EXPLORING THE POTENTIATION OF SENSE OF OWNERSHIP THROUGH PROPRIOCEPTION FOR A SENSORY INTERFERENCE TASK

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ABSTRACT

A strongly perceived sense of ownership (SoO) of an amputees' device paired with agency leads to aspects of embodiment for that device. The purpose of this research was to explore the potentiation of SoO through proprioception while using a tactile feedback modality. In a sensory interference task, participants responded to vibrotactile stimulation presented to their index finger and thumb while experiencing incongruent and congruent visual feedback, with and without proprioceptive feedback. We found that participants' crossmodal congruency effect (CCE) scores for the vibrotactile feedback were higher when experiencing proprioceptive feedback that aligned with the movement of the virtual hand on the screen. Providing prosthesis users with more intuitive and useful sensory feedback may increase their perceived SoO of their device. When paired with agency, this can lead to improving their control performance and device acceptance.

INTRODUCTION

Improving prosthesis control performance can contribute to better user experience while using a device. Effective embodiment, defined as a prosthesis being 'part of' the user and having a psychological investment into the self, has been found to promote better control performance and help restore the perceived integrity of a body that has been altered by amputation [1]–[3]. Research suggests that embodiment arises from the interplay of sense of agency (SoA) and sense of ownership (SoO) [4]. SoA is elicited by the experience of initiating and controlling your actions, and it distinguishes our own self-generated actions from actions generated by others [5]. SoO is defined as the user's perception of their device identifying with and belonging to their body, occurring as the result of the integration and interpretation of visual, tactile and proprioceptive signals [3]–[7]. It is well known that linking augmented feedback to improvements in performance is challenging and researchers need to be strategic and intentional on the purpose and delivery of the sensory feedback [8]–[12]. Exploring sensory feedback for upper-limb prosthesis users that enables SoO and SoA and thus embodiment is accordingly a meaningful area of study.

In recent work, we explored the fusion of tactile and kinesthetic feedback on performance and ownership for two participants with sensory-motor targeted reinnervation [10]. In a similar sensory interference task to what is described in this paper, we found that both participants showed levels of limb ownership that were aligned with able-bodied responses to skin deformation; however one participant had reduced CCE scores when kinesthesia was added to their tactile feedback modality. This result was unexpected and was possibly influenced by technical inconsistencies in the participant's kinesthetic feedback system. The sample size of this work was limited due to international travel requirements and the intensive experimental time required. In order to explore this further with a larger sample size, we re-designed the experiment to accommodate able-bodied participants, as described in this paper.

The goal of this study was to determine the influence of proprioceptive feedback on perceived SoO for a sensory interference tactile feedback task. Existing literature has demonstrated that the crossmodal congruency effect (CCE) score can be used as an objective measure for perceived SoO [13]. To explore the potentiation of SoO through proprioceptive feedback, we calculated CCE scores during a sensory interference task. Participants were subjected to vibrotactile feedback to either their finger or thumb and were instructed to respond where they felt the stimulation via foot pedals. Simultaneous to the vibrotactile feedback, visual feedback was provided on a virtual hand on a screen either congruent or incongruently. Participants completed two sessions of the experiment: with and without proprioceptive feedback.

EXPERIMENTAL DESIGN

Recruitment

Written informed consent was obtained under the guidelines and approval of University of New Brunswick's Research Ethics Board prior to conducting the experiment. Fourteen able-bodied participants completed the study [mean age = 27.7yrs, range = 19–51yrs, 5 female, 1 left-handed]. Participants were randomly assigned feedback modality order to account for learning effects. Participants completed their second session one week after their first at the same time of day in an attempt to ensure similar levels of alertness between the two sessions.

Experimental Setup

Participants placed their dominant hand behind a monitor displaying an image of a hand in the same anatomical position as the participant (Fig. 1 a). Vibro-tactile motors (Precision Microdrives 10mm Linear Resonant Actuators – 4mm type) affixed to the participants index finger and thumb with medical tape (3M, Micropore) provided vibrotactile feedback (2.5G, 175Hz) corresponding to when the virtual hand had grasped the object on-screen (Fig. 1 b). The participants index finger and thumb were also secured to a slide potentiometer (Bourns Inc. 10KΩ 45mm travel range) in order to ensure that the position of their hand matched the position of the image on the screen. When participants pressed a key on a keyboard with their non-dominant hand, the virtual hand on the screen began to close at a fixed speed of 52deg/s. A PC running Processing (Release 3.5.4) displayed the GUI while also controlling the inputs and outputs through an Arduino Uno R3 microcontroller. A motor controller (Adafruit Industries LLC, model 2305) was controlled by the Arduino to actuate the vibrotactile motors.

Simultaneous to the vibrotactile feedback provided to either the participants' index finger or thumb, visual feedback on screen representing an LED was provided to either the index finger or thumb of the virtual hand upon object contact. This visual feedback was either incongruent or congruent to the tactile stimulation (Fig. 2 a). A green circle representing a fixation LED remained in the middle of the virtual object being grasped on-screen, half-way between the index and thumb (Fig. 2 b). Participants were instructed to respond where they felt the tactile feedback via foot pedals (Ammoon Sustain Damper Pedal), indicating with the toe pedal if they felt the vibrotactile stimulation on their index and with the heel pedal if they felt the stimulation on their thumb.

Figure 1: Experimental Setup. a) An able-bodied participant looking at an image of a hand on a monitor with their dominant hand behind the screen in the same anatomical position. Note that the lights were off for all testing conditions. b) The dominant hand of the participant affixed with vibrotactile motors and a linear potentiometer. c) Virtual hand-close indicating the end of a trial with the distractor LED illuminating on the index finger, either congruent or incongruent to the tactile feedback provided to the participants' dominant hand. d) The point of focus for participants, a fixation LED in the middle of the object on-screen.

Participants wore noise-cancelling headphones playing Brownian noise to mask background noise. Participants completed two sessions of this experiment; each session was assigned a different feedback modality. In one session, participants were instructed to keep their hand in a static open position during all trials. In the other, the participant mimicked the hand closing on the screen. Hand position was verified by the linear potentiometer and the trial was rejected if the participant's hand position did not match the position of the hand on the screen at the start and end of the trial, with a tolerance of ±1cm. Participants completed 10 practice trials with the lights in the room on and the Brownian noise off, followed by 10 practice trials with the lights off and Brownian noise on. They then completed four testing blocks of 64 trials each, with the lights off and Brownian noise on. Participants rested for 2 minutes between blocks.

Outcome Measures

The crossmodal congruency effect score (CCE_{Score}) objectively quantifies incorporation without being susceptible to experimenter biases and is calculated as the difference in the mean response time between congruent and incongruent trials [14].

$$CCE_{Score} = \bar{t}_{incongruent} - \bar{t}_{congruent}. \qquad (1)$$

Statistical Analysis

Statistical analysis was performed using RStudio IDE software. A Shapiro-Wilk test was used to investigate homogeneity in the variances of the data. As the CCE score data variances were found to be nonhomogeneous, a Wilcoxon signed-rank test was conducted with CCE score as the dependent variable and feedback modality as the independent variable. The confidence interval was calculated using the standard deviation (95% CI = mean ± 1.96 × SD). All numbers in the text refer to mean ± SD.

IV. RESULTS

To explore the potentiation of SoO through proprioceptive feedback for a vibrotactile feedback modality, we assessed participants incorporation for each condition by calculating their CCE scores when completing the sensory interference task. We found that adding proprioception did indeed allow the potentiation of SoO, achieving significantly higher CCE scores (122.17 ± 61.45) than when only tactile feedback was used (88.61 ± 60.61) (p-value = 0.009), see details in Fig 2.

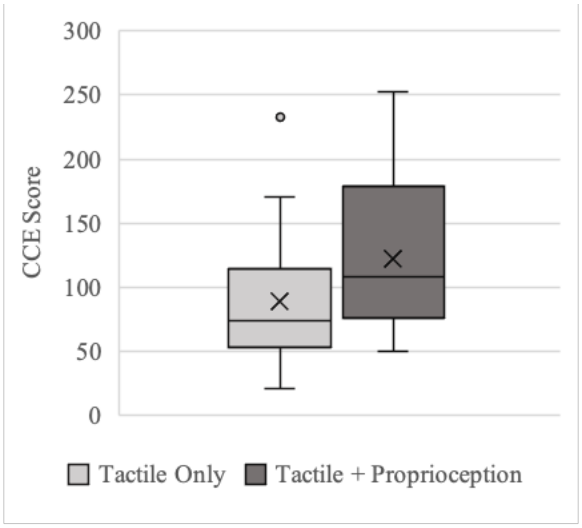

Figure 2: Box-plots showing the CCE scores for the tactile only and tactile + proprioception conditions. CCE Scores increase with the addition of proprioceptive feedback to the feedback modality. The mean of the data is represented as the x within the boxes while the median is represented as the line. The bottom and top of the box represent the lower and upper quartile, containing 50% of the data. The lines outside of the box represent the minimum and maximum values. The circle represents the outlier.

DISCUSSION

The goal of this study was to determine the influence of proprioceptive feedback on perceived SoO for a sensory interference tactile feedback task. To explore the potentiation of SoO through proprioceptive feedback, we calculated CCE scores for a sensory interference task which included two sessions, one with their hand in a static position (tactile only condition) and one with their hand mimicking the hand close on-screen (tactile + proprioceptive condition). We found that participants achieved higher CCE scores in the tactile + proprioceptive feedback condition than in the tactile-only feedback condition, indicating they had a higher level of ownership for the tactile + proprioception feedback modality. This study suggests that SoO can be potentiated through the addition of proprioceptive feedback to a tactile feedback modality. Providing prosthesis users with more intuitive and useful sensory feedback may increase their perceived SoO of their device. When paired with agency, this can lead to improving their control performance and device acceptance.

Although the results found in this study suggest that SoO can be potentiated through the addition of proprioceptive feedback to a tactile feedback modality, this work did not decouple proprioception and kinesthesia. A follow-up study worth considering is to replace the key-press hand close actuation with an isotonic and isometric actuation in order to allow for this decoupling. From there, these results must still be confirmed in the target population. Future studies may access more sensory-motor targeted reinnervation participants as it becomes the standard of care for prosthesis control, neuroma and pain management [10].

During data collection, two participants reported feeling simultaneous vibrations in their index and thumb throughout the experiment. After further investigation, this was determined to be phantom vibration. This is likely due to participants gaining an illusory SoO over the virtual hand on screen due to proprioceptive drift [4]. Two different participants reported that the vibrotactile stimulation was always congruent with the visual feedback. After completing trials with their eyes closed to eliminate visual feedback, it was determined that the stimulation was both incongruent and congruent, however the participants were perceiving the visual stimulation to always be correct. In one case, the subject was not able to correctly respond to incongruent trials rendering their data unusable due to high error percentage (53.1%). One subject was excluded for failure to reliably coordinate their hand close with the hand close on-screen.

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