# Combining Functional Electrical Stimulation and a Powered Exoskeleton to Control Elbow Flexion

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***Abstract*— Functional electrical stimulation (FES) and robotic exoskeletons have each demonstrated promise in restoring functional reaching abilities to individuals with upper-limb paralysis. However, FES is difficult to control due to the constantly changing arm dynamics, and robotic exoskeletons have large power requirements. To achieve the benefits of each method, we have combined FES and a robotic exoskeleton as a hybrid system for controlling the elbow through a flexion and extension trajectory for seven healthy subjects. Compared to an FES-only strategy, our hybrid system resulted in a significant improvement in accuracy (94% reduction in rms tracking error). Compared to a robotic-exoskeleton-only strategy, our hybrid system reduced the required exoskeleton torque commanded by an average of 74%. These results are encouraging for the development of a hybrid FES and robotic exoskeleton system for full-arm control.**

## I. INTRODUCTION

Functional hand and arm control has been identified as the most important restoration goal for individuals with upper limb paralysis [1]. Functional electrical stimulation (FES) and robotic exoskeletons are two technologies which have demonstrated promise in restoring reaching capability to individuals with paralyzed upper limbs due to conditions such as spinal cord injury and stroke.

FES drives motion in paralyzed limbs by sending electrical pulses to the nerves and muscles to elicit muscle activation. FES has achieved reaching motions [2] [3], but the complicated and ever-changing arm dynamics due to fatigue and muscle atrophy make accurate control of a paralyzed arm difficult with FES.

Robotic exoskeletons are often used in rehabilitation settings, having the ability to manipulate the individual's limbs to precisely follow a predefined motion pattern. However, exoskeletons are often large and have high power requirements due to the large motors needed to compensate for the weight of the limbs they are moving. This means that the exoskeletons are relatively immobile and tend to keep the the system in a stationary environment.

The goal of this project is to test the hypothesis that a combination of surface FES and exoskeletons will have a higher accuracy than FES alone and require less power than an exoskeleton alone.

## II. MATERIALS AND METHODS

For this experiment, the MAHI Exo-II [4] was used for the upper-limb exoskeleton, and a transcutaneous electrical stimulation system was used to deliver FES to the biceps. For the FES system, the amount of stimulation was determined by the pulse-width, and we refer to this pulse-width as the stimulation command. The task analyzed in this experiment was a trajectory following procedure in which the user's elbow was tasked in following a trajectory which moves the participant's elbow from full extension to a 50 degree angle, pauses for one second, and moves the elbow back to full extension. Participants were asked to keep their arm limp during testing. The complete setup is shown in Fig. 1.

When used by itself, the FES control law consisted of a feedforward control with a small positional feedback component (referred to as FES control). The feedforward component was determined empirically for each subject by mapping the required stimulation command of the FES to reach a specific angle to the time at which the desired trajectory matched the achieved angle. This was completed for several angles in the trajectory and the command was linearly interpolated for the other angles in the trajectory. The exoskeleton utilized a set-point proportional-derivative controller to track the trajectory (referred to as Exo control). When the two systems were used together, each of the control laws was simply applied at the same time without

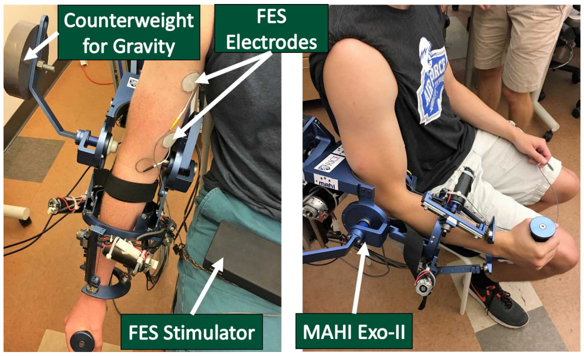

Fig. 1. A subject setup in the MAHI Exo-II with the transcutaneous FES electrodes across the biceps. The subject is shown at the start (0°, left image) and midpoint (50°, right image) of the trajectory.

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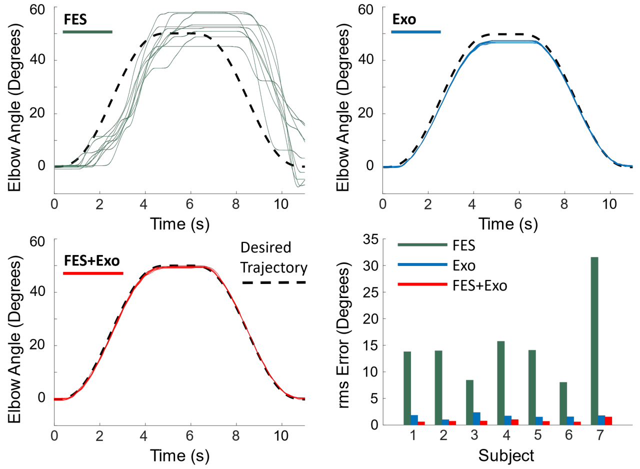

Fig. 2. Representative trials from Subject 1 for the FES control (top left), Exo control (top right), and FES+Exo control (bottom left). The average rms tracking error for each subject and each control method is shown (bottom right). There is a significant improvement in the accuracy of the FES+Exo controller compared to the other controllers.

modification (referred to as FES+Exo control). The subject's arm always remained in the exoskeleton, and passive gravity compensation was provided by a counter weight (seen in Fig. 1) which offset the weight of the exoskeleton.

Seven healthy subjects completed 27 repetitions of the required trajectory. For each subject, nine trials were driven by the exoskeleton alone, nine trials were driven by the FES alone, and nine trials were driven with the combined system. The order of the trials was randomized and unknown to the subjects.

The procedures were approved by the internal review boards at Rice University (IRB #IRB-FY2017-461) and Cleveland State University (IRB #30213-SCH-HS).

## III. RESULTS

Fig. 2 shows the trials from Subject 1 for each of the control strategies (which are representative of the experiments as a whole) as well as the average rms error for each subject. As seen, there was a significant improvement in accuracy for the FES+Exo controller over the FES controller. On average, there was a significant 94% reduction in tracking error with the FES+Exo control compared to the FES control.

Fig. 3 shows the average exoskeleton control effort (sum of the squared torque) for each subject as well as the torque commanded for the trials from Subject 1 which are representative of the results from the other subjects. On average, the FES+Exo strategy resulted in a 74% reduction in exoskeleton control effort than the Exo controller.

## IV. DISCUSSION

The results demonstrate the advantages for using FES and a robotic exoskeleton to cooperatively control elbow flexion. The exoskeleton was able to overcome the inaccuracies of the FES control, and the use of FES resulted in a more power efficient system by taking advantage of the biological actuators (muscles) which were present but not being used by the exoskeleton control.

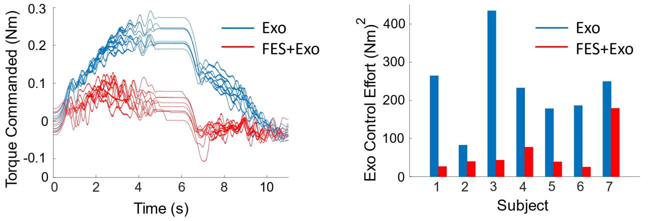

Fig. 3. Torque commanded during representative trials from Subject 1 (left) and the average exoskeleton control effort (sum of squared torques) for each subject (right) which shows a significant reduction in control effort for the FES+Exo controller.

The improvements in tracking accuracy and required exoskeleton effort were achieved using very simple control strategies. These control strategies did not interact, and thus at times may have been working against each other (This can be seen by the negative torques during the FES+Exo trials for Subject 1 in Fig. 3.). Using a more complex controller which guaranteed the two controllers were working cooperatively may further improve the performance. Another area of improvement would be to include FES electrodes to activate the triceps for better controlling elbow extension as gravity alone was not always able to drive the extension over the friction in the exoskeleton. Also, improved modeling procedures would result in a more accurate FES controller which could even further improve the performance.

## V. CONCLUSION

Using an exoskeleton in combination with FES reduces the amount of torque required by the exoskeleton while improving the accuracy of the FES. This provides the groundwork for combining these two methods to use each of the strengths while minimizing the accompanying weaknesses. Further work will be done to explore using lower power, lighter, and more portable exoskeletons in order to understand the full benefits that may come through the combination.

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