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Multidimensional Control Using a Mobile-Phone Based Brain-Muscle-Computer Interface

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Abstract— **Many well-known brain-computer interfaces measure signals at the brain, and then rely on the brain's ability to learn via operant conditioning in order to control objects in the environment. In our lab, we have been developing brain-muscle-computer interfaces, which measure signals at a single muscle and then rely on the brain's ability to learn neuromuscular skills via operant conditioning. Here, we report a new mobile-phone based brain-muscle-computer interface prototype for severely paralyzed persons, based on previous results from our group showing that humans may actively create specified power levels in two separate frequency bands of a single sEMG signal. Electromyographic activity on the surface of a single face muscle (Auricularis superior) is recorded with a standard electrode. This analog electrical signal is imported into an Android-based mobile phone. User-modulated power in two separate frequency band serves as two separate and simultaneous control channels for machine control. After signal processing, the Android phone sends commands to external devices via Bluetooth. Users are trained to use the device via biofeedback, with simple cursor-to-target activities on the phone screen.**

Index Terms—human-machine interface, sEMG, mobile phone, translational research, BCI

I. INTRODUCTION

A new generation of human-machine interfaces for severely mobility-impaired persons is quickly emerging, which uses the body's natural electrical signals, instead of mechanical force devices such as joysticks or sip-and-puff systems [1-3]. For example, new brain-computer interfaces (BCI) use electroencephalography (EEG) or electrocorticography (ECoG) signals generated within the brain itself to control computer cursors or robot arms [4-7]. These devices may be especially useful to those with conditions that leave persons with complete muscle control loss, such as Amyotrophic Lateral Sclerosis (ALS) patients. Most other persons, including those with high spinal cord injury, do have some limited control of a few muscles. All muscles produce electrical activity upon contraction, which may be measured and used as a basis for an external machine interface [8].

Work on brain-computer interfaces was informed by the study of naturally occurring changes in brain activity as a result of real and/or imagined movements/thoughts [9], as well as several important results in non-human primates showing extraordinary control of single/multiple brain neurons through operant conditioning [9-11]. The use of electromyography sensors for prosthetics control predates human brain-computer interfaces, in which typically either total power is manipulated at several muscle sites, or intended motion is decoded from sensors at several muscle sites, to achieve control over powered-prosthetics [12-14]. However, in the same way that single brain neuron control was explored, several researchers previously have shown extraordinary control of single motor neurons[15]. In addition, the brain has the ability to precisely control motor units to achieve all sorts of complex motor skills. This seems to suggest that operant conditioning on EMG signals could lead to new brain-muscle-computer interfaces that use the muscle's electrical signals as a pathway from the motor/premotor cortex to external devices.

Our goal was to develop a system that uses only a single muscle, which preferably was not used for any other natural function. As such, we chose the *Auricularis superior* (AS) muscle (above the ear) which has no known use in humans (animals use a functionally equivalent muscle to direct the ear towards a sound source [16]). The fact that the Auricularis superior muscle is away from the front of the face ensures that the electrode itself and associated wiring can be somewhat concealed from view. A disadvantage of this muscle is that many persons do not know how to access this muscle, and must be trained to contract the muscle (in addition to being trained to create multiple control channels).

The key for our system is the human neuromuscular system's ability to learn how to manipulate surface EMG signals, in ways completely distinct from human muscle movement. In essence, we are high jacking the electrical system of the muscle to create a signal generator that drives external devices. The goal of the current research is to translate our basic sEMG results as previously described, into a useable and functional machine interface that can be used in the community, both for rehabilitation applications (such as environmental control) and for wider-scale community-based data collection to advance basic research on human sEMG control ability. New mobile phone hardware is evolving rapidly with continually more powerful microprocessors, high-resolution touch screen interfaces, and built-in Bluetooth wireless capability. Furthermore, additions and/or changes to the interface become a software upgrade that can easily be downloaded and installed on today's mobile phones. Finally, we note that this device serves as an information technology bridge for in-situ data collection on human sEMG manipulation abilities. It is difficult for severely paralyzed persons to participate in medical studies that require them to travel to a particular laboratory site, at a specific time. This is borne out by the frequent use of healthy subjects in many bioelectrical interface studies, even though the target population is highly paralyzed (e.g. [17-19]). Our interface continuously collects all relevant data on the usage of the machine without need for any user intervention, and stores data on its built in SD card for future analysis.

We note that an expanded description of our phone interface, including detailed human subject evaluation trials and a one-dimensional controller not described here, will appear shortly (Vernon & Joshi 2011 [20]).

II. Previous Work: Neuromuscular Hypothesis and Cursor-to-Target Results

In a previous study also conducted by our group (Perez-Maldonado, *et al.* 2010), we hypothesized that humans would be able to place arbitrary amounts of power in two separate pre-specified frequency bands of the sEMG signal simultaneously [21]. Learning to perform this feat would be accomplished through visual feedback (operant conditioning). Physiologically, the neuromotor system would need to tune the firing rates and recruitment patterns of motor units precisely in order to achieve the desired power levels. (The precise neuromotor adaptation used to achieve this skill is still unknown.) Interestingly, the ability to achieve this task uses the physiological machinery of the neuromotor system, but does not correspond to any common motor task.

In order to test this hypothesis, we developed an experimental cursor-to-target protocol, which is similar to tests conducted with BCI systems [4]. We acquired the sEMG signals of the *AS* muscle of four able-bodied subjects. The subjects were trained, via visual feedback, to manipulate the position of a computer cursor to hit three separate fixed target points on the screen. A resting muscle kept the cursor at the origin (bottom left corner of screen), and a contracting muscle placed the cursor at different positions on the screen. As such, the subjects guided the cursor from the origin to the target. Training proceeded in two steps. First, the subjects learned to access their AS muscle, as this is not a commonly used muscle. This was performed through trial and error with visual feedback with a single sliding bar showing total contraction power. Once the subject could reliably access the muscle, cursor-to-target training proceeded. The raw sEMG signal at the single muscle site was filtered into two channels using two band-pass filters. The normalized power in each channel was combined via a linear mapping to simultaneously control X-position and Y-position of the cursor (Fig. 1, see Section IV for more details). Band-pass filter frequency bandwidths and their mid-points were determined by correlation tests and simulation analysis [21]. Different combinations of power in each frequency band led to different targets (Fig. 2). To hit the first target, the subjects had to place more power in the first band, as compared to the second band. To hit the second target, the subjects had to place equal amounts of power in each band. To hit the third target, the subjects had to reverse the power profile of the first target. Fatigue was minimized by software gains that kept required muscle contraction to below 15% of MVC [21]. Training consisted of 15-16 sessions (1-session per day on non-consecutive days, about 90 minute each) on each target individually, before randomized evaluation trials. (We have not yet studied minimum training time, which is a subject of future experiments.) After training, all four subjects were able to simultaneously control the X and Y positions of the cursor to accurately and consistently hit three widely-separated targets on a computer screen. The targets' size was 0.16 % of the screen area, and the hit-rate ranged from 87-98 % after training. Average hit times for these extremely small targets ranged from 1.9 s - 16.5 s. Typical cursor paths for each of our four subjects are shown in Fig. 3. Details of these experiments have been documented in [21].

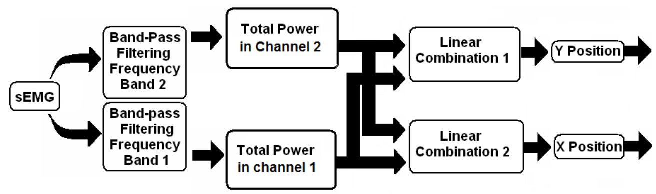

Fig. 1. Block diagram of system developed to generate 2 control signals from a sEMG signal at a single muscle site. The sEMG was simultaneously band pass filtered to generate two signals which were then linearly combined to generate 2 control signals.

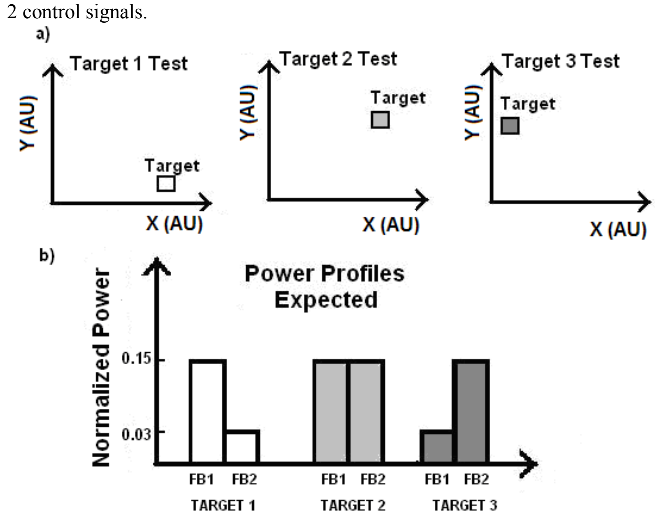

Fig. 2. a) The Cursor-Target tasks for three different targets that each subject was aiming to achieve. b) Power profiles expected for the three different target activities. FB1 and FB2 respectively are the first and second frequency bands found for each subject. See Fig. 3 for actual frequency bands.

III. Mobile Phone Based Prototype

Our previous laboratory-based interface system contained sEMG electrodes, amplifier, digital acquisition card, laptop computer, and standard laboratory software (LabView^{TM}) [21]. Although the laboratory-component setup allowed us to explore human capabilities in manipulating sEMG signals on a limited number of subjects, the setup and configuration of the device was cumbersome and required a specialized biomedical researcher to be present.

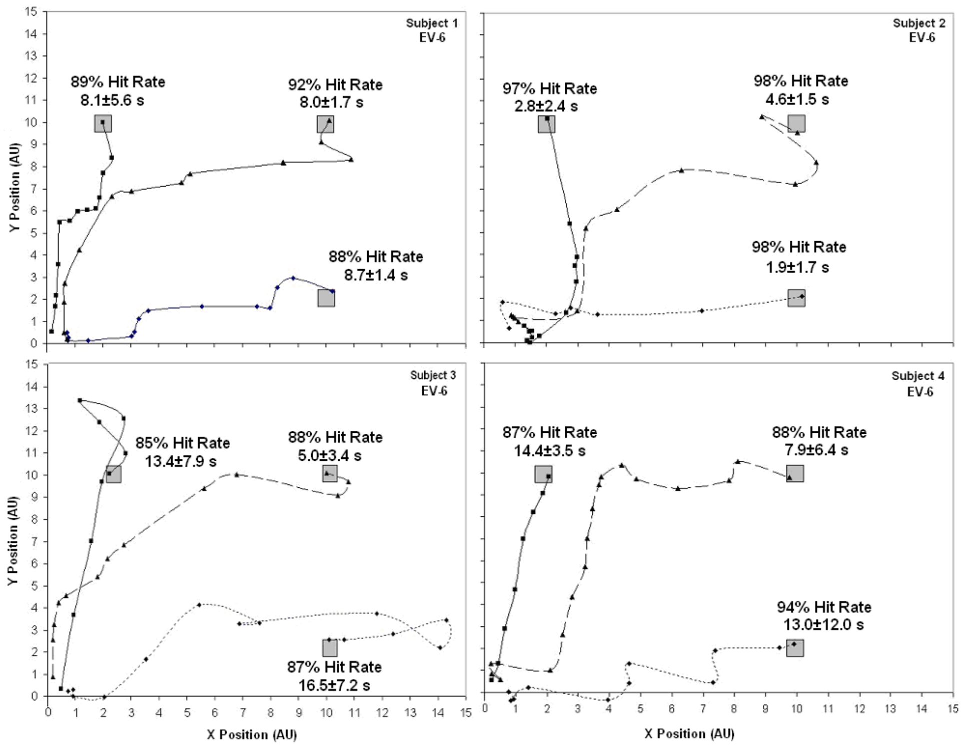

Fig. 3. An instantaneous cursor trajectory generated by each subject when trying to hit the respective targets. Each target area is 1x1 AU and the screen has been reduced from the original size of 25x25 A.U. shown to the user ($-5\leq X\leq 20$; $-5\leq Y\leq 20$), to this 15x15 AU screen The hit rates and times shown correspond to only the last of six evaluation sessions. Frequency bands: 50-70 Hz & 110-130 Hz Subject 1; 60-80 Hz & 110-130 Hz, Subject 2; 40-60 Hz & 80-100 Hz Subject 3; and 40-60 Hz & 80-100 Hz Subject 4. See [21] for more detail.

The hardware architecture of the new interface is shown in Fig. 4 and can be separated into three distinct components: the sEMG sensor electrodes positioned over the Auricularis superior muscle (above right ear pinna), the mobile phone device itself, and any external device(s) that the interface ultimately controls.

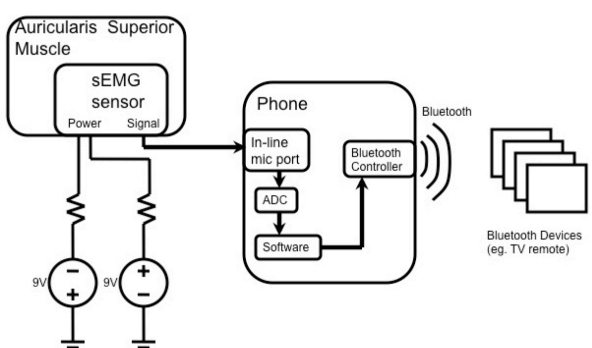

Fig. 4. System architecture of mobile-phone based interface.

A. Surface Electromyographic Electrodes

Surface electromyography is used in many applications within muscle rehabilitation, and many commercial electrodes are available. Typically, electromyography relies on three contact points, where two points measure electrical activity of the same muscle and are used with a differential amplifier to reduce common mode noise, and one contact serves as a ground. Until recently, most sEMG required the additional use of a gel applied to the skin under the electrode. This gel lowers the skin-electrode impedance, and allows measurement of the small electrical signals generated by the surface muscles. With advances in amplifiers and contact materials, more companies are now offering gel-less electrodes that can simply be placed over cleansed skin, and are integrated with sensitive differential amplifiers within a single package. For the current system, we used Motion Lab Systems' Z03-000 sEMG sensor, which has a CMRR of > 100 dB at 65Hz, x300 gain, required power supply range of ±3.5 V to ±15 V and signal bandwidth of 15Hz to 2,000Hz (-3dB). The sensor package itself, as well as the anatomical placement above the ear is shown in Fig. 5. Note that in actual use, the sensor itself is covered by a headband (or similar device) that firmly presses the sensor against the head.

B. Mobile Phone Device

Once the analog differential sEMG signal is measured, we feed the signal into a mobile-phone device. Several mobile phone devices could have been used. We chose the HTC Dream cell phone running the Android operating system. This model contains a 528 MHz Qualcomm MSM7201A processor,

Fig. 5. Motion Lab Systems' Z03-000 sEMG sensor placed on the Auricularis superior muscle. (For visualization only.)

192 MB RAM, 256 MB ROM, 3.2 inch TFT-LCD display with 320 x 480 resolution, and built in Bluetooth and GPS (Fig. 6). A particular advantage with the Android operating system is that it is open-source and the phone itself contains a mini-SD card slot, which we use to write device operation data for later analysis. Input and output to/from the device is gated through the phone's mini-USB port, which is the HTC ExtUSB (11-pin mini-USB 2.0 and audio jack in one). This particular USB port is uncommon in newer phones. However, future versions of the interface will likely use wireless inputs, common in Bluetooth microphone headsets. We created a custom mini-usb connector for the sEMG sensor, in which the analog signal output was connected to the microphone input pin of the phone connector. This allowed the phone to treat the sensor as a headset with built-in microphone, which automatically fed the sensor signal through the ADC within the phone, where it could be processed in digital form. sEMG power spectra lie well below 1000 Hz. We sampled our sEMG signal at the standard available sampling rate of 8000 Hz, and then down sampled to 4000 Hz. Once the measured sEMG signal is processed to create two control channel signals (Section IV), the effect of these two control signals must be visualized for the user. The built–in touch screen on the phone allows effective user interface screens to be built (Section V). Finally, in order to use the phone to control external devices, the phone must output external device-control signals. Again, this can be accomplished using the phone's native Bluetooth emitters, which allow 8 devices to be connected simultaneously. The mobile-phone based device can run entirely on battery power and does not require an active cellular connection for external device control.

C. External Devices (Television)

The phone is able to control devices in the user's environment via use of Bluetooth. We use television remote control as an example of a much broader class of external device control applications. Current televisions are controlled by IR commands and not Bluetooth, so we created a custom phone-television interface device that accepts incoming Bluetooth signals, and outputs appropriate IR commands to a

Fig. 6. Motion Lab Systems' Z03-000 sEMG sensor and Android-based HTC Dream cell phone.

television. A block diagram overview of the hardware for this phone-television interface is shown in Figure 7a, and photograph of the circuitry is shown in Figure 7b. Our custom television device first receives and decodes the IR signals sent from a normal television remote through its built-in IR receiver. It then saves the decoded signal to internal memory for later playback. Both recording and playback of the IR codes are triggered through Bluetooth commands sent from the phone. These commands are one byte in length and are sent via the Bluetooth serial protocol. The byte values '0'–'9' correspond to playing the IR codes for the 0-9 buttons on the remote and the byte values 'a'-'f' correspond to playing the IR codes for channel up, channel down, previous, enter, on/off and mute respectively. The byte values 'g'-'u' correspond to setting the device in a state to record the IR codes. While these are the default commands for the device, more can be easily added if desired.

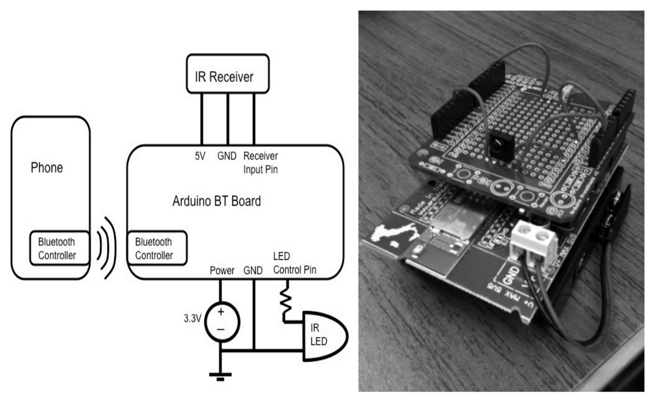

Fig. 7. a) Block diagram overview of the hardware for phone-television interface. b) Circuit photograph for phone-television interface.

IV. SIGNAL PROCESSING

Subjects may change the location of a cursor on the phone screen by contracting their Auricularis superior muscle in such a way as to create the proper electrical signal to move the cursor to the place they desire. Learning to guide the cursor to a new screen position amounts to learning a new motor skill through trial and error. Human ability to control a cursor using

2-band sEMG control is a recent discovery, and the precise brain adaptation mechanisms that allow a person to learn this skill are still unknown [21]. One aim of the currently reported mobile-phone interface is to explore these questions using community based data collection. Cursor location is displayed with various GUIs that are described in Section V. The signal processing needed to transform the single sEMG signal from one muscle site to 2 control channels (X-pos and Y-pos) is shown in Eqns. 1-2. Each term in Eqns. 1 & 2 will be described in the following. The first step of the process is to compute the total power within two different frequency bands of the single sEMG digitized signal. Therefore, the digitized signal is duplicated, and then simultaneously filtered using two digital band pass filters for 20-40 Hz (Band 1) and 60-80 Hz (Band 2). These bands were chosen *ad hoc*, within the standard bandwidth of a sEMG signal.

We used two 4^{th} order IIR filters for band pass filtering. Total signal power at the output of these filters was simultaneously computed every 0.25 seconds, using Parsavel's Theorem (*Power_Band_1* and *Power_Band_2*). These powers are normalized with *Max_Power_Band_1* and *Max_Power_Band_2* values obtained through a short calibration procedure, in which the user maintains an apparent Maximum Voluntary Contraction (MVC) for 5 seconds, and maximum partial power values within this time period are computed for each band. Finally, the scaled-normalized powers in each channel are linearly combined using the coefficients shown in Eqns. 1 and 2 to produce a given cursor-position. The coefficients in Eqns. 1 and 2 are set such that the user can place the cursor anywhere on the phone-screen. Note that if the normalized power in both frequency channels is 1 simultaneously, then the cursor is placed on (X_{pos}=1, Y_{pos}=1), which is defined as the upper right corner of the phone screen. The cursor position can also be scaled according to $Effort_x$ and $Effort_y$ parameters that vary from (0-1] and can be adjusted with on-screen commands. These $Effort_x$ and $Effort_y$ values allow more or less muscle contraction effort to be exerted for the same cursor effect. $Effort_x=1$ and $Effort_y=1$ indicates that full maximal contraction will be required to place the cursor in the upper right hand corner of the phone screen. However, these values are nominally set near 0.15 to minimize muscle fatigue. Also, if the user's muscle condition and abilities are such that the ability to move the cursor favors one direction over the other, the $Effort_x$ and $Effort_y$ can be independently adjusted to equalize control authority in both directions.

$$X_{POS} = \frac{1}{Effort_X}\left[1.75\left(\frac{Power\_Band\_1}{Max\_Power\_Band\_1}\right)\cdots -0.75\left(\frac{Power\_Band\_2}{Max\_Power\_Band\_2}\right)\right] \tag{1}$$

$$Y_{POS} = \frac{1}{Effort_Y}\left[-0.75\left(\frac{Power\_Band\_1}{Max\_Power\_Band\_1}\right)\cdots +1.75\left(\frac{Power\_Band\_2}{Max\_Power\_Band\_2}\right)\right] \tag{2}$$

Since the power in any given band may vary from one sample to the next (0.25 sample period), some smoothing is added so that the cursor will not jump erratically. This smoothing consists of averaging a certain number of previous cursor positions with the newly calculated cursor position and then setting the new cursor position to the average. We typically smooth over 6 previous cursor positions. Another important part of the GUI interface is the rate at which the screen is refreshed. This is important, because a slow refresh rate leads to erratic animations and a frustrating experience for the user. A 30 Hz screen refresh rate leads to smooth cursor motion on the screen, but our system computes a new cursor position at 4 Hz. So, we devised a refresh strategy in which we could refresh the screen multiple times during one computing period. This strategy consists of computing the desired cursor position every 0.25 seconds. However, the cursor is not moved to the calculated position immediately. Instead, while the next sensor data block is recorded and processed, the cursor is gradually moved to the previously computed position over multiple refresh steps. This allows us to increase the refresh rate to 32 Hz while sacrificing at most 0.25s of GUI response time (which is unnoticeable to the user as shown in testing).

V. GUI AND INTERFACE MODES

The proposed system includes various GUIs to help setup and calibrate the system, train the user, and control various devices. Each of these GUIs has a separate screen that can be changed by a helper's finger swipe. Some of these screens and their purposes are discussed below.

A. Signal Test and Calibration Screens

The signal test screen is the first screen presented when the application is started. This screen samples the raw incoming sEMG signal and displays the input in the form of a graph (approximately 0.32 mV/pixel). This screen is used when connecting the sEMG sensor to the skin in order to determine that a good connection has been made, and that minimal noise is corrupting the signal. If unacceptable noise is present in the signal, usually the sensor must be re-positioned, cleaned, or tightened against the skin. After a good sensor connection is established, the system must be calibrated to the user's unique muscle ability. This is done by using the calibration screen (not shown), which prompts the user to contract their muscle for a certain amount of time (nominally 5 secs) and measures maximum power in each frequency band during that time (*Max_Power_Band_1* and *Max_Power_Band_2,* Eqns. 1 & 2).

B. Training Screens

Two training screens exist in the system. The first screen trains persons to contract the Auricularis superior muscle, as most people cannot wiggle their ears. This is achieved by a simple one-dimensional bar that rises in proportion to total sEMG signal strength. Once the Auricularis superior muscle can be contracted regularly, another screen trains persons to move the cursor in X and Y directions. Both screens employ operant conditioning (trial and error), as the user can visually see the effect of muscle contraction on a computer object, and then adjust their contraction to form the intended motion. Note that although Eqns. 1 & 2 form the basis for cursor movement, users do not have any knowledge of these functions. Once the user is comfortable with two dimensional movements, they are ready to begin using the system to control devices. It should be noted that once the user learns to correctly generate the electrical signals at their muscle via contraction, the actual physical movement of the muscle is unnoticeable (isometric contraction).

C. Control Screen

The control screen allows the user to move a cursor to one of several command goals arranged on the (two-dimensional) phone screen (Figure 8a). This screen consists of a black cursor that is moved by the user, three multi-colored *Goal* circles, and a *Rest* quarter-circle. The movement of the cursor is again dictated by Eqns. 1 & 2. To execute a command, the user must hit (reach) a *Goal* circle with the cursor, which will change the color of the goal to a yellow, indicating a 'possible command' state. To confirm the command, the user then returns the cursor to the *Rest* zone by relaxing. Immediately after entering a 'possible command' state, the other two *Goal* targets are removed from the phone screen for a short period of time (1.5 secs) to allow for the user to return the cursor to the *Rest* zone without accidentally hitting another goal. However, the other two targets are reinstated on the screen after the fixed time period so that if the 'possible command' state was a mistake, the actual desired goal may be hit instead. The position and size of the *Goal* circles and size of the *Rest* zone are all adjustable on a separate options screen of the application.

VI. EVALUATION & TELEVISION REMOTE CONTROL

For the current proof of concept, a paralyzed advanced Spinal Muscular Atrophy (SMA) 26-yr old male was the test subject (Figure 8b). All testing procedures were approved by the Institutional Review Board of the University of California, Davis. The subject was chosen for his significant previous experience with our laptop-based implementation as described in [22], which allowed him and his caregivers to provide useful feedback comparing the two systems. Formal evaluation studies using randomized cursor-to-target trials will be reported in Vernon & Joshi 2011 [20].

Our device was retained by the subject for independent use in the last week of July 2010, outside the presence of researchers. The subject's family and nurses were briefly trained on the correct procedure to position the sensor, how to test for correct sensor-skin contact, and device calibration & usage as a television remote control. The primary motivation was to obtain user feedback on the ease of use and potential problems. The subject used the device 3 different days. The subject's aides successfully applied the sensor and calibrated the device independently, and the subject was successfully able to use the device. However, the subject also noted some concerns, including that the headband became uncomfortable after extended use. The subject had also reported a minor muscle twitch between two previous testing sessions that disappeared. These issues are currently being explored. Recently, there has been progress in contactless sEMG sensing through clothing and hair [23, 24]. These sensors may be very useful for our system in the future. Despite the areas for improvement, the independent test showed proof-of-concept that our interface could be used by a subject without need for specialized biomedical engineers.

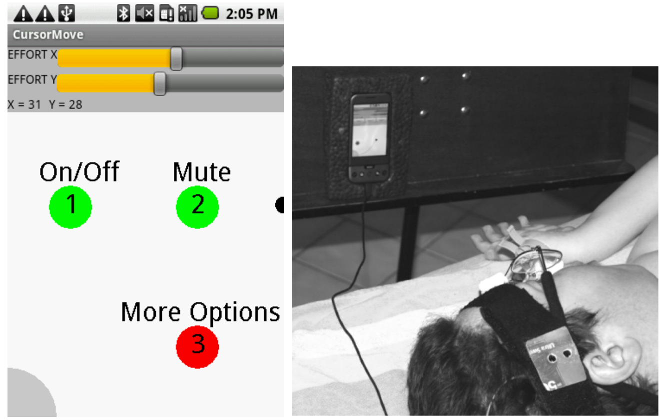

Fig. 8. (a) Precise contractions lead to movement of cursor in both x and y dimensions simultaneously, in order to guide cursor dot to one of three command Goals. (b) SMA subject uses interface in his home.

VII. DISCUSSION & CONCLUSION

A major motivation in developing the mobile-phone version of our interface was the need for data from substantial numbers of paralyzed persons in order to characterize basic facts about our new brain-muscle-computer interface, such as training time distributions across groups and long term health effects. We are now planning studies with rehabilitation physicians to obtain data on the use and usefulness of our new interface. Now that a proof-of-concept device has been developed, we may explore a host of other interface options. We are currently porting our Android code to a variety of new cellular phones/tablets. In this way, the hardware may also be tailored to the patient. Some subjects may require a larger screen or different shaped/patterned targets, for example. Ultimately, the combination of new user-interface methods and mobile-computing technologies could have beneficial impact of the lives of severely paralyzed individuals.

VII. ACKNOWLEDGMENT

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