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DEVELOPMENT OF ELECTROCARDIOGRAPHIC MEASURES FOR COGNITIVE LOAD DURING PROTHESIS USE

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Abstract – Current transhumeral and transradial amputees abandon a significant amount of unintuitive prostheseis. Measuring cognitive workload during prostheseis usage could help researchers develop more intuitive prostheseis and lower abandonment rates. The purpose of this study is to verify the efficacy of heart rate variability (HRV) as a measure of cognitive workload when applied to prosthesis use.

Participants completed a prosthesis control task with a virtual prosthetic hand at two difficulty levels. Participants controlled this hand with a myoelectric sleeve on their forearm. ECG was acquired as the participants completed the virtual target task. The low frequency to high frequency ratio (LF/HF), a measure of heart rate variability sensitive to cognitive load, was calculated for the task.

The results suggest the LF/HF detects changes in cognitive workload during prosthesis use. Future work could use HRV to show the cognitive benefits of advanced prostheses.

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I. INTRODUCTION

Current commercial prostheses are unintuitive and difficult to use. Prostheseis users abandon 23% of body-powered prostheseis and 26% of electrically powered prostheseis [1]. Utilizing residual muscle activity may offer a more intuitive means of prosthesis control. Current commercial myoelectric prostheseis use cumbersome control approaches; for instance, using repeated contractions to switch which degree of freedom (DOF) is being controlled [2]. Improving the usability of a prosthesis may help lower abandonment rates, as the difficulty of use is cited as a major barrier to prosthesis adoption [3]. Few studies explore the cognitive burden of prosthesis use [4][5]. Measuring cognitive workload during prosthesis usage opens a new dimension of analysis focused on the patient, potentially providing increased justification for the clinical implementation of advanced prosthetic systems.

Cognitive workload refers to the amount of cognitive resources expended in performing a task [6]. Heart rate variability (HRV) measures cognitive workload, specifically the ratio of low-frequency signal to high-frequency signal (LF/HF) and the standard deviation of N-N intervals (SDNN), during the performed task [7]. Low-frequency HRV (LF) is between 0.04-0.15 Hz and high-frequency HRV (HF) is between 0.15-0.40 Hz. HRV decreases when cognitive workload increases [8]. HRV, like many other physiological measures of cognitive workload, requires that tasks be adapted to suit recording requirements. HRV generally requires recordings ranging from 5 minutes to 24 hours but functions for recordings as short as 30 seconds [7].

The purpose of this study is to validate the efficacy of HRV as a measure of cognitive workload during prosthesis use. A surface electromyography (sEMG) sleeve attached to the forearm allows the participant to control the prosthesis. sEMG measures the electrical muscle activity from the forearm and feeds the data to software that will translate the electrical activity into prosthesis movement. Participants completed a target task involving large and small targets. The different target sizes alter the difficulty of the task, allowing us to determine if HRV accurately reflects difficulty level and cognitive workload.

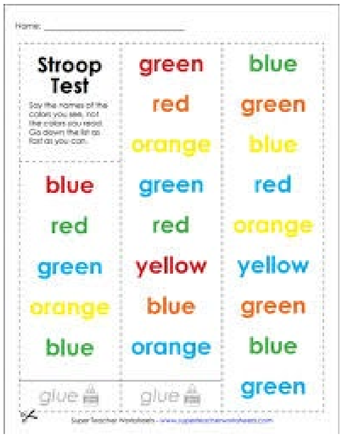
II. METHODS

A. *ECG Acquisition and System Setup*

The shimmer3 ECG device captures (Shimmer Research, Dublin, Ireland) electrocardiogram (ECG) data at 512 Hz. The Shimmer3 ECG Unit utilizes a five-wire, 4-lead electrode setup to save ECG data. ECG recordings were started and stopped by external commands from a MATLAB instrument driver.

B. *Pilot Study*

We validated the ECG system using the Stroop test. The Stroop test presents a name of a color and a mismatched text color. For example, the word is "green", and the color of the word is blue (see Fig. 1). A series of color names are presented to the participant and the participant is asked to either select the color name or the font color with a keyboard response.



Name: ____________________

Stroop Test

Say the names of the colors you see, not the colors you read. Go down the list as fast as you can.

blue
red
green
orange
blue

green
red
orange
green
red
yellow
blue
orange

blue
green
blue
red
orange
yellow
green
blue
green

glue
glue

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Figure 1. Shown are example words that may be administered during the Stroop Tes*t*. Pilot Stroop study was administered using a virtual format from University of Washington's Stroop Test website. Link: http://faculty.washington.edu/chudler/words.html

A baseline reading was taken for a period of 2 minutes. The participant was then asked to take the Stroop test for another interval of 2 minutes. ECG readings from both intervals are analyzed using a MATLAB script utilizing the PhysioZoo HRV analysis software (Israel Institute of Technology, Haifa, Israel). Data files are edited to include the PhysioZoo specific header and file format is changed to .txt. Each ECG data file is sent into the PhysioZoo processing GUI which analyzes the file and outputs HRV metrics. Development of a MATLAB ECG analysis script provided a quicker alternative to this method. Section E contains additional details on ECG processing.

C. *Experimental Procedure*

1) Prosthesis Control. Prosthesis control has been described in depth previously [9]. A sEMG sleeve and 512-channel Grapevine System (Ripple Neuro LLC, Salt Lake City, UT) acquire myoelectric signals from the participant's forearm. Signals are filtered using Butterworth and Notch filters. Manual inspection of individual channels is performed to remove any defective channels.

Specific decode algorithms are described previously [9]. A modified Kalman Filter (mKF) utilizing 48 EMG features predicts prosthesis movement. Decode training is performed using the MSMS virtual hand (Johns Hopkins Applied Physics Lab, Baltimore, MD). The participant is trained on 3 individual degrees of freedom (DOF) which include flexion on the index, middle, and ring finger. Prior to training, study administrators coach participants on movements that they will perform. Participants then mimic flexion movements in a 15-trial block order from index to ring finger, 5 trial per digit. Training data is used for mKF control algorithms to provide proportional control from the sEMG.

3) Target Task. Participants will control a virtual prosthetic hand with the sEMG sleeve and flex the index, middle, and ring fingers to touch targets within the digit's range of motion (ROM). Participants will try to move a single DOF to a desired target position with either a 10% error window (small target, 0.10) or a 35% error window (large target, 0.35) and remain within the target for 5 seconds. Participants are instructed that the task requires that they keep the digit within the target instead of aiming for dead center. The target will disappear after the allotted time and another target will reappear after 3-5 seconds. This constitutes a single trial. A set includes 6 trials per DOF for the same target size. Starting target size is randomized. An example set is as follow: 1) small target task 2) large target task. Participants completed 4 of these sets. The NASA-TLX survey will be administered after the last round of each target size. ECG is recorded during each set of targets.

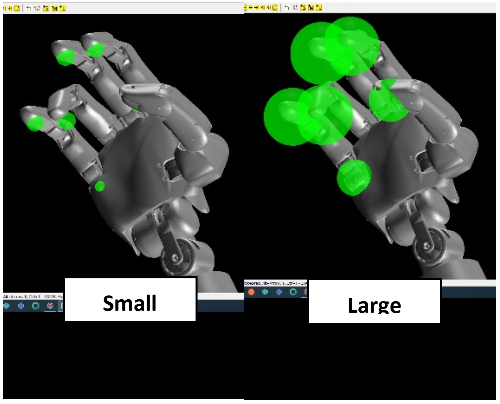

Figure 2: Image of virtual prosthetic arm and sample small and large target sizes. Targets are hidden during algorithmic training as participants mimic flexion of the index, middle, and ring finger.

D. *NASA Task Load Index (TLX)*

The NASA Task Load Index (TLX) survey has been utilized by many studies as a subjective evaluation of cognitive load which adds support to physiological findings [10]. The TLX survey was administered after the target task to support HRV findings.

E. *ECG Data Analysis*

Data is imported from Shimmer3 ECG and exported to .csv files. We modified the file headers and file type to .txt to be importable in the PhysioZoo software suite. ECG .txt files are fed through a MATLAB pipeline utilizing functions from the PhysioZoo instrument driver. The ECG file undergoes prefiltering by a bandpass filter with lower and upper cutoff of 3 Hz and 100 Hz respectively and peak detection via an implemented energy based QRS detector to output an R-R interval time series. The time series passes through a moving-average filter for outlier removal to output N-N intervals. Finally, filtered N-N intervals undergo power spectral density analysis to output the power ratio between LF (0.04-0.15 Hz) and HF (0.15-0.40 Hz).

Comparison of obtained LF/HF values from each trial will include utilizing a paired t-test for statistical significance. A paired t-test is run between LF/HF from all trials of large and small targets.

III. RESULTS

A. *Preliminary Stroop Test Results*

The initial analysis compares the HRV statistics obtained from several participants during taking the Stroop Test and from a resting state.

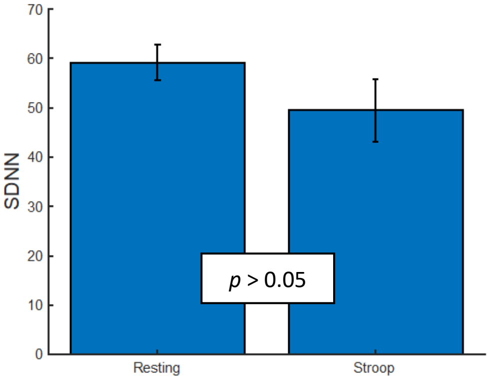

Figure 3: SDDN for resting (left) and stroop (right). Results are presented as aggregate data for all trials (N = 11). SDNN for resting is 59.2 ± 3.63 (mean ± SEM). SDNN for stroop is 49.5 ± 6.3 (mean ± SEM). $p > 0.05$ (paired t-test).

During preliminary testing, SDNN was found to be the most significant measure of cognitive workload; however, SDNN proved unreliable during preliminary target task testing. Testing showed that LF/HF was reliable measure during prosthesis usage. The study uses LF/HF as a measure of cognitive load from this point.

B. *Target Task Results*

11 participants completed the Target Task. The values presented are from HRV analysis on these trials and the NASA TLX results. Bar graphs were generated from the average LF/HF values for large and small target trials across participants and a t-test was calculated for the difference between averages within each participant's results.

	Large (0.35)	**Small (0.10)**
Participant 1	4.13	6.79
Participant 2	0.94	1.42
Participant 3	0.92	1.68
Participant 4	1.44	1.43
Participant 5	12.38	15.35
Participant 6	0.54	0.70
Participant 7	2.54	2.94
Participant 8	3.04	4.09
Participant 9	1.67	1.84
Participant 10	0.78	1.38
Participant 11	5.58	7.97
Average	**3.09**	**4.14**

Table 1: LF/HF values for Participants 1-11 during large and small target trials.

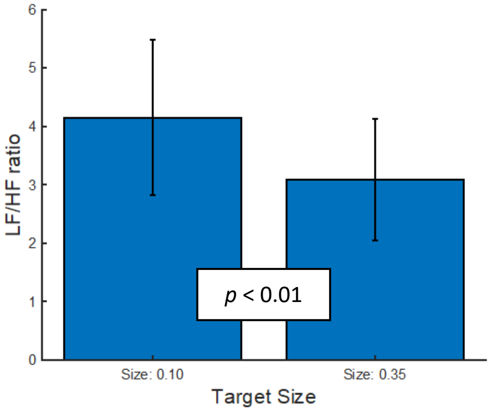

Figure 4: LF/HF ratio for small 0.10 target size (left) and LF/HF ratio for large 0.35 target size (right). Results are presented as aggregate data for all participants (N = 11). LF/HF for small target is 4.0 ± 1.3 (mean ± SEM). LF/HF for large target is 3.1 ± 1.0 (mean ± SEM). $p < 0.01$ (paired t-test).

The small target task resulted in a larger LF/HF ratio than the large target task, indicating the change in difficulty was successfully detected by the LF/HF measure ($p < 0.01$; Fig. 1).

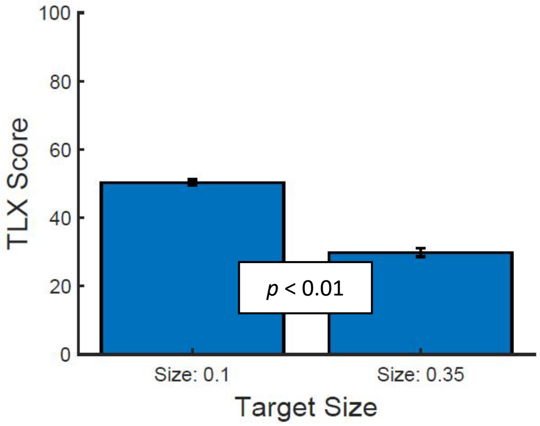

Figure 5: NASA TLX survey results for small 0.10 target size (left) and large 0.35 target size (right). Results are presented as aggregate data for all participants (N = 11). TLX score for small target is 50.3 ± 0.9 (mean ± SEM). TLX score for large target is 29.3 ± 1.3 (Mean ± SEM). *p* < 0.01 (paired t-test).

The NASA TLX supported our physiological findings that the small target was significantly more difficult than the large target ($p < 0.01$, paired t-test).

IV. DISCUSSION

This study evaluated the efficacy of HRV as a measure of cognitive workload during prosthesis usage. The results validate the methodology in using LF/HF heart rate variability analysis to measure the cognitive workload during prosthesis use. The *p* value of < 0.01 for the paired t-test demonstrates a strong correlation for the increase in LF/HF with increasingly difficult tasks. Although the standard error of the mean (SEM) is large for both the large and small target trials, this demonstrates the validity of this analysis method for a variety of individuals.

Predetermined purposeful alteration of the target task for one target to be more difficult allows us to truly validate whether LF/HF is an accurate measurement of cognitive workload. In the future, the LF/HF ratio could be used to elucidate differences in cognitive workload between control algorithms. Illustrated by Fig. 4, the LF/HF ratio increased during the small trial compared to the large trial. In addition to validating the usage of this analysis method for prosthesis usage, the results concur with previous studies which have demonstrated HRV as an accurate measurement for cognitive workload in other settings [7][8][11].

Completion of this validation enables us to use the measure in showing the cognitive benefits of other prosthesis advancements, such a sensory feedback and different control algorithms. Additionally, we would be able to compare the ease of use of advanced prosthesis control and commercial prothesis control.

This study opens a new pathway for more patient-centric evaluations of prosthesis advancements, which may lower prosthetic abandonment. This method of evaluation will be used further in this study as testing will continue with amputees with the “LUKE” arm with haptic feedback. This analysis method will be used to determine if haptic feedback decreases the cognitive workload of a task, resulting in better performance, control, and less abandonment. The system developed to measure and analyze HRV will be implemented into investigating the strain during prosthesis usage with and without haptic feedback.

The use of the Shimmer3 ECG unit provides some limitations to the study results. The Shimmer ECG model was chosen due to its portability and functionality over a long period of time. However, Shimmer utilizes a 5 lead ECG recording method which is less than the standard of the common use of 12 lead ECG, which is most common in hospital observation. Additionally, participants were given a picture illustration of proper ECG electrode placement and placed the electrodes themselves to limit intrusion by the experimenters. Improper placement by the participants could lead to increased noise in the ECG signal; however, noise was limited due to filtering parameters integrated to Shimmer.

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