Functional grip strength increases with FES amplitude and pulse width

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Roughly 2.6 million US residents have spinal cord injuries (SCIs). SCIs often paralyze muscles, disrupting activities of daily living. Physical therapy and mobility aids, the current standard of care, often cannot fully restore movement below the injury; however, functional electrical stimulation (FES) can bypass the injury by stimulating peripheral nerves to cause muscle contractions. Some people with SCIs work on gripping physical therapy; however, we have discovered that functional electrical stimulation can induce functional gripping and increase grip strength by increasing pulse width and amplitude. Specifically, we found that the FES strength-duration curve in a healthy individual fits a reciprocal function in which the x-asymptote is the rheobase (1.436 (mA)). We found that increasing amplitude and increasing pulse width of FES can both increase grip strength (positive parameter-grip strength slopes of 5.7428 x 10-4 ± 1.5819 x 10-4 and 5.8684 x 10-4 ± 9.6452 x 10-5, respectively). We also noted that stimulation frequency should be high enough that the individual pulses are indiscernible. These results inform the FES field on how amplitude and pulse width affect grip strength. Furthermore, the results contribute to the body of evidence supporting FES in clinical rehabilitation for SCI and other conditions such as multiple sclerosis and transverse myelitis.

I. Introduction

Approximately 2.6 million people in the US live with spinal cord injuries [1]. While early-intervention physical and occupational therapy may improve patients' abilities to perform activities of daily living, they generally do not restore movement below the injury [2].

Spinal cord lesions disrupt electrical signals from the brain from reaching the peripheral nerves and causing muscle contractions[3]. However, functional electrical stimulation (FES) can be used to generate movements bypassing the injury by exciting peripheral nerves, resulting in muscle contraction[4].

The research field is starting to develop brain-computer interface-directed FES systems in which implanted electrodes detect motor commands from the cortex, which signal the stimulating electrodes to supply current and cause muscle contraction [5]. Additionally, researchers are looking into using textile-based surface electrodes to incorporate FES technology into clothing items to increase user-friendliness[6].

This paper investigates the combinations of FES parameters that generate functional grasps. We uniquely varied FES amplitude and pulse width to meet a range of grip strength requirements. We found that the FES strength-duration curve is likely a reciprocal function in which the x-asymptote is the rheobase. We also found that increasing FES amplitude and pulse width both can increase grip strength. We additionally noted that for FES to be tolerable, the stimulation frequency should be high enough that the individual pulses are indiscernible.

II. Methods

A. Participants

There were 4 participants in this study ranging from ages 23-25, with a gender make-up of 75% male and 25% female. All subjects were neurologically healthy.

B. Stimulation Hardware

We used a high-voltage stimulator with a compliance voltage of 300 V to provide FES. Two Cardinal Health Kendall ECG H124SG electrodes on the volar side of the dominant wrist (right for all participants) transmitted stimulation to likely the median and ulnar nerves. The conductive hydrogel area of the electrodes had a surface area of 201 mm.

C. Stimulation Parameters

In data collection for the strength-duration curve, we held frequency at 30 Hz and stimulation duration at 1 s while we varied amplitude and pulse width in the data collection process. In data collection for amplitude-weight slopes, we held frequency at 30 Hz for all participants except one (24 F), who required a higher frequency of 45 Hz to complete data collection comfortably. For all participants, we held pulse width at 300 **µ**s and stimulation duration at 3 s while we varied amplitude in the data collection process. For data collection for pulse-weight slopes, the frequencies were the same as in the amplitude-weight slope trials for all participants. For all participants, we held amplitude (mA) at their lowest recorded amplitude in the amplitude-weight slope trials (5 mA, 7 mA, 4.75 mA, 5.7 mA) and stimulation duration at 3 s, while we varied pulse width in the data collection process.

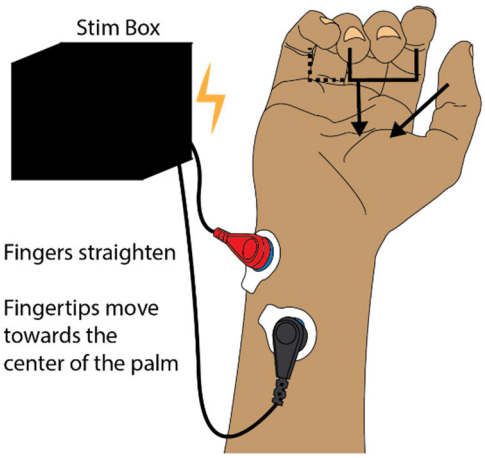

Figure 1. FES can induce movement of fingers by applying current to the skin on the volar side of the wrist, likely stimulating the median and ulnar nerves. Image shows a wrist and hand (volar/palmar side) with two electrodes on the wrist. A stimulation box with a compliance voltage of 300 V delivers stimulation to the wrist electrodes causing at least the first three fingers and thumb straighten and move towards the center of the palm, indicating likely median nerve activation. The pinky only moved in some cases, indicating that the electrodes stimulated the ulnar nerve in some participants but not in others.

D. Strength-Duration Curve

We obtained the strength-duration curve data from one participant (25 M). The data collection started with identifying the amplitude that produced visible movement of at least two fingers during the 1 s stimulation at a pulse width of 300 µs and a frequency of 30 Hz. From there, we kept the frequency (30 Hz) and the stimulation delivery time (1 s) constant. We adjusted the pulse width value in 50 – 200 µs increments and determined the minimum amplitude required to produce visible movement of at least two fingers at each value. We collected only one sample per pulse width value.

E. Chronaxie and Rheobase

We then plotted and fitted the strength-duration curve data points with a reciprocal function, yielding the best fit curve equation of:

$$\textit{Amplitude (mA)} = 770.4\ \textit{(mA*µs)/Pulse Duration (µs)} + 1.436\ \textit{(mA)} \quad (1)$$

We identified the rheobase as the x-asymptote of the function and determined the chronaxie to be the solution of the equation when amplitude was twice the x-asymptote/rheobase.

F. Experimental Design and Metrics

We tested two parameters for effects on grip strength: pulse width and amplitude. Rather than varying the parameters directly, we varied the weight of the gripped object (104 g, 208 g, 322 g, 465 g, 538 g) and thus required grip strength. We then adjusted the amplitude while keeping the pulse width at 300 µs, frequency at 30 or 45 Hz, and stimulation duration at 3 s. For each weight, we recorded the lowest amplitude the participant could hold onto the object for the entire stimulation. We then repeated the process but varying pulse width instead of amplitude. For pulse width trials, we kept the amplitude at the value recorded for the lightest weight.

We used slope as a performance metric to determine the ratio of relative change in parameter value to change in grip strength (weight) for amplitude and pulse width. We took five values of each parameter (1 value for each parameter per weight) from four participants. The five values from each participant for each parameter (y-axes) were plotted against weight (x-axes), yielding eight total scatter plots (4 per parameter, 2 per participant). We obtained lines of best fit, and their slopes from each scatter, producing an N = 4 for slope values for each condition.

G. Statistical Analyses

We ran a statistical analysis to compare the slopes for amplitude and pulse width conditions, which each had four samples (N = 4). Results of Anderson-Darling Tests showed that the data for both conditions were parametric, so we used a paired t-test to assess if there was a significant difference.

III. Results

A. A reciprocal function models the strength-duration curve

A stim box delivered FES of the participant via two surface electrodes on the volar/palmar side of his right wrist (Fig. 1), likely stimulating the ulnar and median nerves. We first found the minimum amplitude to produce visible movement of at least two fingers during the 1s stimulation with a pulse width of 300 us and a frequency of 30 Hz. From there, we kept frequency and stimulation duration constant. We adjusted the pulse width value in increments of 50 – 200 µs and determined the minimum amplitude which triggered movement at each value. The resulting dataset was the minimum amplitude required to elicit movement for pulse duration values ranging from 100 - 2000 µs. The data points formed a visible indication of a

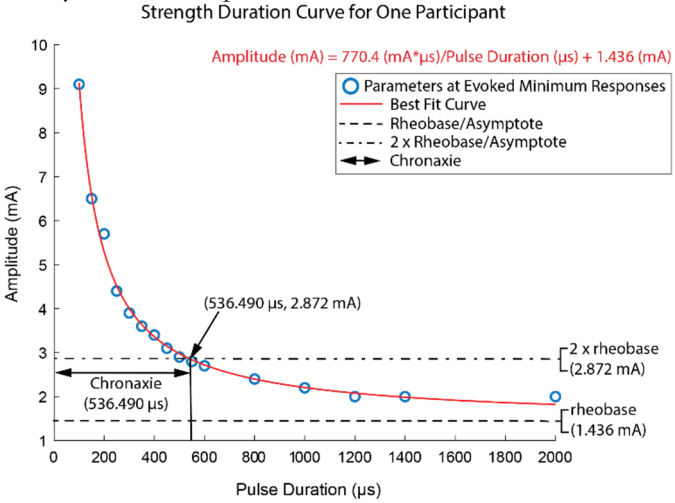

Figure 2. The FES strength-duration curve for one individual can be modeled by a reciprocal function, in which the x-asymptote is the rheobase. Above is the strength duration curve for one participant (24 M) with data points on the minimum amplitudes and pulse widths required to produce visible movement of the fingers at a frequency of 30 Hz and stimulus duration of 1 s. We fitted the data points with a best-fit curve defined by the function Amplitude (mA) = 770.4 (mA*µs)/Pulse Duration (µs) + 1.436 (mA) (Equation 1). We determined the rheobase to be the x-asymptote of the best-fit curve function, 1.436 mA, and the chronaxie was the solution of the equation when we input twice the rheobase 2.872 mA as an amplitude, yielding a chronaxie/pulse duration of 536.490 us.

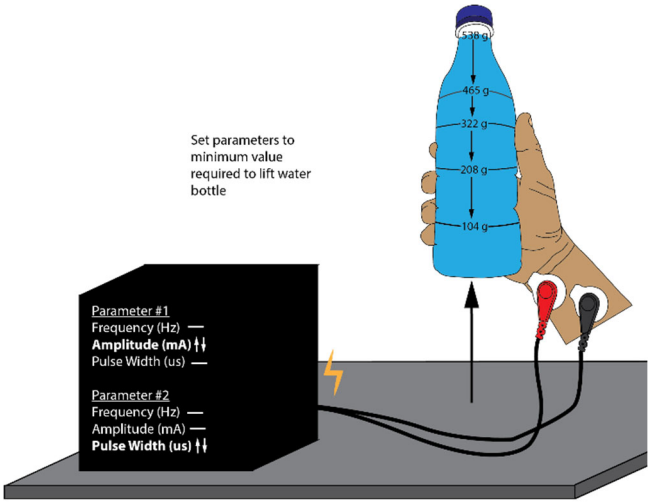

Figure 3. We varied amplitude and pulse width while performing a weight lifting task. We marked a water bottle at 5 roughly equidistant locations. We filled it to the top mark, weighed it (538 g), and set it on a table. We asked the participant to put their hand around the water bottle but not grasp it. We then applied stimulation at a frequency of 30 Hz, pulse duration of 300 us, and stimulation duration of 3 s. We adjusted the amplitude until we found the minimum value where the participant could grab the water bottle, lift it off the table, and hold it for the duration the stimulation. If a participant held onto the water bottle after the stimulation was ended, we determined the trial was affected by voluntary contraction, and redid the trial. Then we poured out water until the bottle was filled to the next highest line and repeated the process, until data had been collected for the lowest line. To examine pulse width, we held frequency at 30 Hz, pulse duration at 300 us, and stimulation duration at 3 s. We set amplitude to and kept at whatever the amplitude was for the lowest weight in the amplitude trials. Then we repeated the general amplitude procedure, only adjusting pulse width rather than amplitude.

reciprocal relationship, so we fitted the data with a reciprocal function to form a best fit curve (Equation 1)..

Equation 1 can calculate probable minimum amplitudes and pulse widths that will trigger movement for this individual at a frequency of 30 Hz and stimulation time of 1 s.

B. *The strength-duration curve's rheobase is the x-asymptote of the reciprocal function.*

The physiological definition of rheobase is the minimum current applied over an infinite duration required to produce "activation" We defined activation as the visible movement of at least two fingers for the entire stimulation. The strength-duration curve's best fit function's limit as pulse duration approaches infinity is its asymptote and last coefficient 1.436 mA, making 1.436 mA the rheobase. The definition of chronaxie is the duration required to evoke activation with an amplitude/applied current of twice the rheobase. We set amplitude (mA) to twice the value of the rheobase (2.872 mA) and used the best fit curve function to solve for pulse duration, the chronaxie, which is 536.490 µs (Fig. 2).

C. *Grip strength increases with both increasing amplitude and increasing pulse width*

We obtained the minimum amplitudes required to hold five different weights at constant frequency, pulse width, and stimulation duration and the minimum pulse widths required to hold five different weights at constant frequency, amplitude, and stimulation duration, for each participant. We then assessed the ratios of relative change in parameters value to change in grip strength (weight) by plotting pulse width against weight and amplitude against weight for each participant and calculating the slopes for the lines of best fit. We found no significant difference (paired t-test, $n = 4$, $p = 0.8866$) between the slopes for amplitude ($5.7428 \times 10\text{-}4 \pm 1.5819 \times 10\text{-}4$) and pulse width ($5.8684 \times 10\text{-}4 \pm 9.6452 \times 10\text{-}5$), which were both positive (Fig. 4). The positive slopes indicate that grip strength increases with both increasing amplitude and increasing pulse width of FES.

D. *FES may be noxious at low frequencies*

The most notable subjective feedback we received during this study was that stimulating at frequencies below the threshold of non-discrimination of individual pulses may be too painful for some individuals for functional electrical stimulation purposes. Additionally, this threshold varied depending on the participant.

IV. Discussion

This study aims to investigate the combinations of FES parameters that generate functional grasps. We found that a reciprocal function models the strength-duration curve for FES on one individual, and the x-asymptote is the rheobase. We found that increasing amplitude and pulse width of FES can both increase grip strength. We additionally noted that for FES to be tolerable, the stimulation frequency should be high enough that the individual pulses are indiscernible.

Prior work has shown that spinal cord lesions disrupt electrical signals from the brain from traveling to peripheral nerves and muscles, resulting in paralysis[3]. Prior work has also shown that FES can bypass the lesion by providing an electrical current to the peripheral nerve through either surface or implanted electrodes [4]. In contrast, here we show that FES can induce functional gripping, and increasing the amplitude and pulse width of FES can increase grip strength.

The work presented here builds off prior works investigating strength-duration curves of activation of wrist and finger muscles with FES in hemiparetic patients by Schuhfried et al. [7]. Also novel from this work was a display and analysis of the estimated mathematical function for the strength-duration relationship in one healthy individual.

Future work should replicate this study in more healthy participants and SCI patients. Researchers should also look into how discrimination of individual pulses affects stimulation function and tolerability, as well as optimal frequencies for functional electrical stimulation. Another area to explore is if and how the FES strength-duration curve coefficients and

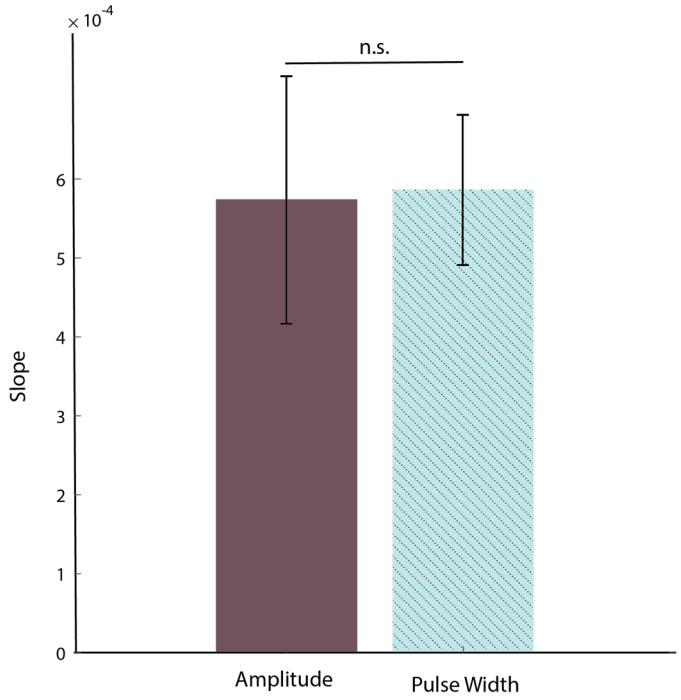

Figure 4. We found no significant difference between the parameter-weight slopes of amplitude and pulse width. We represent the normalized-to-maximum amplitude-weight slope with a solid dark purple bar and the normalized-to-maximum pulse width-weight slope with a striped light blue bar. There two groups had similar results, with amplitude-weight slopes being on average 5.7428 x 10-4 ± 1.5819 x 10-4 and pulse width-weight slopes being on average 5.8684 x 10-4 ± 9.6452 x 10-5. We determined that there was no statistical significance between amplitude-weight and pulse width-weight slopes by a paired t-test (n = 4) in which p = 0.8866.

asymptotes for individuals are related to neuromuscular function.

These results provide the field of functional electrical stimulation with information on how varying parameters affect the strength of the intended movement. Furthermore, the results contribute to the body of evidence supporting FES in clinical rehabilitation for SCI and other conditions such as multiple sclerosis and transverse myelitis.

Author Contributions

All authors contributed to the design of all parts of the experiment. F.M. conducted the data collection process, and D.L. created all figures, ran the statistics, and calculated chronaxie and rheobase. All authors wrote their own individual manuscripts.

References

[1] S. L. James *et al.*, "Global, regional, and national burden of traumatic brain injury and spinal cord injury, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016," *The Lancet Neurology*, vol. 18, no. 1, pp. 56–87, Jan. 2019, doi: 10.1016/S1474-4422(18)30415-0.

[2] "Media Center," *ACS*. https://www.facs.org/media-center/ (accessed Nov. 21, 2022).

[3] M. Jw and S. C, "Spinal-cord injury," *Lancet (London, England)*, vol. 359, no. 9304, Feb. 2002, doi: 10.1016/S0140-6736(02)07603-1

[4] I. Morita, M. W. Keith, and T. Kanno, "Reconstruction of upper limb motor function using functional electrical stimulation (FES)," in *Operative Neuromodulation: Volume 1: Functional Neuroprosthetic Surgery. An Introduction*, D. E. Sakas, B. A. Simpson, and E. S. Krames, Eds. Vienna: Springer, 2007, pp. 403–407. doi: 10.1007/978-3-211-33079-1_53.

[5] J. J. Daly and J. R. Wolpaw, "Brain-computer interfaces in neurological rehabilitation," *Lancet Neurol*, vol. 7, no. 11, pp. 1032–1043, Nov. 2008, doi: 10.1016/S1474-4422(08)70223-0.

[6] H. Zhou *et al.*, "Stimulating the Comfort of Textile Electrodes in Wearable Neuromuscular Electrical Stimulation," *Sensors (Basel)*, vol. 15, no. 7, pp. 17241–17257, Jul. 2015, doi: 10.3390/s150717241.

[7] O. Schuhfried, C. Kollmann, and T. Paternostro-Sluga, "Excitability of chronic hemiparetic muscles: determination of chronaxie values and strength-duration curves and its implication in functional electrical stimulation," *IEEE Trans Neural Syst Rehabil Eng*, vol. 13, no. 1, pp. 105–109, Mar. 2005, doi: 10.1109/TNSRE.2005.843439.