Hands-Free Manipulation of the Computer Cursor Based on the Electromyogram

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ABSTRACT

This paper describes the development and evaluation of a system that processes electromyogram (EMG) signals voluntarily produced by a user and collected through electrodes placed in the user's forehead and temples, for the purpose of hands-free manipulation of the computer cursor. The goal of the system is to enable the user to step the cursor in two directions: horizontally (left and right) and vertically (up and down). In addition, the system allows the user to execute a "click" operation. The immediate area of application and main motivation for the development of this system is in the area of assistive technologies, to facilitate the access of individuals with motor disabilities to computers. However, the system can also be seen as a hands-free remote manipulator control in two axes.

Keywords

Electromyogram, Hands-free operation, Cursor control.

1. INTRODUCTION

It has been documented that there is a large segment of the population that is unable to interact with computers using the standard interfaces provided by manufacturers. For example, it is estimated that there are 250,000 – 400,000 individuals in the United States living with spinal cord injury or spinal dysfunction [9]. Many of these individuals lack the motor capabilities to use input devices, such as mice or trackballs, efficiently. As a consequence, they are very limited in the interaction that they can have with computers based on Graphic User Interfaces (GUIs). Computer interaction based on GUIs requires the user to manipulate the screen cursor efficiently to achieve the following two actions:

- Pointing: Positioning the cursor at the desired location of the screen, over the appropriate area or icon.
- Clicking: Executing the Mouse Down/Up function that is interpreted by the computer's operating system as an indicator to complete the selection of the item associated with the icon at the location of the screen cursor.

In turn, the positions that are dynamically assigned to the screen cursor are specified in terms of horizontal and vertical screen coordinates, and, therefore, pointing requires the user to effect a voluntary action that will change the horizontal and/or vertical coordinates of the screen cursor.

Accordingly, we have pursued the development of a system that interprets electromyogram (EMG) signals produced by voluntary contractions of muscles in the head of the user and commands horizontal (left, right) or vertical (up, down) cursor steps in response. The system also defines a specific combination of facial muscle contractions to execute a "click" operation, which substitutes the "left click" operation in the standard mouse. In a wider context, it could be considered that the goal of the system is to achieve two-axes stepping control of an actuator (the screen cursor), providing an additional execution command ("click").

2. EMG FOR CURSOR CONTROL

Several approaches have been tried in the past to provide users with severe motor disabilities (e.g., paralyzed from the neck down) with alternative ways to control a GUI. Approaches that have attempted to use electrophysiological signals from the brain, i.e., the electroencephalogram (EEG) to communicate commands to the computer have been collectively labeled "Brain-Computer Interfaces" (BCIs). For example, Fabiani et al. [6], and Pfurtscheller et al. [10] have utilized the mu and beta rhythms from the EEG as a source of cursor control. However, present day BCI systems are primarily limited by speed of operation. Current BCIs have maximum information transfer rates of 10 – 25 bits/min [11].

In our own explorations [3, 4] of the prospective use of EEG signals for cursor control we have found that there are two key limitations for the implementation of this idea:

a) Signals picked-up by (non-invasive) scalp EEG electrodes are very small (in the microvolt range) and have temporal and spatial bandwidths that have been significantly limited by the volume conduction process mediating between their origin and their recording sites. This is particularly the case because of the presence of the skull as an interposing medium between the origin and the recording site of EEG signals.

b) While experimental subjects are expected to be able to initiate certain brain processes voluntarily (e.g., movement preparation), most subjects are not accustomed to perform these processes independently.

As such, there may be uncertainty as to whether or not the required EEG patterns are even being created, during BCI experiments.

In view of the above, our group decided to address a different electrophysiological signal, the electromyogram, for the purpose of cursor control. The amplitude of EMG signals is often in the millivolt range, and they are frequently generated by muscles located directly under the skin. In addition, the contraction of a target muscle confirms the generation of the associated EMG signals, and can help in training subjects to voluntarily elicit these signals.

Electromyography is the study of muscle function through monitoring of the electrical signals generated by the muscle [5]. When a surface electrode is placed on the skin above a superficial muscle while it is contracting, it will receive electrical signals emanating from several muscle fibers associated with different motor units. The spatio-temporal summation of these electrical signals results in what is called an EMG signal. Therefore, the EMG signal provides an effective means of monitoring muscle activity. There have been previous attempts to use EMG signals for cursor control. This approach has been used in [7, 12] and our group has reported the results obtained with a previous cursor control system driven by EMG from cranial muscles in [1] and [2]. The development outlined in this paper represents an improved version of those previous efforts. Monitoring the EMG of cranial muscles makes the approach suitable for individuals suffering from severe motor disabilities, who are paralyzed from the neck down.

3. EMG - CURSOR ACTION RELATION

Table 1 summarizes the relationships between facial movements and cursor actions that the system sought to implement. Left and right cursor steps are associated with the contraction of the corresponding Temporalis muscles, located in the left and right temples, respectively. Up and down cursor steps are associated with the raising and the lowering of the eyebrows, which involve contractions of the Frontalis and Procerus muscles, respectively. A simultaneous contraction of both Temporalis muscles (simultaneous left and right jaw clench) is translated by the system into a "click" command.

Table 1. Relations between cursor actions, facial movements and muscle contractions

Cursor Action	Facial Movement	Muscle Contraction
Left	Left Jaw Clench	Left Temporalis
Right	Right Jaw Clench	Right Temporalis
Up	Eyebrows Up	(Right) Frontalis
Down	Eyebrows Down	Procerus
Left-Click	Left & Right Jaw Clench	Left & Right Temporalis

4. METHODOLOGY

4.1 EMG Electrode Placement

Our most recent system for cursor control from cranial EMG signals uses four Ag/AgCl electrodes to collect EMG signals from the muscle groups being monitored. Two electrodes are placed on the subject's temples to detect primarily EMG signals from the right and left Temporalis muscles. Two electrodes are placed on the forehead of the subject. One of them is placed about an inch to the right of the center of the forehead, to monitor the activity of the right Frontalis muscle. The last electrode is placed in between the eyebrows, where the EMG signal due to the contraction of the Procerus muscle will be strongest. The voltages detected by these four electrodes are measured against a common reference electrode placed in the right Mastoid process of the subject. Figure 1 illustrates the placement of the EMG electrodes used in this system.

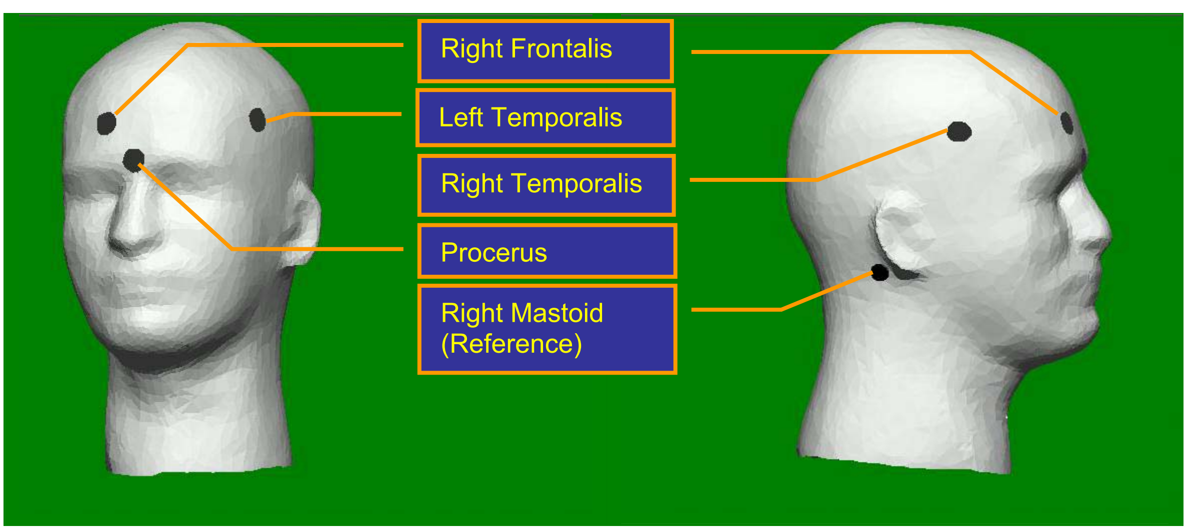

Figure 1. Electrode placement for the EMG cursor control system

4.2 Signal Conditioning

Each of the four referential EMG signals collected by the electrodes shown in Figure 1 was conditioned as follows: Four Grass® P5 Series AC preamplifiers were used to amplify the signals with analog anti-aliasing filters, and with a gain of 10,000 V/V. Each preamplifier also applied a 60Hz notch-filter to each of the four EMG channels. The resulting analog signals were delivered to analog to digital converters appropriate for data storage (for off-line verification), or for online processing, for real-time cursor control.

4.3 Digital Signal Processing of the EMG

The four amplified EMG signals were digitized for their manipulation in a digital signal processing system. During the off-line phase of algorithm evaluation the sampling rate used was 1000 samples per second, whereas a sampling rate of 1200 samples per second was used in the real-time prototype of the system, to gain an additional enhancement of the frequency range of the frequency-domain manipulations performed, and to have a timing compatible with a 1200 baud serial communication system.

The identification of the muscle contracted must be made on more than just the detection of the presence or absence of an EMG signal at a given electrode site. Since the head of the subject acts as a volume conductor, contraction of a given cranial muscle will yield an EMG signal at that particular electrode site, but it will also cause a signal to appear at some of the other electrode sites. Given the necessary closeness of the electrode sites with respect to each other this “cross-talk” EMG may erroneously be taken as a signal originated by the muscle that the electrode is meant to monitor, yielding a false detection. Fortunately, previous studies by LeVeau and Anderson [8], also confirmed by previous observations from our group [1], indicate that the frequency spectra of different muscles may exhibit significant differences. This fact may be partly attributed to the dependence of the frequency content on the contraction length of the muscle. Other factors that affect the frequency spectrum of the EMG generated by a muscle are the motor unit recruitment patterns, distinct motor unit properties (fast-twitch, slow-twitch), conduction velocity, and muscle fatigue [8].

The signal processing approach implemented in our system capitalizes on the spectral differences in the EMG from different muscles. These differences are evaluated in terms of the Discrete Fourier Transform (DFT) decomposition of each of the EMG signals. For a block of N consecutive samples from a discrete sequence x(n), a total of N DFT coefficients, X(k) can be calculated as follows:

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j\left(\frac{2\pi}{N}\right)nk}, \qquad k = 0, 1, \ldots, N-1 \qquad (1)$$

These N complex values indicate the amplitude and phase of the N complex exponential sequences, at increasing frequencies f_0, f_1, …f_k, …f_{N-1}, which cover the range frequency from DC to Fs, the sampling rate, in increments of $\Delta f = Fs/N$.

The system obtains an improved assessment of the frequency composition of each of the EMG channels through the Average Periodogram, in which several (overlapping) data windows are analyzed through the DFT and the magnitudes of the several DFT coefficients, X(k), for the same frequency index k are squared and averaged, to result in a discrete approximation to the Power Spectral Density (PSD) of the sequence under analysis.

While previous approaches to cranial EMG classification [1, 2] analyzed the spectral difference on the bases of partial PSD accumulations, within prescribed frequency ranges, the system presented here focuses in a spectral measure called the Mean Power Frequency (MPF). The MPF is derived from the PSD values as a weighted average frequency in which each frequency component, fk, is weighted by its power, Pk. The equation for the calculation for the MPF is given by:

$$MPF = \left(\frac{f0 \times P0 + \ldots + fk \times Pk + \ldots + fN \times PN}{P0 + \ldots + Pk + \ldots + PN}\right), \quad k = 0, 1, \ldots, N-1 \qquad (2)$$

Our own observations showed that the MPF in the EMG from different muscles lies within muscle-specific ranges. The frontalis muscle has the majority of its spectral content below 200Hz, with an MPF in the range 40Hz – 165Hz. The Temporalis muscles have a significant portion of their spectral content above 200Hz, with an MPF in the range 120Hz – 295Hz. The Procerus muscle has an intermediate spectral content when compared to the Frontalis and Temporalis muscles, with an MPF in the range 60Hz – 195Hz.

Accordingly, the algorithm for the identification of the contraction of specific cranial muscles is summarized as follows:

For a unilateral muscle contraction to be correctly classified by the four-electrode algorithm all the following criteria must be satisfied:

I. The maximum PSD amplitude must exceed the threshold set for that electrode.
II. The sum of the PSD amplitudes for the given electrode must exceed the PSD sums of the other electrodes.
III. The mean power frequency calculated from the PSD must fall into a range consistent with the muscle associated with the electrode.

For the classification of the bilateral contraction of the left and right Temporalis muscles used to trigger the left-click cursor action, all the following conditions must apply:

I. The maximum PSD amplitude thresholds must be exceeded for both electrodes.
II. The PSD sums for both electrodes must be greater than the other two PSD sums.
III. The PSD sums for both electrodes must indicate a fairly balanced bilateral contraction, that is, each PSD sum must be greater than 20% of the total of both PSD sums.
IV. The mean power frequencies calculated from both PSDs must fall into a range consistent with the muscles associated with both electrodes.

5. SYSTEM VERIFICATION

5.1 Off-line Verification of Contraction Classification

For an initial, off-line verification of the ability of the system to correctly identify the muscle being contracted at a given time, five subjects (4 male, 1 female, all able-bodied) were set up with the electrodes as described in the section on electrode placement, and the resulting EMG signals were conditioned and digitized at 1,000 samples per second (each channel), while the subject was asked to follow a timed routine which defined which muscles should be contracted in two pre-specified sequences. Table 2 shows the sequence of movements (and pauses) that each of the subjects completed. The segments in which the subject was directed to execute neck movements were included to test the sensitivity of the algorithm to this unwanted input.

Table 2. The ordering of facial movement sequences

Time	Sequence 1 Facial Movements	Sequence 2 Facial Movements
0s – 20s	No Movement	No Movement
20s – 40s	Right Clench	Right Clench
40s – 50s	No Movement	No Movement
50s – 70s	Eyebrows Up	Eyebrows Up
70s – 80s	No Movement	No Movement
80s – 100s	Left/Right Clench	Left/Right Clench
100s – 110s	No Movement	No Movement
110s – 130s	Eyebrows Down	Eyebrows Down
130s – 140s	No Movement	No Movement
140s – 160s	Left Clench	Left Clench
160s – 170s	No Movement	No Movement
170s – 190s	No Movement	Neck Movement

The four-channel data files collected during the execution of these sequences were then processed as described in the previous section, obtaining the Average Periodogram of each channel sequence and performing the tests indicated by the algorithm for unilateral and bilateral contraction detection. The results from the algorithm were coded according to the following mapping: 0 = No contraction detected; 1 = UP detection; 2 = LEFT detection; 3 = RIGHT detection; 4 = CLICK detection; and 5 = DOWN detection.

Since the expected coded outputs for each timed segment were known, it was possible to establish a comparison with the actual coded result from each run, to determine the percentage of time when the algorithm provided the correct code as output. Figure 2, in fact, shows an example of the sequence of coded outputs provided by the algorithm for a run of sequence 2. It can be observed in this figure that the algorithm provided the correct codes for each movement segment and "0" for the "No Movement" intervals, with just a few instances in which the features of the PSD were misclassified.

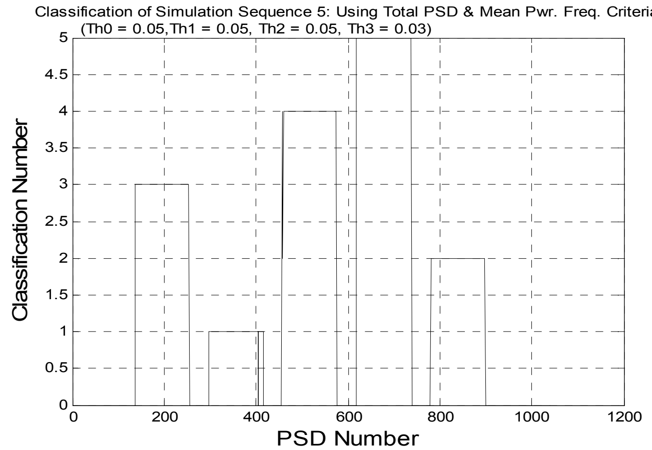

Figure 2. Example of classification sequence produced by the four-electrode classification algorithm

Correct classification percentages were calculated by averaging over the four contraction sequences (two repetitions of each type of sequence) executed for a given subject. These classification percentages are shown in Table 3.

Table 3. Summary of classification percentages on a subject-by-subject basis

Correct Off-Line Classification Results (%)					
Subject Number					**AVERAGE**
1	2	3	4	5	
99.52	99.01	99.08	99.01	95.49	**98.42**

The high percentages of correct classifications reflected in Table 3 confirmed that the proposed combination of electrode setup, digital signal processing and classification algorithm had the potential to provide robust identification of muscle contractions.

5.2 Real-Time Cursor Control Verification

In order to effectively test the cursor control capabilities of the proposed approach, the digital signal processing and classification algorithms were implemented in an Analog-to-Digital Converter / Digital Signal Processing board. The ADC64TM DSP/AD board (Innovative Integration, Simi Valley, CA) performed analog-to-digital conversion on each signal at a sampling rate of 1.2 kHz, and then applied the classification algorithm to these digitized signals in real-time. The board was connected to the computer through the PCI bus. The output of the board was a series of TTL-compliant binary voltage sequences that were consistent with voltage sequences expected from a serial mouse. The Motorola® MC1488C RS-232C driver converted the TTL sequences into RS-232C format and transmitted these sequences into the serial port of the personal computer (PC). The serial mouse driver of this computer communicated with the operating system to produce cursor actions consistent with the serial input. This setup for the real-time manipulation of the PC cursor is shown in Figure 3. A photograph of the elements used for the implementation (except for the PC and the Grass® bioamplifiers) is shown in Figure 4.

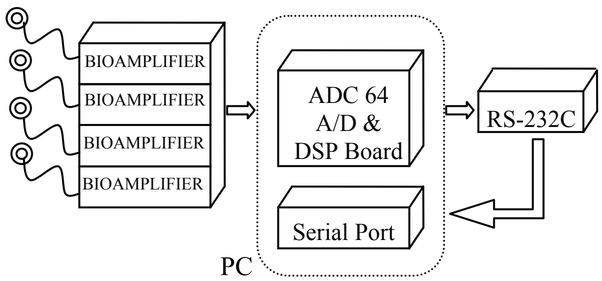

Figure 3. Block diagram showing the functional blocks involved in implementing the EMG-based cursor control approach for real-time performance

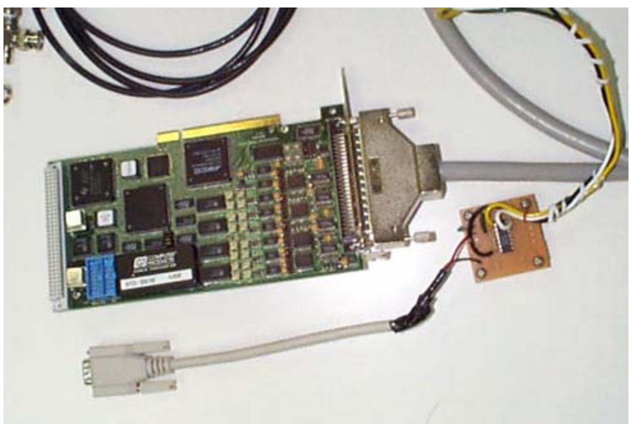

Figure 4. Picture showing three key elements of the real-time implementation: the ADC64 board, the RS-232 driver and the connector to the serial port of the computer

A test program was created in Visual Basic to evaluate the real-time performance of the system. The program was displayed on a 17" color monitor. For each point-and-click trial, an 8.5 x 8.5 mm "Start" button was presented in a corner of the screen and a "Stop" button was presented in the center. The "Stop" button had four possible dimensions: 8.5 x 8.5 mm, 12.5 x 12.5 mm, 17 x 17 mm, 22 x 22 mm. Each subject was instructed to use the EMG-based system to click the "Start" button, in order to begin timing a trial, move the cursor to the "Stop" button, and click the "Stop" button as quickly as possible. After completing a trial, the subject would click a "Next" button to display another trial layout with the "Start" button appearing in a different corner of the screen.

The real-time evaluations were divided in four sessions. During a session only one "Stop" button size was presented. The "Start" button was presented in one of the four possible corners for each trial. A trial that had a "Start" button in a specific corner was repeated five (non-consecutive) times per session. Therefore, there were twenty trials per session and 80 trials per subject. Six able-bodied, male subjects were involved in the real-time evaluation of the system.

The pointing task times found for all subjects and all trials were (mean ± standard error) 13.24 ± 3.28 s. In order to perform Fitts' law analysis on the data, results were aggregated across subjects to give one data point for each task condition (i.e., for each "Stop" icon size). The results are shown in Table 4 where D is the start-stop distance, W is the size (side) of the stop icon, ID is the index of difficulty, MT is the movement time and IP is index of performance.

Table 4. Aggregated point-and-click data for Fitts' law analysis of the EMG cursor control system

D (mm)	W (mm)	ID = log2[D/W + 1] (bits)	MT (s)	IP = ID/MT (bit/s)
180	8.5	4.47	16.12	0.277
180	12.5	3.94	14.89	0.265
180	17	3.53	13.37	0.264
180	22	3.20	12.85	0.249

Using the four movement time (MT) values from Table 4 as ordinates and the four values of index of difficulty (ID) as the corresponding abscissas we can represent the performance of the EMG cursor control system graphically. This is shown in Figure 5. The four circles in this plot indicate the average movement times recorded in the experiment for the four corresponding indices of difficulty. The slope of the regression line fitted to the data and also shown in the figure represents the overall index of performance of the cursor control system (i.e., how the increased level of difficulty impacts the timing of the task).

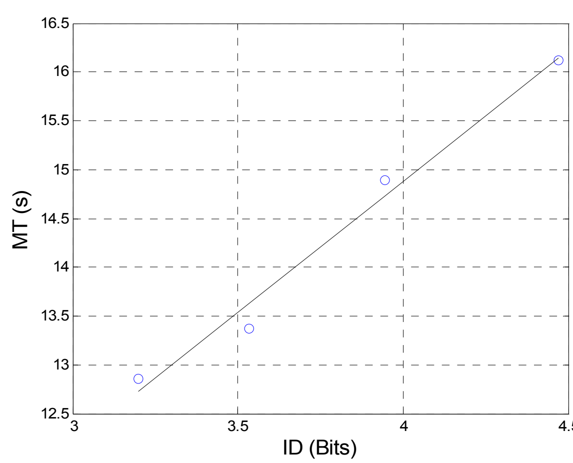

Figure 5. Fitts' law plot for the interface relating movement time to index of difficulty for the four task levels studied

6. DISCUSSION

The results of both forms of system verification, off-line and real-time, reinforce the belief that the EMG-based system can provide an alternative for hands-free manipulation of the cursor in a computer graphic user interface.

Figure 2 and Table 3 summarize the results of the off-line system verification. From both of them, it is possible to appreciate that the EMG-classification system is capable of very accurate differentiation between the EMG signals produced by the four muscles being monitored. Figure 2 stresses the fact that the system does not report false detections during the periods in which the subjects were instructed to execute "No movements". This is a key feature towards the stability of the cursor in the interface, which should remain completely static unless the user specifically commands it to move. The values in Table 3 also reveal that the use of the system does not appear to require individual skills on the part of the user, as all five of the subjects involved in the verification were capable of achieving almost uniform levels of performance with the system. The average accuracy found in the off-line verification experiment was 98.42%, while the standard deviation of the five individual results was only 1.65 %.

The real-time verification represents a more comprehensive assessment of the effective performance of the system, in the context of the specific use for which it is intended. In this assessment, the average time recorded for the task (clicking on a Start button in a corner of the screen, moving the cursor to a Stop button at the center of the screen, and clicking on it) was 13.24 ± 3.28 s. This is an improvement with respect to the average time of 16.35 seconds, reported in [1] for the same experiment using a previous prototype of EMG cursor control system. Figure 5 confirms that this interface behaves approximately according to Fitts' law, maintaining an approximately constant MT/ID ratio through the four task levels tested.

7. CONCLUSION

The EMG-based cursor control system presented in this paper has been shown to provide a robust classification of cranial muscle contractions, in off-line tests. Furthermore, the actual implementation of the system for real-time operation has proved that it provides an alternative, hands-free mechanism to command stepping motion of the screen cursor in four directions and to perform clicks.

While the average task time recorded in the experiments with the proposed cursor control system is shorter than the one reported previously for the same experiment using a prior prototype, it is still much longer than the average time required when the task is performed by an able-bodied user with a standard mouse (typically less than 2 seconds). In order to further reduce the average task time achievable with hands-free operation, our group is studying the integration of an eye gaze tracking system with our EMG cursor control system into a hybrid system that will enjoy the complementary benefits of both of these technologies.

8. ACKNOWLEDGMENTS

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