetic users.

INTRODUCTION

Phantom limb pain (PLP) affects 80% of individuals who have undergone amputations [1,2] and can be managed through neuromodulation techniques like peripheral nerve stimulation [3]. These methods not only help reduce phantom limb pain but also have potential applications in enhancing sensory feedback for neuroprosthetics [4].

Invasive and noninvasive methods for restoring somatic sensations have their advantages and disadvantages. For instance, vibromotors have a limited stimulating range, leading to restricted sensations [5]. On the other hand, the higher spatial resolution can be achieved with invasive techniques compared to noninvasive methods. Neurostimulation systems integrated as part of bidirectional brain computer interface (BCI) enable the discrimination of object size and texture, improving prosthesis embodiment and enhancing motor control [4,6].

Nevertheless, the necessity of invasive feedback for sensory decision-making remains uncertain. This question was explored in our previous study [4], where we demonstrated that prosthetic systems utilizing transcutaneous electrical nerve stimulation (TENS) may offer comparable efficacy to PNS-based systems. Additionally, feedback in bidirectional BCI can be delivered through alternative sensory modalities such as auditory cues [10]. Although these systems do not elicit tactile sensations in the phantom or residual limb, they may reduce cognitive load [11] and enhance performance [9]. Despite extensive research on various forms of sensory feedback, it remains unvalidated whether invasively delivered somatotopically matched feedback can augment sensory decision making in amputees compared to auditory stimulation.

To address this question, we conducted a study with two transhumeral amputees completing a sensory decision-making task under two conditions. In a part of trials, they relied on auditory feedback and in the other part they relied on a PNS-based feedback that projected to their phantom limb as somatic sensations. One patient successfully completed the task relying on PNS feedback, whereas the second patient exhibited greater speed and accuracy when utilizing auditory stimulation.

MATERIALS AND METHODS

Two individuals with amputations took part in the research, both experiencing phantom limb pain (PLP). The study received approval from the Ethical Committee of the Biomedicine School at Far East Federal University (FEFU) under Protocol #4 on April 16, 2021. Prior to their involvement in the experiments, each patient provided informed consent. The study is registered as a clinical trial on https://clinicaltrials.gov/

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Participants S12 and S13 underwent the electrode implantation in their left residual limb on a level of shoulder. The implantation surgeries were conducted at the Medical Center of FEFU. Eight-contact electrodes (Directional Lead for the St. Jude Medical Infinity™ DBS System; Abbot; USA) were implanted in the median nerve of all patients while under endotracheal anesthesia.

After the surgery, both patients underwent though the sensory mapping procedure where the electrode sites that caused sensations in phantom hand were discovered. The details about sensory mapping protocol can be found in a subsequent research [4]. Since sensations evoked by stimulation were stable among seven days, both patients were involved in the experiment to access their ability to sensory decision making. During the sensory mapping, S12 tended to report that his sensations were of high naturalness.

In our previous study we introduced an active exploration task where participants explored invisible objects using artificial tactile sensations provided by TENS and PNS. Here, we used a similar protocol, but with the use of auditory feedback instead of TENS. Thoroughly, patients used their intact limb to scan the tablet surface using a stylus and searched for an invisible object. Whenever the stylus made contact with the object, sensory feedback was provided through sound or electrical stimulation. The objects could be in the shape of a square, circle, or pentagon and they were randomly selected for each trial along with two types of sensory feedback: PNS or Auditory. To increase the difficulty of object recognition, the rotation angle of the object varied for each trial (Fig. 1).

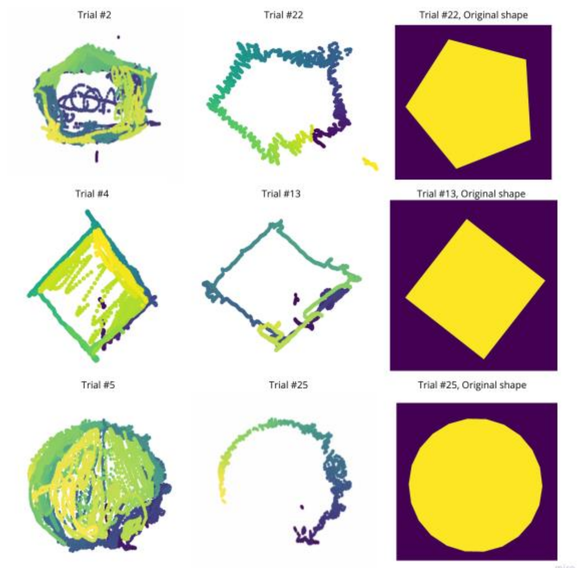

Figure 1. Different shapes of active exploration task.

For trials with auditory feedback, each time the stylus touched an invisible object, 1000-Hz sound was turned on. For PNS trials, two modes of stimulation were employed, namely baseline and target, with identical frequency and pulse width but varying amplitudes. The amplitude in the baseline mode remained below the sensory threshold while it surpassed the threshold in the target mode. The NimEclipse stimulator was linked to the laptop, which was connected to the tablet. Upon tapping the screen area that corresponded to the invisible shape, the Python script transitioned from baseline to target stimulation mode, thereby enabling the subject to perceive the shape. S12 and S13 utilized a stylus held in the intact limb to interact with the tablet. For both S12 and S13, stimulation settings were chosen individually to elicit tactile sensations in the fingers of the phantom limb.

The active-exploration sessions were held on post-surgery days 8 and 20 for each subject. On each of these days, the experiment consisted of two sessions: a learning session and an evaluation session. During the learning session, participants saw the history of their touches of the screen as black lines. For learning session completion, it was required that the subject to correctly guess each object twice for both auditory and PNS feedback. Each time when an object was recognized correctly, the respectful trial was eliminated from the list of unguessed yet trials. Next trial was randomly selected from that list.

An analysis of variance (ANOVA) was performed to compare the trial durations of patients based on two factors: the feedback type (PNS or Auditory) and the experimental day (day 8 or day 20) for each subject separately.

RESULTS

Both subjects could complete the following task using both types of feedback. Patients completed the active exploration task by scanning the tablet with a stylus. During the first trials, subjects attempted to differentiate between objects attempting to draw the entire figure; the trajectory of their movements can be seen in the first column of Fig. 1. Since the experiment operator did not instruct patients on the best approach to resolve this task, it took several trials for both patients to discover the so-called “border strategy”. In this strategy it is expected that a participant discovers objects’ border by detecting the moments of stimulation on and stimulation off switch.

During day 8, both subjects met the requirements for completing the learning part of the task. S13 needed 7 trials to complete the training with only one mistake made (Fig. 2a). S12 completed the learning session after performing 20 trials. During the evaluation part of the session: S12 performed with an accuracy of 17%, and S13 with an accuracy of 67%. The chance level was 33%.

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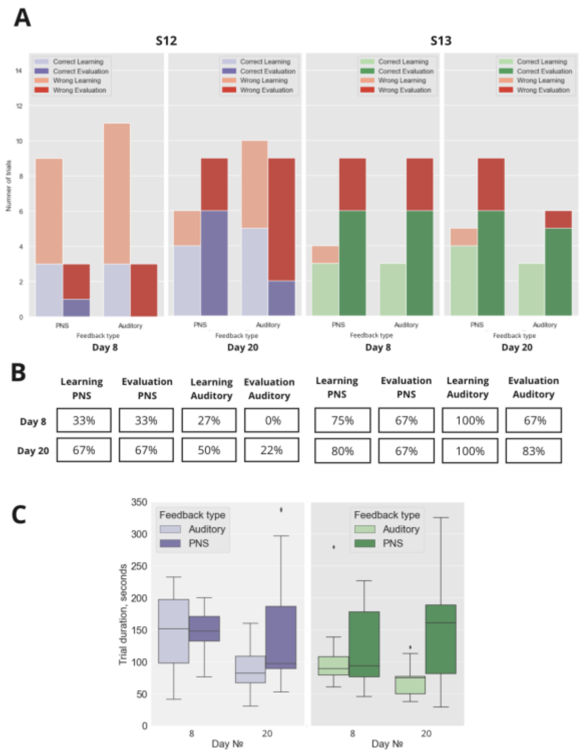

Figure 2. Active exploration task results. (A) - Each panel represents number of trials conducted during day 8 and day 20 for subjects S12 and S13. Bars in each panel represent the number of correctly recognized objects (depicted in purple and green) and erroneously recognized objects (depicted in red) under both PNS and Auditory feedback conditions. Paired bars differentiate the number of trials in learning and evaluation sessions, as S12 and S13 required different numbers of trials to transition to the evaluation session. (B) – Percentage of correctly recognized objects in each experimental session (C) - Variation of trial duration for PNS and Auditory conditions during sessions in day 8 and day 20

During day 20, S12 completed the training session in 16 trials. S13 completed the training session in 8 trials. During the testing session, performance improved in both subjects compared to day 8. Performance accuracy was 44% and 75% in S12 and S13, respectively. In S12, accuracy was 22% when using auditory feedback and 67% when using PNS feedback, while in S13 accuracy made up 67% and 83% respectively (Fig. 2b). S12 mentioned that he felt as if his phantom limb touched the table screen when the PNS-based feedback was used.

We conducted a comparison of the number of seconds taken by patients to complete the trial (trial duration) using ANOVA, considering two factors: the type of feedback (PNS vs Auditory) and the day of the experiment (day 8 vs day 20). The analysis for S12 revealed near significant difference among means of trial duration for two feedback types (F-st(1)=4.167568; p_value=0.045927; two-way ANOVA), for different days (F-st(1)=3.646682; p_value=0.061309; two-way ANOVA) and for the factor interaction (F-st(1)=3.393133; p_value= 0.070766; two-way ANOVA) (Fig. 2c). For S13 the mean trial time was different for different feedback types (F-st(1)=4.681291; p_value= 0.035964; two-way ANOVA) and day-feedback type interaction (F-st(1)=3.345151; p_value= 0.074186; two-way ANOVA), no significant difference was observed for different days (F-st(1)=0.008421; p_value=0.927299; two-way ANOVA).

After the pairwise comparison analysis, we revealed that S12 needed less time to complete auditory feedback trials during the day 20 in comparison with auditory feedback trials in day 8 (Mean diff.=-58.4792 ; p-adj=0.0495; Tukey HSD); PNS trials in day 20 (Mean diff.=59.4498 ; p-adj=0.039; Tukey HSD); PNS trials on day 8 (Mean diff.=-57.5598 ; p-adj=0.0719; Tukey HSD). Similarly, S13 completed auditory feedback of day 20 faster than in PNS trials of day 20 (Mean diff.=73.937; p-adj=0.0354; Tukey HSD).

Eventually, S12 had lower accuracy of object recognition in auditory trials, despite the increased speed. By contrast, S13, having a shorter duration of auditory trials, completed the active exploration task with the higher accuracy in both types of feedback.

DISCUSSION

In this study sensations in phantom limb of two transhumeral amputees were restored with the use peripheral nerve stimulation. To estimate their capabilities of sensory decision making, they completed active exploration task with the use of tablet and closed loop feedback system. One of patient was able to complete the task only with the use of PNS feedback, while the second one was faster and more accurate when used auditory stimulation.

In a previous study, it was demonstrated that active exploration tasks can be performed with comparable accuracy using PNS and TENS feedback [4]. In this experiment, under similar conditions, it was found that these tasks could be successfully completed with auditory feedback. Notably, participant S13 exhibited higher accuracy in shape recognition with auditory stimulation, completing trials more quickly compared to PNS feedback trials.

In the same exploration task, another participant, S12, achieved a higher score in PNS trials than in auditory feedback trials. While the study was limited to two patients, indicating caution in drawing broad conclusions, a distinct difference between the two subjects was observed. This variance may be attributed to two main factors. Firstly, S12, who performed better in PNS trials, likely had greater familiarity with PNS stimulation due to its inclusion in their treatment regime. Secondly, S12 perceived PNS as more natural during sensory mapping. Though, these two observations can be associated, because previously it was shown that long-term PNS stimulation in neuroprosthetics has been associated with an enhanced sense of naturalness [7].

Since PNS is a primary method for sensory restoration in upper-limb prostheses [6], it is of great interest to understand the benefits and limitations of PNS

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compared to other stimulation approaches. PNS can evoke natural tactile feedback, enhance embodiment in upper-limb prosthetic devices, and alleviate PLP [4,6,8]. These preliminary findings suggest individual variability in response to different feedback modalities, albeit within the constraints of a small sample size. They underscore the potential importance of personalized approaches in designing sensory feedback systems of bidirectional BCI systems and prosthetic users particularly, while acknowledging the need for further research with larger and more diverse cohorts

CONCLUSION

PNS is an efficient approach to provide feedback to amputees in sensory decision-making tasks and allow them to differentiate between different objects relying on tactile information. However, at least for some patients, alternative sensory feedback devices could offer upper-limb amputees the opportunity for feature recognition without the need for surgery and associated risks.

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