American Orthotic and Prosthetic Association (AOPA) Center for Orthotics and Prosthetics Leraning and Outcomes/Evidence-Based Practice (COPL)

Final Summary 2-28-14

Project Title: Cognitive Workload During Prosthetic Use: A quantitative EEG outcome measure

Investigators: Sean P. Deeny, Ph.D, postdoctoral fellow; Arun Jayaraman, P.T., Ph.D.

General Items:

1. If human subjects or patient information is used, please provide IRB number/certification and any forms/documents approved for use with patients.

   IRB status: Aproved, Study ID STU00062490.

2. **How have funds been used to date?** The funds to date have been spent on stipends for participants ($2880.00), Research Assistant support ($4989.49), Lab supplies (EEG caps, gel, etc: $1894.14), and engineering support for repair of an amplifier ($1005.00), totaling $10,768.63.

3. **How will the remaining funds be used?** The remaining funds of $4,225.37 are being returned to your office.

4. **Please provide a 2 to 3 page description of the accomplishments of the project to date including where the work is being conducted, who the participants are, what progress has been made to date, and what work remains until the project due date.**

Institutional Review Board Status

The protocol (Study ID STU00062490) was reviewed by the Institutional Review Board Office at Northwestern University, and approved in May of 2012. The IRB was renewed in May of 2013.

Participants

Twenty participants completed the protocol, and 2 additional participants have completed half of the protocol. All participants were able-bodied control participants, recruited from Northwestern University undergraduate and graduate programs.

Review of Methods

All subjects were trained and tested on two approaches to myoelectric control of the virtual arm, direct control (DC) and pattern recognition control (PRC). Continuous EEG was recorded during the testing sessions. The order was counterbalanced such that half of the participants learned DC first, and half learned PRC first. For both DC and PRC, participants engaged in three conditions: passively viewing the arm (view), controlling the hand in 1 degree of freedom (DOF; easy), and controlling the hand in 3 DOF (hard). The task was to move the hand from an initial location to a target location using 1 (easy) or all 3 (hard) of the DOF, which included wrist flexion/extension, wrist supination/pronation, and hand open/close.

Behavioral Data Collection and Analysis. The virtual arm software provides detailed performance results for testing trials. Percent correct reflects the percent of completed trials within the 24 second trial time window. The mean completion time reflects the average time to complete the trials that were correctly completed within the 24 second window.

EEG Data Collection and Analysis. EEG data is being collected at 17 electrode sites (see Figure 1: FP1, FP2, F3, Fz, F4, T7, C3, Cz, C4, T8, CPz, P3, Pz, P4, O1, Oz, O2) across the scalp based on the international 10-20 system (Jasper, 1958). The primary data analysis will focus on three midline sites, frontal midline (Fz), central midline (Cz), and parietal midline (Pz).

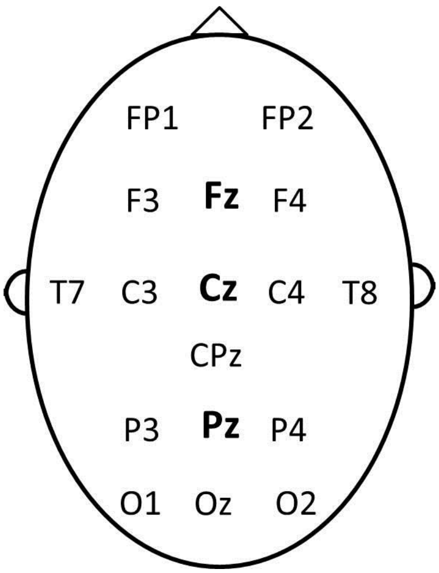

Figure 1. Illustrates the electrode montage for EEG data collection. Electrode names are indicated by the region of the brain (F=frontal, T=temporal, C=central, P=parietal, O=occipital) and by numbers indicating left hemisphere (odd), right hemisphere (even), and the letter “z” for midline positions (Jasper, 1958). Data analysis will focus on Fz, Cz, and Pz.

An event-related potential (ERP) is an electrophysiological response that is time-locked to a stimulus, in this case, an auditory stimulus. Miller et al. (2011) showed that the amplitude of the ERPs, when presented with a novel auditory probe, was inversely related to the cognitive workload of the primary task, in their case, the video game Tetris. Miller and colleagues used this technique to examine cognitive workload in students who were passively viewing the video game Tetris (view), playing Tetris at level 1 (easy), and playing Tetris at level 8 (hard). Multiple peaks elicited by the auditory stimulus across the three electrode sites (Fz, Cz, and Pz), showed a significant inverse relationship between peak amplitude and level of cognitive workload (view, easy, hard). The same approach was employed here to examine ERP amplitude to novel auditory stimuli while passively viewing the virtual arm (view), moving the hand in 1 DOF (easy), and moving the hand in 3 DOF (hard).

Essentially, the approach reported by Miller et al. is an examination of the neural resources available for an attentional response to the novel auditory probe. If the primary task is low in cognitive demand (e.g. the passive viewing, or 1 DOF condition), greater neural resources will be available to process the auditory probe stimulus, and the amplitude of the ERP peaks will be high. If the primary task is high in cognitive demand (3 DOF), the amplitude of the response to the auditory probes will be lower. Multiple peaks are elicited following the onset of an auditory stimulus reflecting different aspects of sensory and cognitive processing of the stimuli. The peaks are named for their polarity (P=positive, N=negative), and the typical latency of the peak. The N100 is therefore a negative peak occurring approximately 100 milliseconds (msec) following the onset of the sound. The peaks reported to be sensitive to cognitive workload in Miller et al. (2011) included the N100, P200, P300, and late positive potentiation (LPP; ~570-600 msec). The most prominent effects occurred at the parietal midline site (Pz), but significant effects were also reported at the frontal (Fz) and central (Cz) midline sites.

Based on the results presented by Miller and colleagues, the amplitudes for the N100 and P200 peaks for all three electrodes (Fz, Cz, Pz) and the amplitudes of the P300, and LPP peaks at Pz will be subjected to repeated measures ANOVAs to examine main effects for the cognitive workload factor (view, easy, hard), and the arm control factor (DC, PRC). As such, 10 separate 3 (cognitive workload) x 2 (arm control) repeated measures ANOVAs will be run. Post-hoc analyses will be conducted on ANOVAs resulting in significant main effects for either factor (cognitive workload, arm control condition), or significant interactions.

EMG Data Collection and Analysis. Six bipolar electrodes are placed on the forearm of the non-dominant arm. The EMG collected from the forearm is used in real-time to control the virtual arm, and saved to a file for each individual trial for offline analysis. The overall amplitude of muscle activation across the trials for both DC and PRC will be analyzed to examine the physical effort required for each condition.

Self-report. Participants filled out a questionnaire immediately following testing in both conditions to assess the perceived effort of controlling the arm. The questionnaire consisted of 7 questions on a 5-point Likert scale regarding the difficulty or ease of controlling the arm.

Results

EEG Results. Figure 2 illustrates the strong general inverse relationship between ERP amplitudes and cognitive workload for P200, P300, and LPP. Main effects and ERPs are pictured for electrodes Cz and Pz, where most of the effects occurred. No significant main effects or interactions emerged for cognitive workload on the N1 component. Consistent with Miller et al. (2001), the main effects for cognitive workload were significant at all three electrode sites (Fz, Cz, Pz) for P200: Fz ($F_{2,34}$=5.15; p=0.011), Cz ($F_{2,34}$=12.90; p<0.001), and Pz ($F_{2,34}$=5.03; p=0.012). P200 effects at Cz and Pz are pictured in Figure 2 (a-d). Post-hoc tests revealed that for P200 at Cz, the view condition differed from both the easy and hard conditions. For P200 at Fz and Pz, the hard conditions differed from the view conditions. Significant main effects emerged on P3 at Pz ($F_{2,34}$=7.67; p=0.002) and LPP at Pz ($F_{2,34}$=5.61; p=0.008), and are pictured in Figure 2 (b, e, f). For both P300 and LPP, pots-hoc testing revealed that the hard conditions were significantly different from the view conditions.

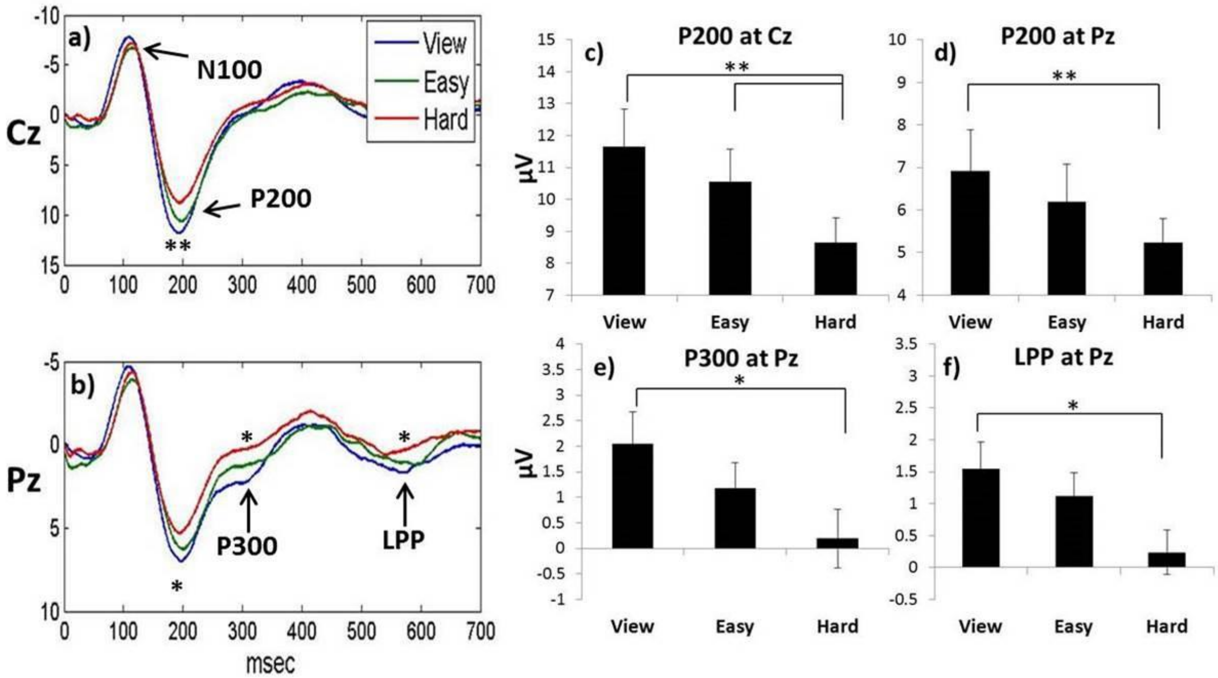

Figure 2. *p<0.05, **p<0.01. ERPs and main effects for the cognitive workload measure on the view, easy, and hard conditions for DC and PRC combined. Note that positive and negative on the y-axis are traditionally reversed for ERP graphs; as such positive is graphed down. a) Electrode Cz, where the P200 effect was most prominent. b) Electrode Pz, where the P200, P300, and LPP all exhibited cognitive workload effects. c-f) Average amplitude graphs for P200 at Cz and Pz, P300, and LPP.

To compare DC and PRC, two-tailed paired samples t-tests were run on hard conditions for P200 (Fz, Cz, Pz), P300 (Pz), and LPP (Pz), which all showed main effects for cognitive workload. Because t-tests do not control for multiple comparisons like Tukey HSD, the number of analyses was limited to only the peaks that exhibited significant main effects in the current study, and were also reported to be significant in Miller et al. [37]. A significant difference in average amplitude in the hard condition emerged for LPP (t_{17}=-2.35, p=0.031), with PRC exhibiting a higher LPP amplitude relative to DC. Figure 3 illustrates the ERPs at Pz for DC and PRC in the hard condition.

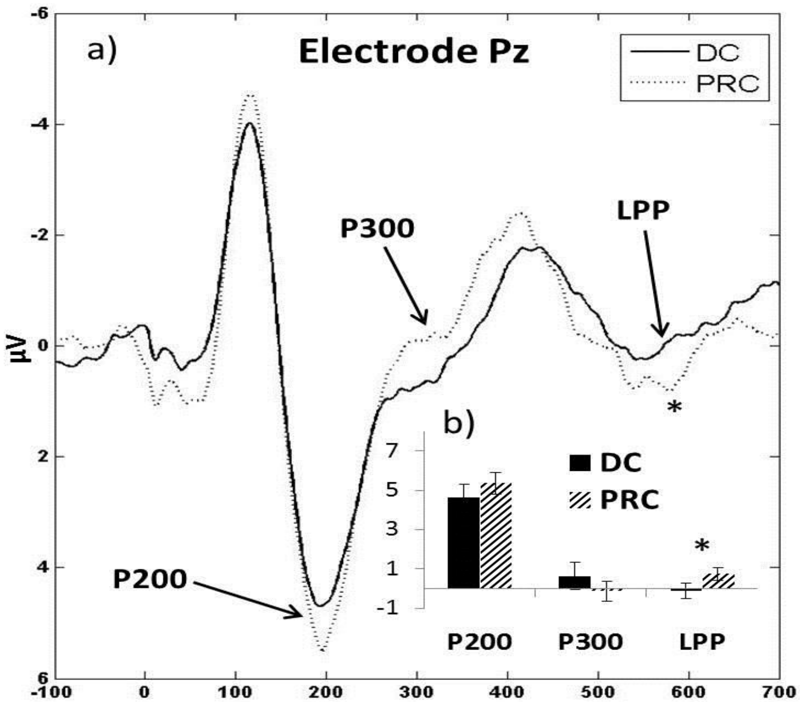

Figure 3. *p<0.05. DC and PRC ERPs and amplitudes for electrode Fz in the hard condition. a) Visual inspection of the ERP shows that in the hard condition the P300 was not visually prominent, and close to zero. b) Although LPP was not visually prominent, the difference was significant between DC and PRC, with higher amplitude for PRC.

Behavioral Results. Generally performance was better for PRC than for DC, although some individual participants performed better in the DC condition. Overall, based on the first 10 participants, PRC resulted in faster completion time in the hard condition (p=0.046). Percent correct was higher for PRC than DC, although the difference only approached significance (p=0.11) (See Figure 4 a&b).

EMG Results. Figure 4 (c & d) illustrate EMG for the virtual arm task. AUC analysis revealed that EMG activation was not different between DC and PRC in the easy condition. In the hard condition participants required greater EMG activation across all six electrodes combined (Figure 2c) using DC (5422.4, SD=1714.8) relative to PRC (4322.5, SD=1064.3; t_{15}=3.2; p=0.005).

Self-report Results. There were no differences between DC (mean=15.1, SD=3.8) and PRC (mean=16.3, SD=4.4) on the self-report questions examining difficulty.

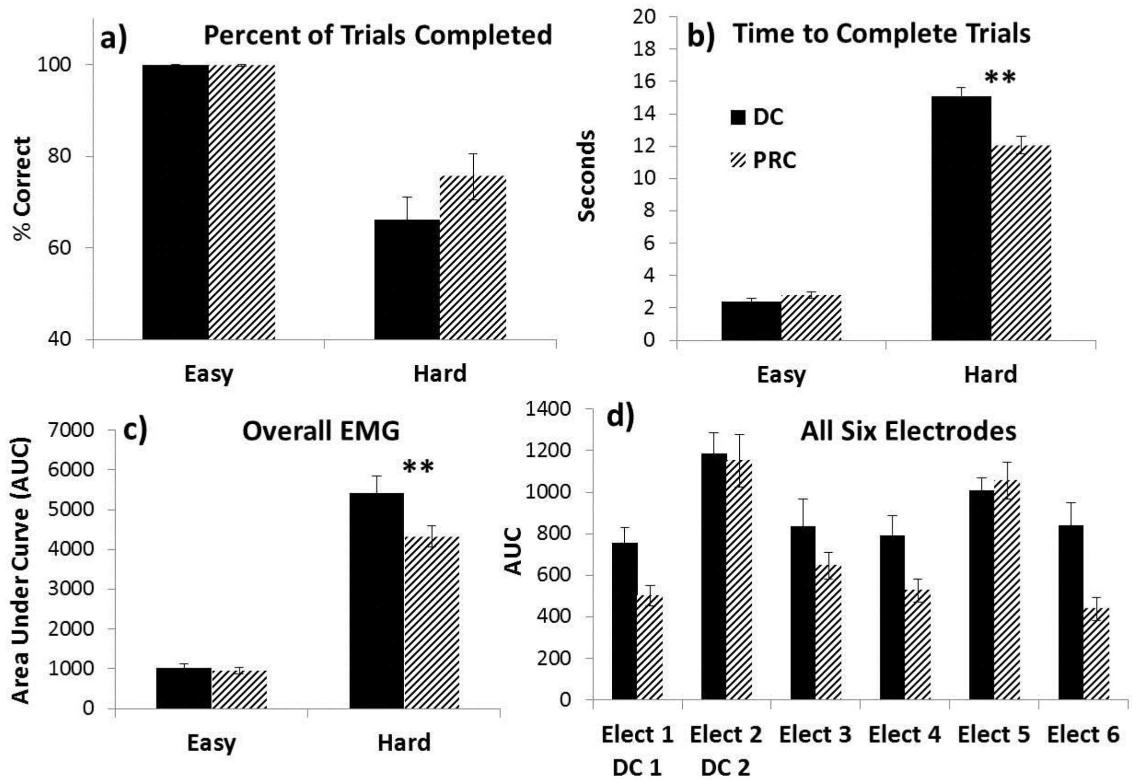

Figure 4. **p<0.01. Virtual arm task performance and EMG results. a) Percentage of trials completed within 24 seconds. b) Average time to complete successful trials; participants took significantly longer to complete hard trials using DC relative to PRC. c) AUC for all six electrodes combined; AUC was higher in the hard condition for DC relative to PRC. d) AUC for all six electrodes in the hard condition; DC was controlled using electrodes 1 (wrist flexor) & 2 (wrist extensor) only.

<u>Discussion and Future Efforts.</u>

The results confirm the efficacy of EEG as a viable measure of cognitive workload. The P200, P300 and LPP main effects for cognitive workload achieved significance, with amplitudes reflecting an inverse relationship to cognitive workload of the primary task. Furthermore, the LPP peak distinguished between the DC and PRC myoelectric control strategies in the hard (3DOF) condition. A higher amplitude LPP when using PRC relative to DC in the hard condition is consistent with lower cognitive workload for complex movements using PRC compared to DC.

Aim 1 of this research effort was to determine whether EEG can reflect cognitive workload during prosthetic limb use. This aim was achieved, and strong effects for cognitive workload were observed.

Significant main effects of cognitive workload were demonstrated in the omnibus tests for P200, P300, and for LPP. The results are remarkably consistent with the results of Miller et al., 2011, who employed the same paradigm to examine cognitive workload during play of the video game Tetris™. Consistent with the previous report, P200 exhibited cognitive workload effects across all three sites (Fz, Cz, Pz), with the strongest effect over the vertex (Cz). Main effects were also found for P300 and LPP at electrode Pz. No significant cognitive workload effects were found in the current study for N100, although N100 effects have been shown in previous studies (Kramer et al., 1995; Miller et al., 2011; Ulllsperger et al., 2001).

The P300 is one of the most commonly studied cognitive ERP components over the last several decades (for a review, Polich et al., 2007). In the current study the P300 exhibited a strong cognitive workload effect, however, in the hard condition for both DC and PRC, the P300 was virtually absent in the grand average across all subjects. The P200 and LPP components have received less examination in cognitive neuroscience in general, and in the cognitive workload literature relative to P300, yet both P200 and LPP exhibited strong effects in the current paper, and a previous paper using a very similar paradigm (Miller et al., 2011), and identical novel auditory tones (Fabiani et al., 1996). Although the P200 was considered by some researchers in early studies to be the tail end of the N100-P200 complex, more recent studies have demonstrated that the P200 is an independent component that can be elicited through visual, somatosensory, and auditory modalities, and is maximal over the vertex (for a review see Crowley et al., 2004). It has been suggested to represent early processing of emotionally or motivationally relevant stimuli (Paulman et al., 2013). The LPP, often referred to as the late positive component or complex (LPC), has been proposed to reflect continued or enhanced elaborate processing of emotional or arousing stimuli (Paulman et al., 2013; Kanske & Kotz, 2007), and has been suggested to exhibit positivity with latencies ranging from 300 milliseconds to several seconds (Hajcak et al., 2009). In the current study, the grand average across all subjects was used to identify the LLP peak in a relatively narrow time window for analysis (Handy, 2005), from 570-590 milliseconds, which is temporally consistent with the LLP reported in Miller et al., 2011.

Aim 2 of this effort is use the EEG measures to compare the cognitive workload of two myoelectric strategies.

The results indicate that the ERP measures are sensitive to subtle differences in cognitive workload between different myoelectric control conditions. Having exhibited significant cognitive workload effects across both DC and PRC conditions, P200, P300, and LPP were compared between DC and PRC conditions in the hard and easy tasks. LPP exhibited a significant difference between DC and PRC, and only in the hard condition. Amplitude was higher in the PRC condition than the DC condition. The result is consistent with the interpretation of lower cognitive workload using PRC relative to DC in complex movements (3DOF).

<u>Dissemination</u>

The results of this work are under review in the Journal of Neural Engineering, offering the simple ERP approach as a new outcome measure for prosthetics work, and more generally, for Human-Machine Interaction research. The method is easily adaptable to a variety of tasks including lower limb prostheses and exoskeletons. A second paper is in preparation for examination of the spectral content of the EEG, and reporting of the EMG results.

<u>References</u>

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