TOWARDS OBJECTIVE ASSESSMENT OF OWNERSHIP OVER A PROSTHESIS

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ABSTRACT

Conventional motor assessments provide limited actionable information to prosthetic clinicians and engineers. Recent work has sought to develop objective ways to measure psychological aspects of a person controlling a prosthesis to develop more powerful motor assessment tools. One area of emphasis has been to develop a way to objectively measure device ownership, a key component of embodiment. Assessment of ownership has historically been limited to subjective questionnaires but here we use a spatial interference reaction time task, the crossmodal congruency task (CCT), to objectively assess this key factor in supporting prosthesis use. We improve the CCT protocol to increase its usability. We aim to establish a causal link between ‘device ownership’ and the crossmodal congruency effect, a correlational link observed in previous work. In this paper we summarize our efforts to develop a comprehensive platform to assess ownership and share results from an initial study.

INTRODUCTION

Emerging prosthetic devices using peripheral nerve interfaces [1], [2], targeted reinnervation [3], [4] and non-invasive control and feedback strategies [5], [6] show promise. However, the methods used to assess these technologies often provide limited information. Performance measures, such as the Box and Blocks Test [7], the Southampton Hand Assessment Procedure [8] and the Jebsen Hand Function test [9], provide little mechanistic insight with results that can be distorted by interacting compensatory movements [10]. Functional assessments like the Assessment of Capacity for Myoelectric Control [11], although shown to be reliable [12], rely on subjective scoring provided by trained raters. Recent efforts in the development of motor system assessments have focused on objective measures that are theoretically-grounded in neuroscientific and psychological principles [13]. Quantifying aspects of a prosthetic system that are involved in control of an intact limb may aid in identifying deficiencies in the engineered systems that might *explain* differences in observed motor performance. The goal is to use assessments to inform, target and customize device improvements to try to better mimic their biological system counterparts.

Recent efforts to develop objective assessments have focused on measuring the psychological factors that are involved in a motor system. One goal in engineering a prosthetic device is to convey to the user a sense of embodiment [14]. That is, the device is felt as an integrated part of one’s body [15]. Although there remains some debate about what psychological aspects contribute to the sense of embodiment, it is thought that both a sense of ownership and a sense of agency (or control) over the device are required [16], [17]. Much work has been done to assess ownership, agency, and embodiment overall but these studies typically rely on subjective questionnaires [4], [18]. Furthermore, these studies are often correlational, lacking direct experimental manipulations to identify causal links between factors contributing to embodiment. When experimental manipulations are undertaken, they usually focus on one aspect of embodiment (e.g. ownership [19] or agency [20]), and not their interaction.

We have undertaken a series of studies [21] to explore embodiment using a standardized simulated prosthesis system. We aim to simultaneously assess the sense of agency and the sense of ownership using objective measures. In this study we focus on ownership assessment. But why is it important to measure ownership and agency with respect to prosthetic devices? We argue that if a device is more incorporated into one’s body image by feeling (ownership) and moving (agency) like one’s own biological limb, it will be more functional and more useful. We anticipate that increases in ownership and agency will lead to better motor performance, reduced user frustration, increased device use and reduced rates of device rejection which has been shown to be a key roadblock in prosthetic device implementation [22].

Our recent work has developed objective ways to measure the sense of ownership using an adapted crossmodal congruency task (CCT) [23], [24]. An increase in ownership is correlated with an increase in the reaction time (RT) difference between congruent (aligned) and incongruent (misaligned) sensory stimulation. This RT difference is called the crossmodal congruency effect (CCE) score. Here we present an improved protocol for assessing ownership using a simulated prosthesis. First, we highlight the improvements we have made on our previous work and that of Marini et al. [25]. Then we describe results from an initial study and ongoing experiments to validate this new experimental platform. Finally, we present our upcoming experimental plans to better understand the dynamics of device ownership and its interaction with the sense of agency.

IMPROVING THE CROSSMODAL CONGRUENCY TASK

We first sought to develop an improved objective ownership assessment. Across individuals, we observe high variability in CCE scores [26]. This would imply that within-subject assessment may be more informative (as in [25]). However, due to a practice effect observed with the repeat use of the CCT [26], we expect changes in CCE scores with repeat task completion. Therefore, we looked to improve the implementation of the CCT by reducing inter-individual variability to allow for the use of between-subjects designs in future experiments.

One potential reason for the high variability in CCE scores was due to the random trial order presented to participants. In our previous work [23], the stimulus condition (congruent vs. incongruent, and location) was randomized independently for each trial. Typically, half of testing trials are congruent and the other half incongruent. However, if during initial practice and testing trials the actual percentage congruent were not 50% (which is likely in small samples of random trials) we might see different learning dynamics occur. Congruency expectation might lead to different responses and variable CCE scores, early model learning that could persist throughout testing. When presented with different percentages of congruent trials in other psychophysics tasks, we see significant changes in the RT differences between congruent and incongruent stimuli [27].

We analyzed previously collected CCT data [26] to determine if a congruency sequence effect is present in CCT results. RT data on correctly discriminated trials were sorted into four groups representing the possible congruency combinations for each pair of trials: Congruent then congruent (CC); Incongruent then congruent (IC); Incongruent then Incongruent (II); and Congruent then Incongruent (CI). We calculated the RT z-scores for each subject and ran a one-way ANOVA with Bonferroni-corrected post-hoc comparisons for the results in each trial congruency pairing.

Trial pairs for which congruency is switched show slower RTs than when congruency is consistent between two trials (Figure 1). Although this observation was not statistically significant as determined by a one-way ANOVA, the trend in Figure 1 shows a congruency sequence effect. Therefore, we updated the CCT protocol to use pre-generated pseudo-random sequences of trial conditions as is common practice with studies using different interference tasks like the Stroop Test and the Flanker Task [27]. We generated pseudo-random sequences of test stimuli that ensured each paired order of trials appeared equally often. This ensured no more than 4 trial types (e.g., 4 congruent trials) could occur in a row. We generated 4 different test sequences of 64 trials each, and the order of these 4 sequences is randomized for each participant. We similarly generated 3 practice sequences of 8 trials each and the order of their presentation was randomized during the practice phase.

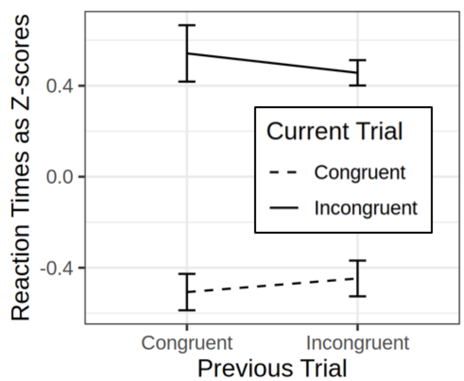

Figure 1. RTs for different congruency sequence pairs during the CCT.

IMPROVING THE PROSTHESIS SIMULATOR SETUP

One study using a simulated prosthesis with CCE assessment used a fixed prosthesis mounted to a table with the able-bodied user controlling hand open and close [25]. This approach could potentially limit the degree of embodiment attainable and provides for less realistic movements than the freely moving simulated prosthesis we use here. Our previous work in this area used a heavier simulated prosthesis [23], [28]. By reducing the mass, from 1.43kg to 0.66kg, we expect reductions in EMG signal noise and user fatigue. We also use an improved mechanotactile tactor [21] to apply force feedback on the user's fingertips, driven proportionally by signals from force sensitive resistors embedded in the index finger and thumb of the prosthesis. We ensured that with no force applied to the finger/thumb sensors, there was no contact between the tactor and the user's skin. This approach was not taken in [23] and may explain some unexpected results in that study.

TEST PLATFORM VALIDATION

We ran an initial study to determine if the newly developed system would operate consistently and lead to consistent ownership assessments. Written informed consent per Rhodes College IRB oversight was obtained for each participant. After a participant donned the simulated prosthesis and MyoBand (see [21] for hardware details), EMG settings were calibrated. Two of the eight electrodes were used: the one with the highest signal-to-noise ratio (SNR) during wrist flexion and the one with the highest SNR during wrist extension. The participant's baseline EMG activity and maximum voluntary contraction (MVC) activity were measured and used to set the activation threshold and gain, respectively, for both electrodes. The threshold was set at about two times the baseline EMG activity level, and the gain was adjusted to map the prosthetic hand velocity from the threshold (V_0) to the MVC level (V_{max}). Wrist flexion was mapped to hand close, and wrist extension to hand open.

Participants trained by grasping an object with the prosthesis (right hand) and moving it to the left over a barrier 14.5 cm high. The object was dropped after crossing barrier, the experimenter retrieved the object and placed it back on the right side of the barrier for the user to start the next movement. Two participants completed 30 training movements with a break halfway through for two different training conditions. In the voluntary control condition, the person's EMG activity controlled the hand. In the involuntary control condition, the experimenter controlled the opening and closing of the hand with the participant matching the hand movement with their EMG activation. After training, participants completed a questionnaire assessing embodiment, ownership, agency and localization. Table 1 shows the ownership statements to which users indicated their agreement on a continuous scale [from Strongly Disagree to Strongly Agree] that was converted into a -5 to +5 score.

Switching between involuntary and voluntary control would affect agency as shown in a concurrent study [29], but not ownership. We observed similar ownership scores across both conditions in both participants (Figure 2).

Table I. Ownership post-training questions [31]

OWNERSHIP
I felt like I was looking directly at my own hand, rather than at a prosthetic hand.
I felt like the prosthetic hand was my hand.
I felt like the prosthetic hand was part of my body.
I felt like the prosthetic hand belonged to me.
It seemed like the prosthetic hand became to resemble my real hand.
OWNERSHIP CONTROL
I felt like my real hand was turning rigid.
It seemed like I had more than one right hand.
The prosthetic hand started to change shape, colour, and appearance so that it started to (visually) resemble my hand.

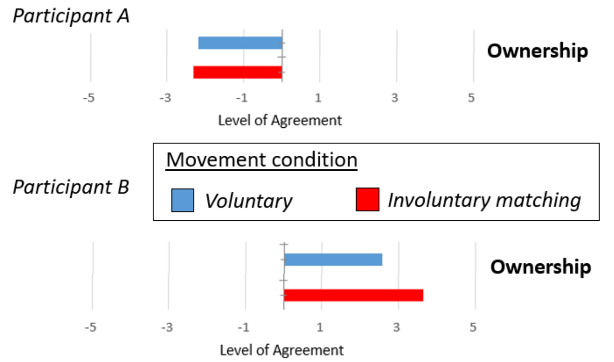

Figure 2. Average response on ownership questions for each participant and condition.

DISCUSSION

This study's results suggest that the updated simulated prosthesis is a suitable platform to test questions related to device ownership. The device is lighter than those used previously and we observed consistent ownership results via questionnaire assessment in an initial study. Ongoing studies will attempt to validate the objective psychophysics-based CCT by investigating the correlation between questionnaire results and CCE scores. We are also seeking to determine the training duration necessary to elicit device ownership. To further validate the CCT as an ownership assessment we can experimentally manipulate the level of ownership (e.g. by adding feedback delay), and then observe the sensitivity of the CCT response compared to the sensitivity of questionnaire results.

We provide some evidence that the CCE is subject to the congruency sequence effect like the Stroop task [30]. For future statistical analysis, we will use a multi-level mixed effects design to further control cofounding variables and quantify order effects more precisely. Additionally, we will run a CCE experiment which varies the percentage of congruent and incongruent trials to see if the congruency sequence effect can be mediated by participant expectations of future trials.

This is ongoing work intended to characterize embodiment development during prosthesis use. Our next step is to characterize the training duration necessary to elicit ownership with our prosthesis simulator system. Previous studies using simulated prostheses have shown quite varied durations of training necessary from about an hour [23] to 30 hours [25]. We expect to observe embodiment with much shorter durations of training because we are using a dynamic prosthesis simulator, unlike [25], that is lightweight (unlike [23]) and we have adopted a new protocol aimed to reduce the inter-individual variability in CCE score results.

In our study establishing the relationship between training duration and ownership for this device, we will also implement the CCT along with the questionnaires. Both previous studies using CCE assessment with robotic hands [23], [25] did not correlate CCE results with results from established questionnaires. We expect to see ownership increase with increased training duration and expect a positive correlation between questionnaire results and CCE scores.

Once the validation studies are complete, we can test various questions related to prosthesis ownership and how this concept interacts with other psychological aspects of device use. For example, we can look at how emerging feedback systems affect device ownership. We will also investigate the relationship between ownership and agency in prosthesis use. Previous work has focused on one of these aspects alone, or relied on subjective questionnaires. Along with concurrent work developing a robust measure of agency [29], we can objectively assess both ownership and agency at the same time in the same platform.

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