Effect of Grip Aperture Size on Time to Fatigue with Electrical Stimulation of Biological Arm

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***Abstract*—The long-term goal of this research is to address issues with grip aperture sizes caused by electrocutaneous stimulation for rehabilitation. Individuals with stroke and spinal cord injury (SCI) experience permanent disabilities, varying from minor mobility disruptions to total limb paralysis. Current advancements in neuroprosthetics allow for the integration of a brain-computer interface (BCI) and functional electrical stimulation (FES) to reanimate paralyzed limbs. With this is mind, we wanted to look at the grasping abilities that FES can produce. We compared two aperture sizes for the index finger and thumb to understand the impact aperture size has on the time until fatigue. We found that the smaller sized grasp led to faster fatigue and the inability to hold the object. There was a significant difference in the time to fatigue (p = 3.633e-15), but not a significant difference between participants (p = 0.9989). These results highlight an important factor to consider for the development of neural prostheses: the ability to hold objects of varying size and weight using the same level of stimulus. Using these findings, more robust systems can be developed. More broadly, these results can be applied to the field of virtual reality (VR) and be used to create more realistic experiences.**

***Index Terms*—Functional Electrical Stimulation, Fatigue**

I. Introduction

In 2005, there were over 250,000 people living with a SCI, which can range from still having mobility to tetraplegia [1]. To go along with this, over 80% of amputations are caused by trauma, making them a sudden and severe ailment [2].The adjustment from biological arm use to prosthetic use is sudden, and not made easy with the current systems. A major problem with current prosthetics is the grip strength; it is either too strong and crushes objects, or too weak and drops them [3]. While it has been found that FES increases muscle conditioning and strength, and eventually fatigue resistance, novel users have not yet undergone this type of conditioning and can find the stimulation fatiguing [4]. While this conditioning is now standard in the protocol of setting up the devices, the use of single electrodes still has a high chance of causing fatigue due to the distributed branching of muscle nerves [5]. Understanding what movements have a higher chance of causing fatigue in single channel stimulation systems allows for adaptations to be made to help mitigate this effect.

FES can be divided into three categories: restoration of sensor functions, restoration of skeleto-motor functions and the restoration of automatic functions [6]. We will focus on the restoration of skeleto-motor functions, specifically the mimicking class of neuroconduction devices. These devices aim to generate movements which mimic normal, voluntary movements. This is done by creating short, electrical pulses to generate contractions in paralyzed muscles [7]. Modulating the intensity of the stimulation can allow for activation of surrounding muscles, and the joints they innervate with, causing complex motions.

Recent work using FES for spinal cord injuries has improved walking and balance [8] and significantly improved grasping functions [9]. Participants in the FES-assisted walking group significantly improved their spinal cord independence measure. Similarly, FES combined with physical therapy significantly improved grasping function across multiple different voluntary grasp motions. These studies show the drastic improvement that a FES system can give to SCI patients, but both still face the same issue of causing muscle fatigue.

In this paper, we compare two grip aperture sizes and their time to fatigue to understand the implications of more fine motor movements on FES control. While it is known that one of the main limitations of FES systems come from the fatigue caused, a deeper dive into the relationship of the movement generated and the time to fatigue has yet to be looked at. We believe a better understanding of this relationship will help get us closer to solving the overarching issue. We took a very simple approach and used only a single channel of stimulation and only two sizes to compare. We did this to have a starting point for the relationship between aperture size and fatigue, which can later be built on in more complex applications. We found that the time to fatigue varied significantly between aperture sizes (p = 3.633e-15). We also tested for significant difference between the participants and found no significance (p = 0.9989).

II. Methods

A. Participants

Four human subjects participated in this study, with 100% being female and ranging in age from 22-28. All participants were healthy, intact individuals with no neurological impairments.

B. Stimulation Hardware

To deliver the simulations, a 1 channel, high voltage stim box was used. This consisted of an Arduino Uno with a top shield. The compliance voltage of the stim box was 15V. The electrodes used were medi trace, 3.6cm diameter electrodes. The electrodes were placed on the inner thumb and forearm (as shown in figure 1).

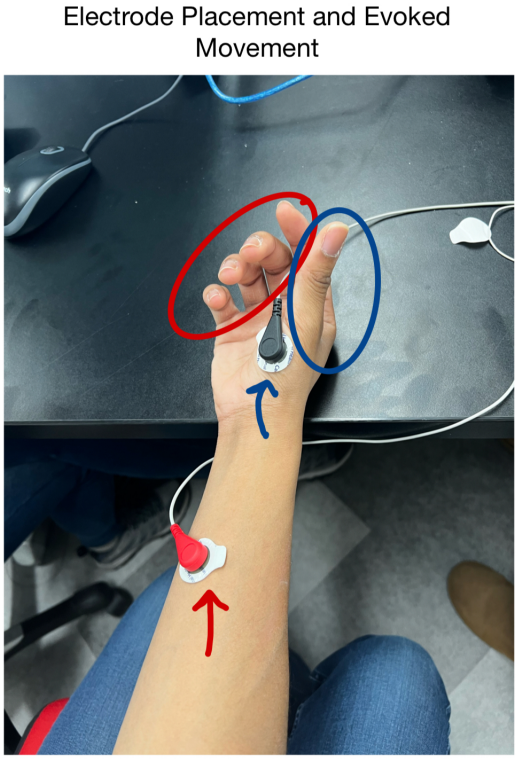

Fig. 1. We used two electrodes - one placed on the fatty part of the thumb and one placed in the center of the forearm. The evoked movements can be seen in the fingers. The forearm electrode is responsible for the index, middle, ring and pinkie finger movement. The thumb electrode is responsible for the thumb moving towards the mid-line of the hand. Together, the total evoked movement creates a grasping point between the thumb and the index finger, while also moving the rest of the fingers in.

C. Stimulation Parameters

In this study, we used constant stimulation parameters for each participant. We found the current threshold for each participant by iteratively testing different amplitudes until the correct movement was elicited. The values for each participant, in milliamperes, were 8, 7, 6, and 5.5. For the pulse width and frequency, we kept them the same for all participants and set them at 500ms and 30Hz, respectively.

D. Strength-Duration Curve

To calculate the strength duration curve, we used one participant and delivered the stimulation to their wrist and thumb. We looked for an immediate twitch in the thumb to indicate movement. We started at 100ms pulse width and varied the current until a small twitch was seen in the thumb. We looked for an immediate twitch for each step, allowing about 1-2 seconds after initializing the stimulation. We delivered the stimulation for a total of 4-5 minutes for the entire test. We took one sample at each current for each pulse width, this was to not cause fatigue of the muscles before completing the curve.

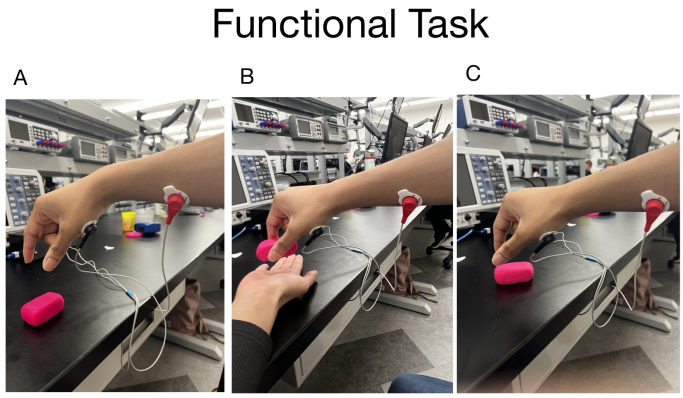

Fig. 2. The functional task involved grasping a block of playdoh on either a longer or shorter side (to have variation in aperture size). A) First, the stimulus was delivered to create the correct grasping position. B) The arm was then moved down to grasp the playdoh, without adjusting the hand grip. Once the grip was established, the support hand was removed. C) Once the grip loosened enough, the playdoh was dropped. This is what was considered fatigue for this task.

E. Chronaxie and Rheobase

The Rheobase is the minimum current that can elicit a response from the membrane [10]. For this experiment, we used a twitch in the thumb as our response. The value for the rheobase was found by iteratively testing different current amplitudes per each pulse width. We started at 100ms and continued stepping up by 100ms until the current needed to create the twitch leveled out. For this study, the rheobase was found to be 4mA. The Chronaxie, which is the time needed to activate a twitch at two times the rheobase, was found by multiplying the rheobase by two, which is 8mA and finding the time that correlated with that, which was 190 microseconds.

F. Experimental Conditions

For this study, we compared two different aperture sizes for the finger grip to understand the effect on fatigue time. We created a shape out of playdoh, which weighed 56 grams and had one side measuring 50mm and another measuring 25mm. We used the same stimulation parameters for both aperture sizes to have consistent stimulation and just vary the grip size needed to hold the object. To do this, we had to stimulate enough to cause the small aperture size, so we found the base current needed for each participant to be able to grasp the small side of the playdoh and used those values (which are listed in the stimulation parameters) for all trials.

G. Performance Metric

We measured the time it took for the object to fall from the grip and called that the ”fatigue time”. We then compared

the fatigue time for each aperture size to see if there was a difference in the average time to fatigue. For each participant, we ran 4 trials per grip size, totaling in 8 trials per participant. We did not run any more than that because we found that the grips started to loosen due to long term stimulation.

H. Statistical analysis

We first ran an Anderson-Darling test to check for normalcy, and found the data to be normally distributed. We then ran an ANOVA to test for significant differences between the aperture sizes (n = 16), with just one factor being compared: time. Finally, we ran a multi-compare between the participants to check for significant difference in fatigue time between participants (n = 32).

III. Results

A. The strength duration curve shows the relationship between the membrane potential and the stimulus delivered

We stimulated on the forearm and thumb of one participant using the stimulation box set to 30Hz and varying current and pulse width to develop the strength-duration curve (exact stimulation locations shown in figure 1). We varied the pulse width by 100ms per trial and stepped through currents, starting at 2mA, until we got a response. We consider a twitch in the thumb to be a membrane response. As the curve shows, the current needed for a response is higher at lower pulse widths, and decreases as the pulse width increases, until finally leveling out at the rheobase of 4mA.

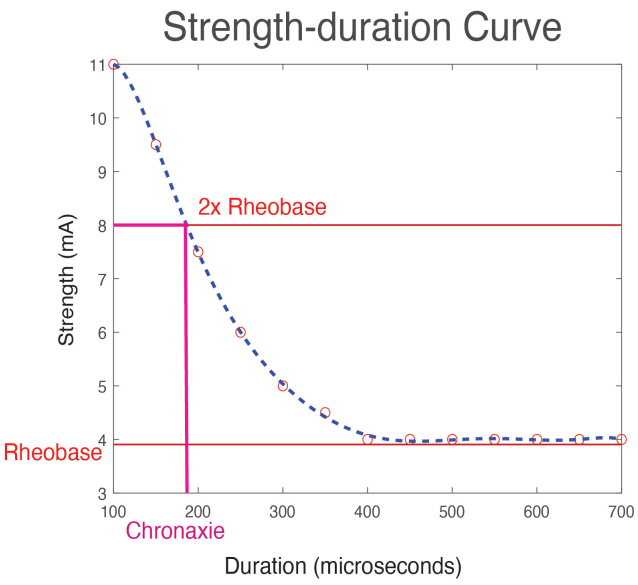

Fig. 3. The strength duration curve shows the relationship between the membrane potential and the stimulus delivered. The Rheobase is the minimum current that can elicit a response (in this case, a twitch in the thumb). This was found by iteratively testing different current amplitudes per each pulse width, until the current needed leveled out - which in this case gives a rheobase value of 4mA. The Chronaxie, which is the time needed to activate a twitch at two times the rheobase (in this case, 8mA), was found to be 190 microseconds.

B. The Rheobase was found to be 4mA and the Chronaxie 190ms

The rheobase is found by identifying the smallest current needed to elicit a response. This is done by iteratively testing currents for each pulse width until a response is seen, in this case a twitch in the thumb. Once the values for current stay constant as the pulse width increases, it is reasonable to consider that value the rheobase. In this study, the rheobase is 4mA. For the chronaxie, it is the time needed to elicit a response at a current two times the rheobase. This is found by identifying two times the rheobase, which is 8mA, and tracing down to the time, which is 190ms in this case. All of the values that elicited a responses and the identification of the rheobase and chronaxie can be seen in figure 2.

Identification of the rheobase and chronaxie are important because they inform about the underlying physiological responses of the cells. Understanding these responses is imperative for understanding the excitation and subsequent conductance velocity.

C. The aperture size has a significant effect on time to fatigue

We measured the time the object was held for each aperture size, for each participant. The exact motion can be seen in figure 3. We used 4 trials per size, per participant, with no changes in the stimulation between trials. We found that the aperture size has a significant impact on the time to fatigue, as seen in figure 4. The p value is 1.633e-15 for the aperture sizes. We also checked for significant difference between participants (figure 5) and found no significant difference (p = 0.9989).

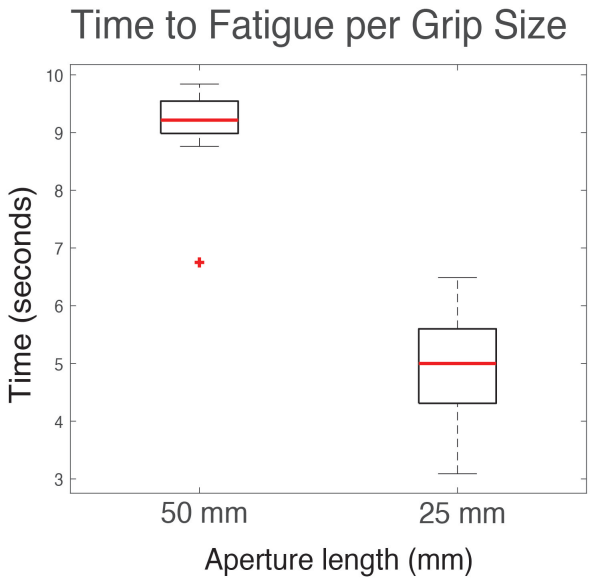

Fig. 4. Comparison of the aperture sizes. An A-D test was run to test normalcy, which found the data to be parametric. A one factor ANOVA was then run to test for significance. There is a significant difference between the time to fatigue for the two sizes (p = 1.633e-15, n = 16).

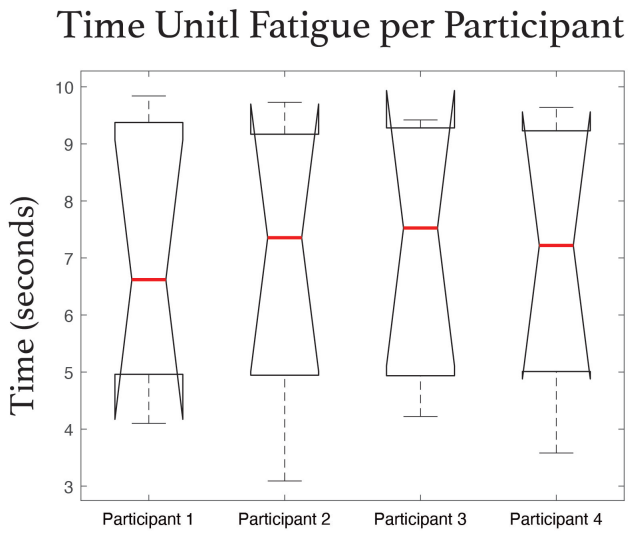

Fig. 5. Comparison of the time to fatigue between participants. An A-D test was run to test normalcy, which found the data to be parametric. A multi-compare was then run to test for significance difference for the time to fatigue between the participants. There is not a significant difference between the time to fatigue for the participants (p = 0.9989, n = 32).

D. The stimulation needed to cause this grip was uncomfortable for able-bodied participants

In order to create the small grip size, the stimulation had to be at a high level. Each participant found this level of stimulation to be quite uncomfortable, with one saying "my hand feels numb". Although the discomfort went away once the stimulus stopped being delivered, some found their hand to feel strange for a short period after, with one participant finding it hard to write immediately following their trials.

IV. Discussion

The objective of this study was to identify the impact aperture size has on time to fatigue with functional electrical stimulation of biological limbs. We found that there is a significant impact on the fatigue time for the smaller versus the larger aperture size. We also found that there was no significant difference between participants, which reinforces the effect of the aperture size. For biologically intact limbs, the stimulation needed to create the aperture sizes was uncomfortable, but did not leave a lasting effect.

Prior work has shown how FES can be used to improve grip strength and griping function in spinal cord patients. Prior work has also shown how FES can improve the independence of spinal cord injury patients by restoring some function. In contrast, here we highlight some possible limitations with FES by showing the impact of using the same stimulation for varying aperture sizes. Even for the same task (holding a block), the variation of the grip needed shows a significant impact on the time to fatigue.

The work presented here builds off of prior works that show how FES can be used to improve grip strength and gripping ability. Novel from this work, we look specifically at the fatigue time and the impact the grip size has on fatigue.

Future work should look at more grip types and aperture sizes to further narrow down the impact these have on fatiguing. Also, the study should be recreated using persons without total control over their limbs to see if the effect is the same.

This work provides a starting point for further investigation into the ideal set up for limb reanimation or prosthetics by highlighting some limitations that FES has when trying to use the same stimulation for varying applications. These findings directly impact the field of neuroprostheses by showing the issues in FES when it comes to fine motor movements. This could help to reduce the rejection of prosthetic limbs by creating more robust systems. This work can also be applied to the field of VR by showing how the same stimulation can be used in two different applications (grips).

V. Author Contribution

RM wrote the manuscript and performed statistical tests. CA helped design the study. GO recorded the findings and recordings. NP modulated the values and set up the hardware.

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