TOWARDS QUANTIFYING THE SENSE OF AGENCY AND ITS CONTRIBUTION TO EMBODIMENT OF MYOELECTRIC PROSTHESES

Cierra J. Stiegelmar [1], Daniel H. Blustein [2], Jonathon W. Sensinger [3], Jacqueline S. Hebert [4], and Ahmed W. Shehata [4]

[1]Faculty of Science, University of Alberta, Edmonton, AB, Canada. [2]Department of Psychology, Rhodes College, Memphis, TN, USA. [3]Institute of Biomedical Engineering, University of New Brunswick, Fredericton, NB, Canada. [4]Division of Physical Medicine and Rehabilitation, University of Alberta, Edmonton, AB, Canada

ABSTRACT

Myoelectric technology has the potential to improve prosthetic device functionality. However, device rejection rates remain high, an observation partly attributed to a lack of sensory feedback and difficult control strategies in these devices. Sense of agency, or feeling of control over one's actions, may be able to address these high rejection rates, but existing studies tend to rely on subjective questionnaires to study this experience. Evidence suggests that intentional binding, the compression of the perceived time interval between a voluntary action and its sensory effect when an individual feels in control, may be a quantifiable correlate of the sense of agency. However, existing intentional binding protocols are susceptible to expectation bias and are attentionally demanding for participants. Psychometric assessment tools, such as two-alternative forced choice, may be able to quantify this subjective experience while avoiding bias and attentional demand. In this work, we developed an experimental protocol that uses a psychometric assessment method, namely a two-alternative forced choice paradigm, to study intentional binding and the sense of agency. Here we present preliminary results from 2 able-bodied participants using a myoelectric simulated prosthesis fitted with mechanotactile feedback during voluntary and involuntary control conditions for a grasp-and-release task. These results show that responses to sense of agency questionnaire items are affected by voluntary and involuntary control of a prosthesis.

INTRODUCTION

Researchers report high rejection rates among advanced myoelectric prosthesis users [1] with mean adult and pediatric rejection rates of 23% and 32%, respectively [2]. Lack of sensory feedback [3], [4] and difficult control strategies [5], [6] are both argued to play a part in myoelectric prosthesis rejection. These factors may reduce an individual's sense of embodiment over a device, which may also contribute to device rejection [7].

Embodiment, which refers to the feeling that occurs when one experiences their body as their own and that they exist within it [8], [9], is made up of three interrelated factors: localization, ownership, and agency. Localization refers to one's assumption of where their body exists in space [10], [11]. The sense of ownership describes the feeling when one experiences their body as belonging to oneself [11]. Agency occurs when agreement between sensory predictions and sensory experiences leads to a feeling of control over one's actions and the resulting impact on the surrounding environment [12]. The experience is stronger when predicted sensory consequences of a voluntary motor action match the actual sensory consequences of the action [4]. Agency likely has great implications for prosthesis use because it depends on sensory information and certainty of control, which are factors that contribute to prosthesis rejection [3], [6]. In fact, increasing the sense of control may improve prosthesis acceptance [4].

This sense of control (agency) is commonly investigated using questionnaires, which provide valuable insight into the experience [13], [14]. However, the subjectivity in questionnaire response systems can introduce bias and limit comparison of results. A quantitative and objective investigation of psychophysical phenomena would allow for unbiased data analysis and comparison. When used alongside subjective questionnaires, it may lead to a more holistic understanding and informed approach to prosthesis technological development and training methods.

Intentional binding (IB) refers to the compression of the perceived temporal interval between action and effect when an individual feels in control of their actions, which may serve as a quantifiable correlate of the sense of agency [15]. Temporal estimation procedures can be implemented to quantify and compare a participant's estimated action-effect intervals for voluntary and involuntary control. In these experiments, involuntary control is used as a baseline value in which participants have no sense of agency over the movement. However, reporting methods used in existing studies are susceptible to response bias or are attentionally-demanding [16]. The use of psychometric approaches to quantify IB may mediate these issues.

One psychometric assessment method, known as a two-alternative forced-choice (2AFC) task, presents participants with two stimuli that differ by a specific parameter. The participant is asked to consistently identify and select the target stimulus out of the two stimuli. A correct response indicates that they are able to perceive the difference between the two stimuli. This procedure uses an adaptive approach to determine the level of difference between the two stimuli presentations at which the participant is able to indicate the correct target stimulus with only 50% (chance) accuracy [6], [17]. This method can be applied to IB research by quantifying a participant's perceived action-effect intervals for voluntary control with respect to involuntary control.

Here we developed an experimental protocol that uses a psychometric assessment method to objectively quantify the sense of agency, by determining a participant's perceived action-effect intervals for voluntary control with respect to perceived action-effect intervals for involuntary control. In order to ascertain the validity of this protocol, we first had to determine the influence of voluntary and involuntary control on sense of agency with a commonly used questionnaire [22].

MATERIALS AND METHODS

Experimental setup

The experimental setup consisted of a robotic hand with four fingers and a thumb that were driven simultaneously using a linked bar mechanism attached to a single Dynamixel servo motor (MX-64AT). This hand allowed for only 1 degree of freedom for hand open/close. Participants controlled the robotic hand using isometric muscle contractions sensed by an array of eight low power multi-channel operation electrodes (Myoarm^{TM} band) placed around their forearm [18]. A PC running MATLAB (Release 2019b, The MathWorks, Inc., Natick, Massachusetts, United States) and BrachIOplexus software [19] was used to record the control signals during the experiment. The controlled robotic hand was attached to the participant using a modified commercially available wrist brace (MedSpec Ryno Lacer) that restricts hand and wrist movements. Two mechanotactile tactors [20] were fitted on the participant's index and thumb fingers and noise-cancelling headphones playing Brownian noise were placed over the participants ears to ensure that audio cues were occluded. A black sheet (1 x 1 m) was placed over the able-bodied participant's shoulder to ensure that their arm was completely obscured, encouraging embodiment of the prosthesis hand (Figure 1. a). The same experimental setup can be used for persons with transradial amputation by replacing the simulated prosthesis system with a modular transradial socket [21] with the mechanotactile tactors placed on the residual limb (Figure 1. b).

Table 1: *Sense of Agency questionnaire items adopted from* [22]. *(A) denotes Agency; (AC) denotes a control question*

Item	Type
The prosthetic hand moved just like I wanted it to, like it was obeying my will.	(A)
I felt like I was controlling the movements of the prosthetic hand.	(A)
I felt like I was causing the movement that I saw.	(A)
When I initiated movement, I expected the prosthetic hand to move in the same way that I intended.	(A)
I felt like the prosthetic hand was controlling my will.	(AC)
I felt like the prosthetic hand was controlling my movements.	(AC)
I could sense the movement coming from somewhere between my real hand and the prosthetic hand.	(AC)
It seemed like the prosthetic hand had a will of its own.	(AC)

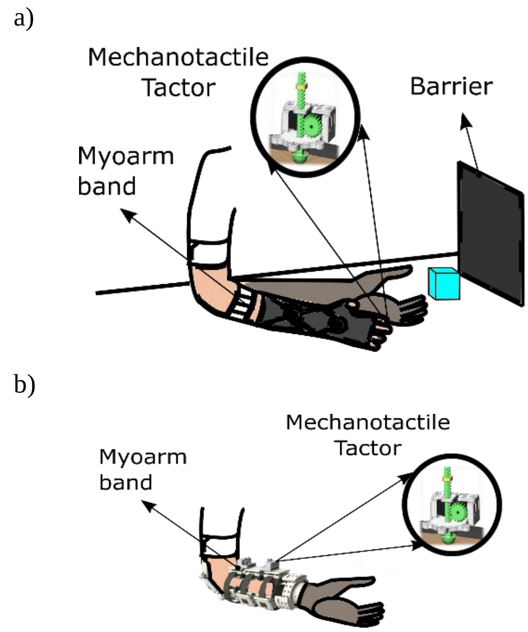

Figure 1: *Experimental setup. a) An able-bodied participant wearing the simulated prosthesis with mechanotactile tactors attached to their index and thumb fingers. Note that the participant's hand is covered by a black sheet during the experiment. b) A participant with* a *transradial amputation wearing the modular transradial* prosthesis *with mechanotactile tactors placed on their residual limb.*

Experimental protocol

Participants: 2 able-bodied female participants over the age of 18 years were recruited for this study. Written informed consent according to Rhodes College IRB was obtained from participants before conducting the experiment.

Participants wore a simulated prosthesis (Figure 1. a) and sat comfortably in front of a table that had a cube (57mm x 57 mm x 57 mm) on it and a barrier (W x H: 25 x 14.5 cm) placed perpendicular to the surface of the table. Mechanotactile tactors were placed on their fingertips and electromyography (EMG) signals from the wrist

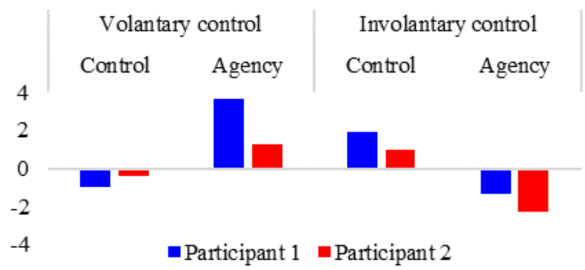

Figure 2: *Average response to sense of agency questionnaire items for voluntary and involuntary control*

flexor/extensor muscles were mapped to the prosthetic hand's open and close controls. The contact forces on the prosthetic hand were mapped to the function of the mechanotactile tactors placed on the participant's fingers. The experimental protocol consisted of the following 3 blocks.

Block 1: Voluntary control

Participants controlled the prosthesis using the calibrated EMG controller and received tactor feedback on their fingertips when the prosthetic hand contacted an object, with a force proportional to that which was placed on the prosthesis' fingers. Each participant was asked to operate the prosthesis to complete a grasp-and-release task that consisted of grasping an object, transporting it over a barrier, placing it down, and releasing the object (30 trials with a 2-minute break halfway through). After this training, the participant was asked to fill out an embodiment questionnaire. Table 1 shows a list of the sense of agency items that were on that embodiment questionnaire.

Block 2: Involuntary control

The experimenter controlled the opening and closing of the prosthetic hand and the participant received tactor feedback on their fingertips when the prosthetic hand grasped the object. The participant was asked to mimic the prosthetic hand movement by contracting the muscles corresponding to this observed movement during the grasp and release phases of the task [grasping the object, transporting it over a barrier, placing it down, and releasing it (30 trials with a 2-minute break halfway through)]. After these trials, the participant filled out the embodiment questionnaire.

Block 3: IB familiarization and testing

During the familiarization phase, the participant was asked to grasp an object, and attend to the moment when the prosthetic hand began to move and the moment that they received the tactor feedback. Ten trials of voluntary control familiarization occurred before the ten trials of involuntary control familiarization. The testing phase of this block included pairs of trials; one voluntary trial and one involuntary trial. Involuntary trials included variable speeds (either faster or slower control). Participants were presented with the trial pairs and were asked to indicate which of the two trials felt faster. If participants were correct, the difference between the speeds of the two trials was reduced until the participant achieved a 50% correct response rate. If they were incorrect, the difference between the two trials was increased (following an adaptive staircase method). The test progressed until the termination condition of the adaptive staircase was reached (23 reversals). The final value achieved indicated the participant's perceived action-effect intervals for voluntary control with respect to their perceived action-effect intervals for involuntary control.

Outcome measures: Data included the responses to the embodiment questionnaire items, rated on a visual analogue scale (0-10). This questionnaire consisted of 20 items that were randomly ordered. In this paper, we focus on 8 of these items pertaining to the sense of agency. The mean of the responses to the 4 agency items for each participant and the mean of the responses to the 4 agency control items were reported. Data from testing block 3 are not reported here.

RESULTS

Similar to our previous study [23], the average responses to agency questionnaire items for the voluntary control with mechanotactile feedback were at least 4.2 times higher than the average responses to control agency questionnaire items. Conversely, the average responses to agency questionnaire items for the involuntary control with mechanotactile feedback were at least 1.6 times lower than the average responses to control agency questionnaire items. These results indicate that the sense of agency as measured using a subjective questionnaire may be affected by voluntary and involuntary control conditions. Comparing participants' average responses to agency questionnaire items between voluntary and involuntary conditions show that involuntary control may have a negative effect on sense of agency and, therefore, the overall embodiment of a device.

DISCUSSION

The aim of this study was to determine the influence of voluntary and involuntary control on the sense of agency with a commonly used questionnaire assessment [22]. This step is crucial for the development of an experimental protocol to objectively quantify the sense of agency by correlating it with intentional binding. We found that involuntary control with feedback may reduce the sense of agency as determined by the administered questionnaire. This finding may be a result of participants not being in control of the prosthetic hand, but also could have been driven by any unexpected effect of the prosthesis touching an object. In our recent work [23], we showed that even with voluntary control, delaying the mechanotactile feedback (> 500 ms) can negatively influence responses to agency questionnaire items. It is worth noting that responses to control questions were slightly affected by the order of condition presentation. These observations warrant an investigation of an objective assessment procedure that allows for an unbiased approach and simple reporting method. We propose to utilize IB and the agency questionnaire, to further investigate the roles that IB, agency, and embodiment play in advanced myoelectric prosthesis use. This investigation can be implemented in able-bodied participants with the use of a simulated prosthesis, or in participants with amputation, which will allow for the investigation into IB in naïve as well as experienced myoelectric users. The methodology presented will allow for quantification of IB in a range of prosthesis users with various sensory feedback strategies in a standardized manner.

A standardized IB method will allow for more efficient data comparison between research centres. To evaluate this assumption, we plan to implement this protocol in a multi-site investigation with a collaboration between three research centres at the University of Alberta, Edmonton, AB; the University of New Brunswick, Fredericton, New Brunswick; and Rhodes College, Memphis, TN, USA. The breadth of this investigation will assist in moving the field of embodiment research toward a more standardized approach, especially for the investigation of psychophysical phenomenon in myoelectric prosthesis users. A standardized methodology will lead to more efficient evaluation of myoelectric devices and technology, prosthesis training protocols, and evaluation of prosthesis embodiment.

ACKNOWLEDGEMENTS

This work was supported by the Undergraduate Research Initiative and the Sensory Motor Adaptive Rehabilitation Technology (SMART) Network at the University of Alberta.

REFERENCES

[1] S. M. Engdahl, B. P. Christie, B. Kelly, A. Davis, C. A. Chestek, and D. H. Gates, "Surveying the interest of individuals with upper limb loss in novel prosthetic control techniques," *J. Neuroeng. Rehabil.*, pp. 1–11, 2015.

[2] E. A. Biddiss and T. T. Chau, "Upper limb prosthesis use and abandonment: A survey of the last 25 years," *Prosthet. Orthot. Int.*, vol. 31, no. 3, pp. 236–257, 2007.

[3] U. Wijk and I. Carlsson, "Forearm amputees' views of prosthesis use and sensory feedback," *J. Hand Ther.*, vol. 28, no. 3, pp. 269–278, 2015.

[4] P. D. Marasco *et al.*, "Illusory movement perception improves motor control for prosthetic hands," *Sci. Transl. Med.*, vol. 10, no. 432, pp. 1–13, 2018.

[5] D. J. Atkins, D. C. Y. Heard, and W. H. Donovan, "Epidemiologic Overview of Individuals with Upper-Limb Loss and Their Reported Research Priorities," *JPO J. Prosthetics Orthot.*, vol. 8, no. 1, pp. 2–11, 1996.

[6] A. W. Shehata, E. J. Scheme, and J. W. Sensinger, "Evaluating Internal Model Strength and Performance of Myoelectric Prosthesis Control Strategies," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 5, pp. 1046–1055, 2018.

[7] A. Hodrien, A. J. Galpin, D. J. Roberts, L. Kenney, and others, "Exploring the impact of hand movement delays and hand appearance on myoelectric prosthesis embodiment using Immersive Virtual Reality," *Annu. Rev. Cybertherapy Telemed.*, vol. 15, 2017.

[8] V. I. Petkova and H. H. Ehrsson, "If I were you: Perceptual illusion of body swapping," *PLoS One*, vol. 3, no. 12, 2008.

[9] M. Tsakiris, "My body in the brain: A neurocognitive model of body-ownership," *Neuropsychologia*, vol. 48, no. 3, pp. 703–712, 2010.

[10] M. R. Longo, F. Schuur, M. P. M. Kammers, M. Tsakiris, and P. Haggard, "What is embodiment? A psychometric approach.," *Cognition*, vol. 107, no. 3, pp. 978–998, Jun. 2008.

[11] M. Rohde, M. Di Luca, and M. O. Ernst, "The Rubber Hand Illusion: Feeling of Ownership and Proprioceptive Drift Do Not Go Hand in Hand," *PLoS One*, vol. 6, no. 6, pp. e21659–e21659, Jun. 2011.

[12] P. Haggard, "Sense of agency in the human brain," *Nat. Rev. Neurosci.*, vol. 18, no. 4, pp. 197–208, 2017.

[13] H. H. Ehrsson, B. Rosen, A. Stockselius, C. Ragno, P. Kohler, and G. Lundborg, "Upper limb amputees can be induced to experience a rubber hand as their own.," *Brain*, vol. 131, no. Pt 12, pp. 3443–3452, Dec. 2008.

[14] P. D. Marasco, K. Kim, J. E. Colgate, M. A. Peshkin, and T. A. Kuiken, "Robotic touch shifts perception of embodiment to a prosthesis in targeted reinnervation amputees," *Brain*, vol. 134, pp. 747–758, 2011.

[15] P. Haggard, S. Clark, and J. Kalogeras, "Voluntary action and conscious awareness," *Nat. Neurosci.*, vol. 5, no. 4, pp. 382–385, 2002.

[16] A. M. Cravo, P. M. E. Claessens, and M. V. C. Baldo, "The relation between action, predictability and temporal contiguity in temporal binding," *Acta Psychol. (Amst).*, vol. 136, pp. 157–166, 2011.

[17] M. R. Leek, "Adaptive procedures in psychophysical research.," *Percept. Psychophys.*, vol. 63, no. 8, pp. 1279–1292, 2001.

[18] A. W. Shehata, L. F. Engels, M. Controzzi, C. Cipriani, E. J. Scheme, and J. W. Sensinger, "Improving internal model strength and performance of prosthetic hands using augmented feedback," *J. Neuroeng. Rehabil.*, vol. 70, no. 15, 2018.

[19] M. R. Dawson, H. E. Williams, G. S. Murgatroyd, J. S. Hebert, and P. M. Pilarski, "BRACHIOPLEXUS: MYOELECTRIC TRAINING SOFTWARE FOR CLINICAL AND RESEARCH APPLICATIONS," in *review Myoelectric Control Symposium*, 2020.

[20] K. R. Schoepp, M. R. Dawson, J. S. Schofield, J. P. Carey, and J. S. Hebert, "Design and Integration of an Inexpensive Wearable Mechanotactile Feedback System for Myoelectric Prostheses," *IEEE J. Transl. Eng. Heal. Med.*, vol. 6, 2018.

[21] B. W. Hallworth *et al.*, "DEVELOPMENT OF A TRANSRADIAL MODULAR ADAPTABLE PLATFORM FOR EVALUATING PROSTHETIC FEEDBACK AND CONTROL STRATEGIES," in *review Myoelectric Control Symposium*, 2020.

[22] A. Kalckert and H. H. Ehrsson, "Moving a Rubber Hand that Feels Like Your Own: A Dissociation of Ownership and Agency," *Front. Hum. Neurosci.*, vol. 6, p. 40, 2012.

[23] Ahmed W. Shehata, M. Rehani, Z. E. Jassat, and J. S. Hebert, "Mechanotactile Sensory Feedback Improves Embodiment of a Prosthetic Hand During Active Use," *Under Rev. Front. Neurosci.*, 2020.