# Natural Control of Triceps Stimulation Using FES

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## Abstract

Individuals with C5/C6 spinal cord injury have paralyzed elbow extensors, yet retain weak to strong voluntary control of elbow flexion and shoulder function. Previous studies have shown that functional electrical stimulation (FES) of the triceps provides sufficient elbow extension strength and control to greatly improve function. With triceps stimulation applied at a constant level, elbow angle is controlled naturally by voluntary flexion opposing the stimulated extension. An alternative is a reciprocal control scheme employing biceps EMG to modulate triceps stimulation. With reciprocal control, increasing biceps EMG proportionally reduces triceps stimulation. A PC based lab system was designed to test the feasibility of reciprocal control. Reciprocal control increased the range of elbow moments, was stable during maintained elbow angle or isometric moment, and used less stimulation. Reciprocal control of triceps stimulation using biceps EMG is an effective method for restoring elbow extension to C5/C6 spinal cord injury patients.

## Introduction/Background

Functional electrical stimulation (FES) has restored motor function to individuals with spinal cord injuries [1-3]. Individuals with C5/C6 tetraplegia are left without voluntary control of upper and lower extremity muscles. Voluntary movements include elbow flexion, some shoulder movement, and in C6 subjects wrist extension. Elbow extensor muscles, important for reaching during activities of daily living, are paralyzed. Although mechanical orthoses can compensate for the elbow extensor muscles [4,5], FES provides a cosmetically acceptable solution using the patient's own natural muscles.

Two FES systems used mechanical sensors to modulate triceps stimulation [6,7]. In one without sensors, an implanted triceps electrode was stimulated at a constant level [2]. Using voluntary antagonist control, the user controlled elbow angle by voluntary elbow flexion opposing the stimulation. Good functional restoration was achieved. However, constant stimulation decreases the maximum flexion moment about the elbow since a user must flex against a stimulated extension moment. An alternative control method varied stimulation [7]. However, it required mechanical sensors and did not provide for maximal stimulation in many different arm positions.

Electromyograms (EMG) from voluntary muscles have proportionally controlled stimulation to paralyzed muscles [8,9]. The biceps is under voluntary control in C5/C6 spinal cord injury. Reciprocal control proportionally reduces stimulation to paralyzed muscles in response to EMG from a voluntary muscle. Biceps and triceps are antagonists, providing natural control with little training. EMG occurs naturally, detectable with implantable devices for a cosmetic solution [10].

Reciprocal control of elbow extension has three main goals: increase the total range of elbow moments compared to no or constant stimulation, reduce the total stimulation delivered compared to constant stimulation, and be at least as stable as constant stimulation.

## Methods

Surface EMG from the subject's biceps was recorded. Blanking EMG amplifiers eliminated the stimulation artifact [11], rectified the signal, and applied a selectable gain (Figure 1). The FES external control unit was interfaced to a PC based lab system. The external control unit sent stimulation commands to the patient's implanted system via an RF link.

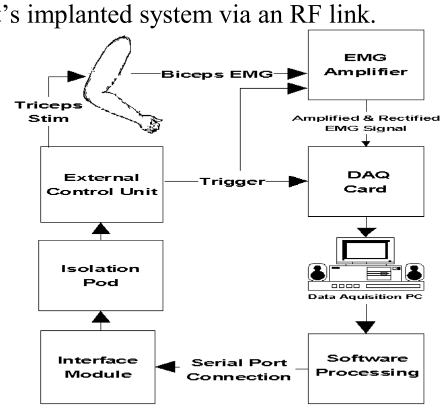


**Figure 1.** Hardware block diagram.

A trigger signal, provided by the external control unit before the stimulating pulse, initiated blanking and the start of EMG collection (Figure 2). Stimulation was delivered to the triceps at 12 Hz, therefore, biceps EMG was sampled at 2500 Hz for 80 ms. Software removed the blanked portion, calculated the root mean square value of the remaining segment, and normalized it.

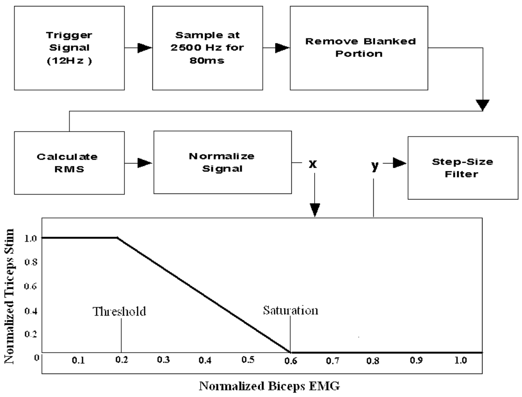


**Figure 2.** Software block diagram.

Stimulation was delivered to the triceps at 20mA, 12Hz, with a variable pulse width based on the control signal. The output of the reciprocal controller (normalized triceps stimulus pulse width) was one for signals below 0.20. For signals between 0.20 and 0.60 the output decreased linearly from one to zero. Signals above 0.60 produced zero output. An adaptive step-size filter [9] provided fast transitions between command levels and maintained stable command at intermediate levels while filtering out command errors and noise.

Three male subjects had previously been implanted with hand grasp systems that included an implanted triceps electrode. One subject had a system in each arm. Their ages were 37, 50, and 23 for subjects 1, (2,3), and 4. An Internal Review Board approved the research and all subjects gave informed consent.

We compared the range of maximal flexion and extension elbow moments with three control schemes. Subject's arms were fixed into an elbow moment transducer (EMT) [12]. The subject's arm was positioned in the horizontal plane at shoulder height with the elbow fixed at 90 degrees. One trial had subjects relax for seven seconds to create maximum stimulated extension and then maximally flex for seven seconds to create maximum flexion. Twelve trials were completed: four without stimulation, four with constant maximal, and four reciprocal control.

We assessed the ability of the subjects to control specific isometric moments using the EMT. The subject's goal was to track seven discrete isometric moments for seven seconds each using visual feedback via a computer monitor: 100, 66, and 33% of maximum flexion with constant stimulation, and 0, 33, 66, and 100% of maximum stimulated extension. We also measured the subject's performance maintaining specific elbow joint angles. An electrogoniometer measured elbow angle. The goal of the subject was to track five discrete elbow angles for seven seconds each using visual feedback via a computer monitor: 0 (extended), 30, 60, 90, and 115 degrees.

One set of trials for both moment and angle tracking consisted of two trials using constant stimulation and two trials using reciprocal control. The first three seconds of each level was allowed to reach the target. RMS error was calculated over the last four seconds to determine how well subjects maintained stability.

An ANOVA was completed on the dependent variables maximum flexion moment, maximum extension moment, moment tracking error, and position tracking error using S-PLUS 2000. The independent variable was control method. P-values were obtained for the control method to determine significance.

## Results

Subjects achieved the largest possible range of elbow moments using reciprocal control (Figure 3). Triceps stimulation was reduced significantly during maximum flexion and typically maximized during extension. The maximum flexion moment depended significantly on the control method ($p<0.000001$). With reciprocal control, the flexion moment was the same as with no stimulation, whereas with constant stimulation it was significantly lower.

There was no statistically significant difference in elbow extension moments using reciprocal control versus constant stimulation ($p=0.04946$). Since the subjects tested had no voluntary elbow extension there was the expected increase in the extension moment using reciprocal control compared to no stimulation.

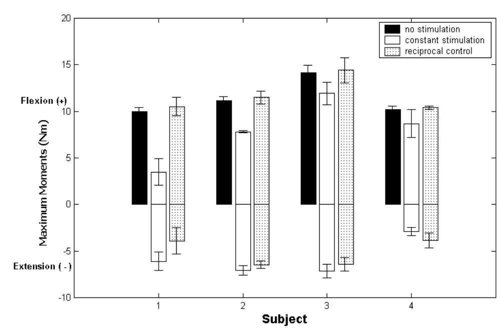


**Figure 3.** Results of elbow moment range testing.

Reciprocal control was effective at maintaining stable elbow moments and angles (Figure 4). Errors were small and there was no significant difference between reciprocal control and constant stimulation. Reciprocal control reduced the amount of stimulation used in both moment tracking and angle tracking. Stimulation decreased with increasing flexion moment or angle as expected with reciprocal control.

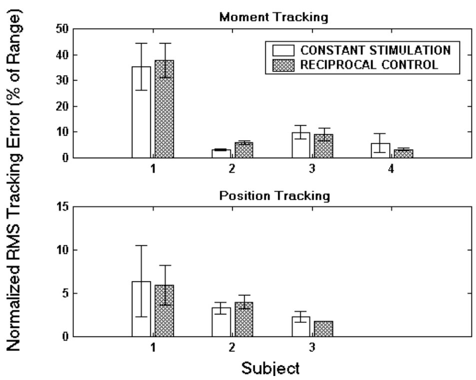


**Figure 4.** Normalized RMS tracking errors.

## Discussion/Conclusions

Reciprocal control is an improvement over the constant stimulation voluntary antagonist control scheme used in current clinical elbow control neuroprostheses. Reciprocal control makes possible the maximal range of elbow moments with stable and accurate control of angle or moment. Reciprocal control decreases the total amount of stimulation and hence should reduce biceps and the triceps fatigue.

Subjects achieved these experimental results with little to no training. In order to modulate stimulation and make it easier to flex the elbow, subjects flexed the elbow. This method could be used for other degrees of freedom where voluntary control of one direction of movement can be augmented by stimulation of paralyzed antagonists [13].

Reciprocal control has shown promising results, however, many times a subject may wish to relax their biceps without triceps stimulation. Subjects at the C5/C6 level have shoulder muscles under voluntary control. It has already been shown that an artificial neural network (ANN) using these muscles as inputs can detect arm position [14]. Monitoring EMG from several voluntary shoulder muscles as well as the biceps should yield intent information as to when to turn triceps stimulation on. Increasing the control degrees of freedom from one (biceps) to many (including shoulder muscles) should increase flexibility of control.

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**Acknowledgments:** This work was supported by the Rehabilitation Research and Development Program of the Department of Veterans Affairs and NIH Training Grant T32-HD07500. We gratefully acknowledge Robert F. Kirsch Ph.D., Dominique Durand Ph.D., William D. Memberg M.S., Anne Bryden O.T., Ron Hart M.S., and Scott Snyder M.S.