Command Generation for FES Enhanced Grasping in Persons with Cervical Spinal Cord Injury Utilizing Surface EMG

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Abstract - This research resulted in a practical method to alter the intensity of the grasp using the wrist extensor's surface electromyogram (sEMG) to control the intensity of FES. The process extracts threshold information from wrist extensor muscles sEMG using receiver operating characteristic (ROC) techniques to detect two distinct levels of volitional wrist extension. These levels could be used in any combination to implement specific commands to, "increase" or "decrease" stimulation intensity to finger flexor muscles for enhanced grasping. The process discriminated between true commands and potentially false signals arising either from activities of daily living or stimulation artifacts. Twenty subjects, ten tetraplegic and ten controls were studied. The subjects were instructed to follow predetermined visual cues from a computer monitor. EMG was recorded and processed from wrist extensors on the same limb, with and without electrical stimulation applied to the finger flexor muscles. The overall percent of correct recognitions for SCI subjects was 84%.

Keywords: FES, EMG, Tetraplegia

Introduction

Paralysis of the upper extremities is a most debilitating injury. Due to this injury, most patients are totally dependent upon other people or various means for the performance of fine and gross motor tasks. Persons with cervical injuries in the range from C_5 to C_7 may have the ability to move their arms about, but are unable to develop enough force to grasp and hold objects. This deficit limits them in the simple activities of daily living (ADL) necessary for survival. Each subject exhibits different losses of neuromotor function, and recovers at an individual, specific rate. In the United States, approximately fifty percent of all spinal cord injured persons have injuries at the cervical level [1].

Many of these subjects develop a method of finger flexion for grasping light objects, referred to as a tenodesis grasp. As defined by Somers [2], tenodesis grasp is partially caused by the tightening (shrinking) of the elongated finger flexor muscles, so that when the wrist is extended, the fingers may flex with a minimal grasping force. Persons with C_6 or higher tetraplegia may naturally develop a tenodesis grasp to manipulate objects. The tenodesis grasp is usually strong enough only to move light objects. These persons need to increase their grasping force to hold objects securely while moving them.

A lot of work has been done on functional electrical stimulation (FES) in spinal cord injured (SCI) patients [3]. Hand grasp neuroprostheses are FES systems designed to provide prehension and release for tetraplegic patients [4]. Neuroprostheses increase independence by restoring the ability to grasp and manipulate objects in the absence of external adaptive modifications such as orthotics. Functional electrical stimulation has been used extensively to provide grasp and release for individuals with spinal cord injury at the C_4-C_6 level [5,6,7,8,9].

For FES, electrodes are attached to paralyzed muscle groups, due to spinal cord injury, for delivery of a graded electrical stimulus for activation and control [10]. The resultant movement is controlled by residual voluntary movements of the tetraplegic individual. Contralateral shoulder motion has been a common choice of a command interface for grasping neural prostheses [11,12,13].

This study was motivated by the recognised need to enhance the grasping of tetraplegics by controlled stimulation in real time. Our main objective was to develop a practical method to detect two distinct levels of volitional wrist extensor electromyographic (EMG) activity in the presence of stimulation and ADL. Fast and slow wrist extensions were targeted for detection. Combinations of these levels could be used to form commands. The targeted SCI population had volitional control of the wrist extensor muscles, with or without minimal voluntary control of muscles for finger flexion. Hence, many tetraplegics may have the ability to execute the FES assisted tenodesis grasp. The commands, derived from the volitional movements, are to adjust the stimulation intensity for tenodesis grasping. Two commands, (1) decrease stimulation and (2) increase stimulation, are expected to be necessary. The process may be utilised for the rehabilitation of subjects with intact wrist extensors, who lack volitional control of their finger flexors.

Using ipsolateral wrist extensor muscles to initiate the commands complicates the detection or recognition process due to the close proximity to the site of stimulation of the finger flexor muscles of the same forearm. Another problem with the site of detection located so near the site of stimulation, the desired site of movement, is that when the limb is moved to an object, or moves it, these activities must be discriminated from commands.

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Method

A. *Subjects*

Twenty male adult subjects were studied. Ten controls were healthy and able-bodied and the other ten were SCI in the C_3-C_7 cervical vertebral zone. The SCI subjects retained control of their arms; their trunks were stable and could perform wrist extension against gravity, but were lacking finger flexor control.

B. Experimental set up

The surface electromyograms (sEMG) were recorded with stainless steel electrodes from the wrist extensor muscles, approximately 4 cm distal from the elbow joint while the subjects were seated. The sEMG was amplified (gain: 375), band-pass filtered (5-1200 Hz, 24 dB/oct) and digitized (12-bits, 400 μs sampling time) in 40 ms epochs of 100 samples. A 66MHz 486DX2 personal computer implemented the process including digitization using a National Instruments AT-MIO16 data acquisition board, with connections made to a National Instruments BNC 2080 connection board. Electrical stimulation was applied to the finger flexor muscles at a constant frequency of 25 Hz, inter-pulse interval of 40 ms and pulse width of 150 μs. The acquisition was triggered by the onset of the first stimulation pulse. Visual cues to prompt the subject to attempt specific tasks were displayed on the computer monitor. A switch was monitored to report whether the stimulation was on or off.

A test board, similar to that used at Case Western Reserve (CWR), [14] was constructed to assess the ADL. Three of their applicable ADL were incorporated in our evaluation of this process. The activities all included grasping, lifting, moving, placing and releasing an object from a designated initial site to a final destination. The three objects were: (1) a 5 cm cubic toy building block, (2) VHS videocassette and (3) a 6 oz juice can.

C. Protocol

The recording and stimulation electrodes were placed on the subject, as stated, seated at a table in front of a computer monitor. The thresholds for detecting the two distinct levels were determined while the subjects were prompted to attempt to complete the tasks by a sequence of visual cues on the computer monitor. The calibration consisted of two parts: Stimulation On and Off. The sequence of tasks with Stimulation On was: “Relax” - “Fast” - “Relax” - “Fast” - “Relax”, repeated four times for each of three tests. The Stimulation Off sequence of events was: “Relax” - “Fast” - “Relax” - “Fast” - “Slow”, also repeated four times for each of three tests.

The test board was then positioned in front of the subject to record EMGs during ADL. The subject was instructed to "Relax", attempt two consecutive "Fast Wrist Extensions" (FWE) followed by a "Slow Wrist Extension" (SWE). Then the subject moved his hand to the object in the target area. The stimulation was turned on by the test administrator, the subject grasped the object, lifted and moved it to the final destination. While at the final destination, the subject performed two FWE, to turn the stimulation off, which was done by the test administrator. The object was then left in the final destination and the subject moved his hand back to the initial resting area while the test administrator reset the object to the initial position. This was completed as many times as possible in one minute.

D. Off-Line Data Analysis

A one-second, 2500 point, running average window that moves 100 points at a time was assembled, with the running average subtracted from the previously recorded EMG, resulting in volitional EMG Fig. 1. The volitional EMG was then rectified, summed (integrated) over the 100 points, baseline corrected and normalized. The difference between consecutive 100-point sums was also taken. The integration was reset to zero at the start of each 100 points. The running average, volitional EMG, integrated rectified EMG (IREMG) and difference of the sums were saved for the recognition processing along with the status of the stimulation switch. When a stimulation switch change was recognized, either signifying that the stimulation was recently turned on or off, the running average was reset and re-assembled.

To set the thresholds for detection, receiver operating characteristic (ROC) analysis was performed on the calibration data. ROC is a graph of the functional relation between the proportion of times that Alternative A (*hit rate, true-positive*) is chosen when it occurs and the proportion of times that Alternative A is chosen when Alternative B occurs (*false-alarm rate, false-positive)* as the decision criterion varies [15]. The two quantities in question vary together from low to high as the criterion for choosing Alternative A is relaxed. The ROC is not biased by the decision criterion [16]. The ROC curve, Fig. 2, presents all intermediate performance information in an objective form and depicts the inevitable trade-off in every decision criterion. The results are completely independent of any assumption one makes about the statistical distributions of the events produced by signal plus noise, or by noise alone. The measure of accuracy of the system chosen is the area beneath the ROC curve. This area ranges from 0.5 to 1.0, with 0.5 corresponding to pure chance and 1.0 to perfect classification.

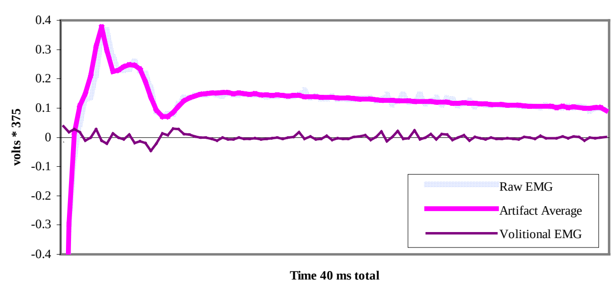

Fig. 1, Raw EMG processing. The running average is subtracted from the raw EMG resulting in volitional EMG. This is 100 samples, 40ms taken while stimulation is on.

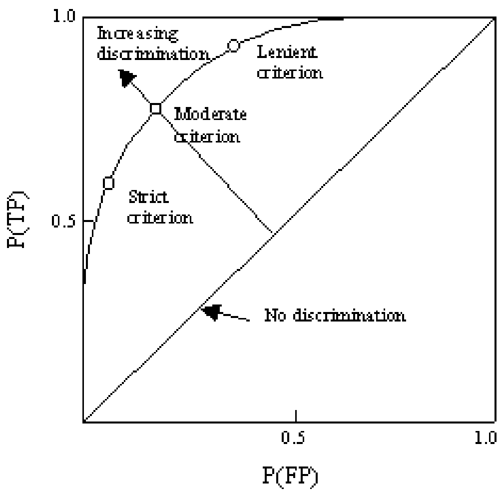

Fig. 2 Sample ROC curve. P = probability, TP= true positive, FP= false positive.

In this analysis, a Slow during a Relax event was deemed a "False Negative." A Fast during a Slow event was also a "False Negative" and when the stimulation was on, a Fast during a Relax event was termed "False Negative." Proportions to associated "False Negatives" were found and charted for the three types of "True Positives." As a simple algorithm for finding a threshold, a diagonal was drawn from the upper left to lower right corners of these ROC curves. The closest point on the conservative side of this diagonal was determined and the associated normalized level became the value used for the threshold of recognition for that variable, i.e., Slow or Fast with stimulation or Fast without stimulation.

The recognition program used these three personal levels, or thresholds, to search the subject's processed ADL data. If the stimulation was off, the search was for FWE and SWE. If the stimulation was on it searched for a FWE. Software smoothing filters were used to interpret the results. For the FWE, a moving window of five consecutive points was compared with the threshold. If two out of the five consecutive points were above the FWE threshold, a FWE was recognized. SWE smoothing used a ten consecutive point moving window. A SWE was recognized if eight out of ten points were in the SWE threshold range. The outcomes were saved and evaluated to determine the efficiency of the process.

Results

The subjects were able to follow the visual cues from the computer. They were all able to perform the ADL, including the SCI subjects in the presence of the FES. Surface EMG signals were obtained, the running average was subtracted, resulting in volitional EMG. The volitional EMG was then rectified, integrated, baseline corrected and normalized. Recognition thresholds were determined using the ROC analysis and signal recognition was accomplished on all the data.

A representative sample of the outcome is shown in Fig. 3. Two sequences of EMG from FWE, FWE, and SWE without stimulation, and FWE, FWE with stimulation are shown with the resultant processing and recognition. The average percentage of correct recognitions of the three signals, FWE and SWE with the stimulation off as well as FWE without stimulation for each subject is displayed in Fig. 4. Table 1 summarizes the combined percentage of correct recognitions for both study groups.

Discussion

At present, the most popular command channel is the contralateral shoulder. Since earlier research had suggested that EMG did not have enough information content to be used accurately for a command channel, it was abandoned. The objective of this research was to reassess the use of EMG as a command channel. Our approach was to use the duration while specific thresholds of IREMG were above the detected level, rather than quantifying the intensity of the IREMG for a proportional command. This type of command control interface (CCI) is more close to the tetraplegic population's action of grasping directly, than contralateral shoulder control [6,10] since many already utilize WE for tenodesis grasping.

The CWR system requires a proportional control input to select different types of grasps, which is accomplished by moving the contralateral shoulder through a predetermined range of motion. The CWR system needs control of multiple independent proportional commands which is more complicated, and as shown by Mark Johnson,[12] it is not always possible in C_5 level tetraplegics. This CCI described here can also produce a proportional command; one way to accomplish this is by the subject performing a SWE for a period proportional to the desired value.

Using the forearm as the CCI allows for independent activation: each forearm may control a device for the corresponding hand. For cosmetic appearance, the forearm control could be covered by a shirtsleeve. Since this is an ipsilateral control, care must be exercised to consider possible false command generation caused by such activity of the limb that is not intended to generate commands, such as ADL or muscular spasms. Another major concern is contamination of the signal from electrical stimulation. The EMG is in the range of millivolts and the stimuli to the skin are tens of volts.

Interference was noted from the stimulation system being attached to the subject while EMG was being recorded,

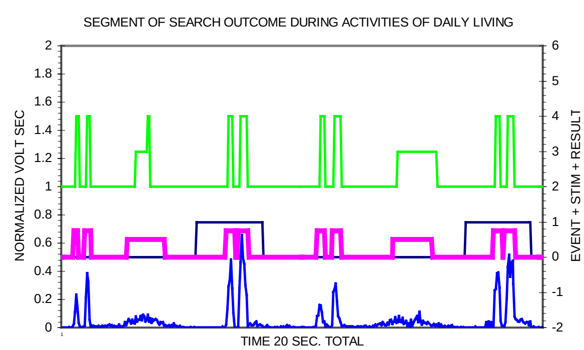

Fig. 3, The upper trace is the outcome of the recognition program. The middle trace is a composite of the "Template" for this test and the stimulation indicator. The bottom trace is the normalized baseline corrected IREMG. Right axis legend: (Template: 0 = Relax, 0.5 = Slow, 0.75 = Fast), (Stimulation: 0 = Off, 1.0 = On), (Result: 2.0 = Relax, 3.0 = Slow, 4.0 = Fast).

even without stimulation. The interference was predominately at 60 Hz and 500 Hz. The 500 Hz interference was intermittent and it originated from some external source. The noise was more evident when the subject's skin was dry, causing higher electrode to skin impedance. Had the skin been prepared, this might have been avoided. The skin was not prepared to make the test more similar to a practical system where, for an SCI subject, orthotics should be designed to be simple to don. By not preparing the skin, the robustness of signal processing techniques was demonstrated in the presence of the noise.

Conclusion

Using the thresholds obtained by the ROC method for the two Fast and the Slow wrist extensions, the overall percent of correct recognitions for SCI subjects was 84%. It should be noted that most of these subjects had never used this device before their test session and were not given time to practice. They began to use it immediately, and all the data, as they were learning to follow the video cues and instructions, complete with the errors, were included in the analysis. The errors mostly occurred during the calibration tests, with the calibration data used for determining the recognition thresholds. Had the subjects been given more time to practice with the system, the recognition rate would very probably be higher. The eighth SCI subject was having uncontrollable muscle spasms during his test session. The "MIN" column of Table 1 reflects his results. This series of studies has clearly demonstrated the feasibility of using ipsilateral control of FES for stronger grasp for tetraplegics, using slow and fast wrist extensions even in the presence of stimulation.

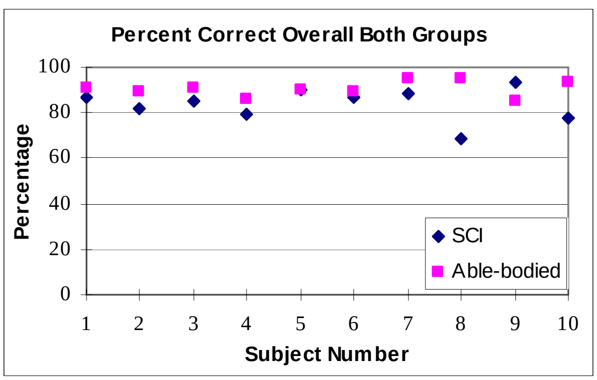

Fig. 4. Percentage of correct recognitions overall for each subject from both groups, ◆ = SCI subjects, ■ = Able-bodied subjects.

Table 1. Final results, (M = mean, SD = standard deviation).

	SCI			
	M	SD	MAX	MIN
% Fast Stim Off	82.18	8.68	94.4	64.43
% Fast Stim On	87.07	11.77	99.14	63.33
% Slow	83.82	3.79	88.57	78.69
% Overall	83.96	7.02	92.98	68.97

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