Improving Prosthetic Reaction Time via Incorporating Stimulating Feedback

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***Abstract*—The long-term goal of this research is to explore the incorporation of stimulation feedback on improving human reaction time. The number of Americans with limb loss is 1 in 190 and expected to double by 2050. Electrical properties of neurons and the basic nerves for motor communication are still present in the residual limb of amputee individuals and can be utilized to restore motor movement. Prior work has shown that haptic feedback does improve reactions, however this was only explored using iBCIs. Here we explore the use of EMG signals to control a game and obtain similar results showing that best performance is achieved when both visual and stimulation feedback were present, as opposed to just one or the other. Statistical significance was found between all feedback approaches with p values of about 0.011, 0.026, and 0.029. The results provide a stepping stone in neuroprostheses by contributing findings that support the intuition behind incorporating sensory feedback to improve reaction time of prostheses. They may also be applied to adjacent fields, such as the gaming industry through integrating neural engineering into VR.**

I. Introduction

Currently, nearly one in 190 Americans live with limb loss. This number is predicted to double by the year 2050 [1]. As the number of individuals with this neurological impairment is likely to grow, it is important that efforts are focused on creating more intuitive tools to help these individuals adjust and improve their quality of life. Current clinical standards of care for these individuals focus on addressing pain treatment, exercise therapy, and educating these patients and their caregivers [2]. Although those aspects are vital, there are limitations when it comes to activities of daily life or leisure activities, and community integration [2]. One vital component to improving traditional prostheses is the impact of individuals reaction times to external stimulus for eliciting movement in their prosthetic.

Due to the electric spike behavior between the human brain and the body's senses and movements, engineers can take advantage of the electrical communication from the brain to the muscles to artificially elicit motor muscle movement and sensory feedback through the electrical stimulation of afferent and efferent neural pathways. When a limb is lost, the majority of the nerve wiring are still intact up to the lost limb [3]. Utilizing these frameworks allows for prosthetics to be robotically controlled through efferent neurons and sensory feedback to be delivered through afferent neurons, leading to a better embodiment of the prosthetic limb and it's daily use.

Previous state-of-the-art research has explored the effects of peripheral haptic feedback on intracortical brain-computer interface control (iBCI). Deo et al. have demonstrated iBCI cursor control with continuous skin-shear haptic feedback on the back of the neck of a person with tetraplegia. They found that cursor control performance increased significantly when the participant was given haptic feedback, compared to only visual feedback [4].

The objective of this paper is to build upon the work of Deo et al. by exploring the human reaction time based on variations of external input. Similar to their approach, we will be specifically focusing on determining the impact of visual versus stimulus external input, and the combination of the two on reaction time. However, having a iBCI implanted is a invasive procedure, therefore our research explores an alternative approach using EMG signal acquisition. The application for our approach will be tested using a T-Rex dinosaur game, similar to the one on Google Chrome. Ultimately, a Matlab control algorithm was interfaced with a Python Dinosaur game to control the reactionary aspect of the game. The medians of game scores indicate that best performance was achieved when both visual and stimulation input were present, as opposed to just one or the other. This was verified with statistically significant results between the the three game playing approaches. Overall, positive subjective remarks were received from participants in agreement that both visual and stimulus feedback improved their gaming experience.

II. Methods

A. Participants

Three human subjects were recruited for this study. The group was 100% female with ages that ranged from 21-22 years-old. All participants were considered healthy in terms of neurological condition.

B. Signal Acquisition

Within this study, the BackYard Brains Muscle SpikerShield was used to sample and acquire the EMG signals. The device consists of a single channel and had a sampling rate of 330 bytes/ms, or 330 kHz. It had a surface-EMG electrode which was used to take measurements from the calf muscle of the participants, as seen in Figure 1. Two electrodes were placed vertically along the calf muscle, about 5 inches apart. A third grounding electrode was placed on the ankle bone.

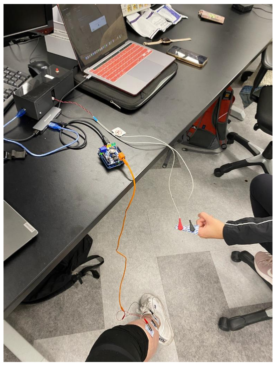


Fig. 1: **Experimental setup.** EMG data is collected from the calf of the first participant that is playing the game. Stimulation is delivered to the index finger of the second participant, who will indicate to the first participant that an obstacle is approaching with a light tap to their back or shoulder. Both hardware units are connected to the laptop which is running the game in the small display window.

To acquire the data, two software systems were used. The Arduino platform was used to upload code to the device's on-board micro controller and deliver the sampled data from the EMG electrodes to the computer. MATLAB was then utilized to control the Arduino execution and serve as the interface between the data and the python environment which controlled the game.

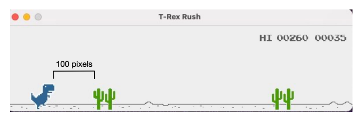
C. Control Algorithm

A control algorithm was developed in Matlab to determine a binary control signal that detects if the participant is jumping or at rest. The algorithm was designed to be a callable function that would return the jumping control indicator upon its function call. Within the function, raw EMG data is first acquired for 10ms. Then, the absolute value of the sampled data was taken to eliminate negatives that may interfere with threshold comparison. If the data is larger than a threshold of 1.5V, then the control signal is set to 1, indicating a jump. If it is below this threshold, than the control is zero, indicating a rest. The threshold was determined visually by running a signal acquisition test and deciphering a level that would differentiate resting noise from muscle jumping activity, seen in Figure 4. In contrast with previous approaches, the control algorithm could not have been made continuous in this case due to the later interface between Matlab and Python environments. Python requires Matlab to return a value before being able to use it within its script. Therefore, instead of the signal acquisition being continuous in Matlab, it is continuously called back-to-back in the Python script. The python script will use Matlab's jumping control indicator to make the dinosaur jump in the game.

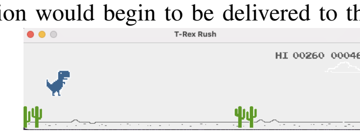
D. Stimulation Hardware and Parameters

The hardware components used in the stimulation aspect of this study were the stimulation box and the surface electrodes which connected to the subjects. The electrodes were 3cm in diameter. One stimulating electrode and one grounding electrode was placed on the top and bottom of the index finger on the right hand, as shown in Fig. 3a. The stimulation box was a one-channel high-voltage stimulator, developed in the University of Utah's NeuroRobotics lab, with a compliance voltage of 320V.

Delivered through a single electrode, the stimulation consisted of a charge-balanced bi-phasic symmetrical pulse with its cathodic phase first. The current-regulated system was utilized to create a stimulating waveform with characteristics of a 3.9mA pulse amplitude, 75μs pulse width, and a frequency of 25Hz. As the original plan for this experimental game was to have the stimulation and EMG acquisition occur on the same person, these characteristics were tweaked to attempt to decrease the noise interference introduced by the stimulation box to the EMG signal. After this unsuccessful attempt and various other methods to make this work, the decision was made to make the experiment a two person game. Since a comfortable waveform had already been found for all participants, the characteristics were not shifted after that point. The stimulation box controls were written in Matlab and called from python within the game code.



(a) Image was taken about 100 pixels before an upcoming obstacle where stimulation would begin to be delivered to the participant.



(b) Image was taken in the middle of a successful jump controlled based on the EMG recordings of participant. Stimulation was stopped as soon at the dinosaur passed the coordinate of the cactus mid-jump.

Fig. 2: **Example screenshots of the game user interface (GUI) mid-play for EMG recording and stimulation incorporation.** Game scores are reported in the top right corner of the GUI, where the left-most number is the high score and the right-most number is the current score for that game.

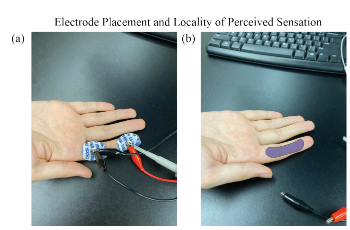


Fig. 3: (a) Stimulating (red wire) and grounding (black wire) electrodes placed on the participant's right index finger for induced tactile stimulation. (b) Image of participant's right hand with palmer side facing up. The purple area, which falls between the electrodes, indicates the perceived sensation felt by the participant.

E. Experimental Design and Metrics

The experiment design surrounded an application of incorporating tactile stimulation and EMG recordings into the well-known lovable Google Chrome T-Rex game. The essence of the experiment from a clinical perspective is to test an individuals reaction time based on visual versus stimulating feedback. Therefore, the game experiment had three approaches, playing using only visual input of the game window, playing using only stimulus feedback and not looking at the game at all, and playing using both visual and stimulus feedback.

The python source code for the game was pulled from github [5]. The matlab code controlling the hardware units was provided in Matlab. A real-time interface was developed between Matlab and Python using a python library called Matlab.Engine, which allows for python to connect with a matlab environment and call matlab functions through its own script. There were two matlab environments open, one to handle the stimulation code and another to handle the jump control generation. All matlab functions were called in the background of the python script as to not interfere with the game and cause a glitch.

The stimulation to the participant was introduced at a fixed point in the game, precisely when there was a 100 pixel distance between the dinosaur and the upcoming cactus obstacle, seen in Figure 2a. The stimulation would stop under three conditions: once the dinosaur has passed the coordinate of the obstacle on a successful jump (Figure 2b), upon the death of the dinosaur if it fails to jump, or if the game is canceled mid-play. The stimulation parameters were kept constant throughout the game, leading to a stable stimulation for the participant.

As mentioned in the Control Algorithms Section, the EMG recordings were sampled over 10ms and a jump control signal was returned based on this time window. Within the Python code, this control algorithm function was called in the background. A check was executed on every frame of the game to determine when the function had returned. It would then immediately use that jump control signal for the dinosaur's movement, and call the function to start again all within that same frame. Doing so allowed for a virtually continuous EMG recording to control the dinosaur without glitching.

A few other aspects were changed in the game to make it easier. The ducking elements were removed from the original game to limit the degrees of freedom for control to one. The speed of the game was also reduced.

The performance metric was the score achieved by the participant for each game approach. The score within the game increased with every frame, therefore it is analogous to a time measurement of game survival. The game speed increased after every 100 points were achieved. For the three game approaches, each participant had seven trials where they played the game and their final score was recorded. Therefore, each participant contributed 7 samples to each game approach, and 21 total samples to the study.

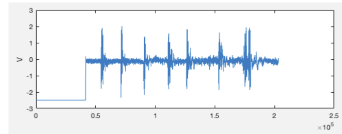


Fig. 4: **Example of raw unfiltered EMG data acquired by the Muscle SpikerShield.** Electrodes were placed on the calf of the participant, while they were asked to jump periodically throughout the acquisition. Periods of rest and jumping are visually distinguishable through the spikes in voltage throughout the recording. Recording was used to determine a jump threshold of 1.5V within the game control.

F. Statistical Analysis

To begin the statistical analysis, the data from all three participants was combined for each of the three game approaches. It was tested to detect any outliers and they were removed if necessary. Then, a test of normality was conducted and the data was determined to be non-parametric. The data was considered to be unpaired as there were multiple participants contributing to the data for each game approach. Therefore, the rank sum statistical test was used to compare the three approaches against eachother. There was a sample size of 21 per game approach. The final boxplot comparing the different parameters can be seen in Figure 5. The results between all three approaches was statistically significant, with p values of 0.01087, 0.026396, and 0.02857. The statistical significance and the rise in median score values seen in Figure 5 indicates an increase in performance as stimulation is introduced to the game approach.

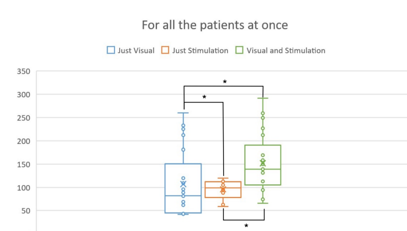


Fig. 5: **The medians of game scores indicate that best performance was achieved when both visual and stimulation input were present.** Statistical significance (*) was found between all three game approaches, using an unpaired non-parametric rank-sum test. The p values for the comparisons between Just Visual - Just Stimulation (blue to orange), Just Stimulation - Visual and Stimulation (orange to green), and Just Visual - Visual and Stimulation (blue to green) were 0.01087, 0.026396, and 0.02857, respectively. Median game scores ± IQR are represented as that of the combined participant data (n = 21) per game approach.

III. Results

A. A Matlab control algorithm ran in the background of the Python game and was used to control the dinosaur's jumps.

A Matlab control algorithm determined a binary control signal that detects if the participant is jumping or at rest. The algorithm worked by recording EMG data for 10ms, taking the absolute value, and using threshold comparison. The control was set to 1 if the data passed a threshold of 1.5V, and was 0 otherwise. The control algorithm was implemented in a single function call format so it could be called from the Python code, run in the background, and return a control value used to guide the dinosaur's jumping movement.

B. Github dinosaur game source code was utilized and updated to fit experiment design.

A real-time interface was developed between Matlab and Python using Matlab.Engine. The python game called the hardware-driven matlab functions throughout the game. Stimulation was delivered to the first participant when an obstacle was 100 pixels away from the dinosaur. Stimulation turned off when the dinosaur jumped over the obstacle, as in Figure 2b, upon the death of the dinosaur, or if the game is canceled. EMG recordings were sampled over 10ms windows and ran in the background to mimic a virtually continuous control over the dinosaus' jumping movement. The game speed was reduced from the original code and the ducking elements of the game were removed. The GUI interface can be seen in Figure 2.

C. The medians of game scores indicate that best performance was achieved when both visual and stimulation input were present.

The performance metric was the score achieved by the participant for each game approach. The score within the game increased with every frame. The game speed increased after every 100 points to increase game difficulty. For the three game approaches, each participant contributed 7 trial samples, making a total of 21 samples per approach for statistical analysis. Statistical significance was found between all three approaches and highest game scores were achieved when both visual and stimulation input were present, seen in Figure 5.

D. Positive overall subjective remarks were received.

A disclaimer should be stated that remarks mentioned are subjective, but can still be useful information for the improvement of future experiments. With this in mind, positive feedback was received about the experiments. A participant was quoted, "The game was intuitive and a very fun experiment to participate in! The broader application and initial results seem promising. This team went above and beyond for the game implementation to make an enjoyable experience for us!" Collectively, participants agreed that receiving a stimulation definitely improved their reaction times and their scores.

IV. Discussion

This paper's objective was to explore the human reaction time based on visual versus stimulating external inputs, and the combination of both. The findings from this paper conclude that a Matlab control algorithm can be used to interface with a Python Dinosaur game to control the reactionary aspect of the game. In addition, the medians of game scores indicate that best performance was achieved when both visual and stimulation input were present, as opposed to just one or the other. This was verified with statistically significant results between the the three game playing approaches, with p values of 0.01087, 0.026396, and 0.02857, as seen in Figure 4. Overall, participants were in agreement that both visual and stimulus feedback improved their gaming experience.

Prior work through Deo et al. has shown that cursor control performance was increased significantly when the participant was given haptic feedback, compared to only visual feedback [4]. Prior work has also only shown that this is true when using an intracortical brain-computer interface control and peripheral haptic feedback on the back of the neck. In contrast, here we show that similar results can be obtained without the use of an invasive iBCI, but instead with non-invasive EMG recordings of muscles.

The work presented here builds off of prior work by establishing a similar testing experiment, but expanding the potential use-case of this technology beyond tetrapolegic individuals, to amputees and prostheses. Also novel from this work is the application to a common game using a matlab to python real-time interface, which provides insight to the VR technology realm.

Future work should replicate these findings with a solution to the noise interference that the stimulation box introduces to the Muscle SpikerShield EMG recordings. The current findings technically take into account two reaction times, so doing this would allow for both stimulation and EMG recordings to done on the same participant as they are playing the game, providing a better focus on a single reaction time. Doing so will likely improve the reaction times even more as it is taking out the middle man and the time it takes to communicate a stimulation delivery from one person to another.

This paper's work has a direct impact on the field of neuroprostheses by contributing findings that support the intuition behind incorporating sensory feedback to improve reaction time of prostheses. The findings may also be applied to adjacent fields, such as the gaming industry and VR development as our application introduces evidence of integrated gaming and neural systems for a better experience for the player. Clinically speaking, the development of this work provides a foundation for improvements in prostheses and their embodiment by the individual amputees who will use them, by increasing the intuitiveness of their responses to external inputs that may help those controlling the prosthetic movements. Improvements in prostheses can significantly impact the quality of life for amputees, providing a better approach for daily tasks and independence.

V. Author Contributions

All authors contributed to the overall experiment design and parameter decisions. PTZ developed the game experiment setup with the incorporation of python gaming software and matlab-driven hardware. EW and GS helped with EMG signal acquisition diagnostics. GS tried EMG signal filtration in an attempt to reduce stimulation noise in the recordings. EW and PTZ were involved in participant data collection. HK performed statistical analysis and aided in experiment brainstorming.

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