Single Electromyographic Sensor Control of Multi-Function Technologies for Persons with Severe Mobility Limitations: A Case Study

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1. Abstract

This paper presents a case study demonstrating the efficacy of using electromyographic (EMG) control to navigate a power wheelchair, manipulate power seating actuators, and operate a full featured Smartphone. The subject has an advanced form of spinal muscular atrophy leaving him paralyzed with only a surviving left pectoralis muscle and slight movement in his right thumb. System configuration and operational techniques are described for using an EMG sensor to trigger a single-switch scanning controller. The aim was to leverage the single EMG sensor interface to optimally control multiple technologies. A priority was placed on enabling the subject to independently switch between target technology applications. Practical uses of the technologies and examples of increased independence and productivity are discussed.

Significant ease of use, precision driving capabilities, and high speed control was demonstrated within multiple environments by optimizing EMG sensor responsiveness and exploiting customizable configuration settings and drive profiles. By the end of the first month the subject was comfortably using the maximum scan rate of 0.25sec, could perform no-stop turns and doorway entries, and could fully operate seating actuators to control *tilt-in-space, backrest recline, footrests elevation, headrest angle,* and *seat elevator.* The EMG sensor was further leveraged to control switch access to an iPAQ 6925 Smartphone. Negligible fatigue with regard to EMG switch activations resulted in the subject using the mobile device frequently, and the *anywhere, anytime* availability extended the subject's productivity far beyond the reach of his adaptive desktop workstation.

Conclusions:

a) Single EMG control is a viable means for persons with severe mobility limitations to independently navigate a power wheelchair.
b) Single EMG sensor control of seating actuators can significantly increase independence and improve quality of life for persons with severe mobility limitations.
c) Single EMG sensor control of a Smartphone can significantly increase independence and productivity of persons with severe mobility limitations.
d) Persons with severe mobility limitations can leverage a single EMG sensor interface to successfully control multiple technologies supporting independence and productivity.

Evidence from this case study supports the need for persons with severe mobility limitations to consider the optimal transition time to single EMG control, as opposed to pursuing less effective control systems through a chain of forced transitions. The subject in this case study spent many years with reduced mobility and functionality as a result of clinging to the concept (not the benefits) of proportional control.

2. Introduction

It is estimated that between 2.1 and 2.7 million Americans need wheelchairs to accommodate their physical disabilities (Simpson, 2008). The preferred and most common method of power wheelchair control is a joystick. This method is quite intuitive to the user and involves an insignificant learning curve. If a person does not have the dexterity or strength to control a joystick, multiple switch array systems can be used. A common system of this type is a head array which offers directional control through head movement. A similar but more limiting system is a sip-and-puff device which offers directional control through a 2-way switch activated by “sips” and “puffs” of air from the user. Over 60% of those needing wheelchairs have specific symptoms which interfere with the use of traditional control interfaces (Simpson, 2008). According to Simpson, this subgroup of approximately 1.5 million Americans require some sort of semi-autonomous “smart wheelchair” to be mobile, otherwise, they must rely on a caregiver to push them in a manual wheelchair. Significant research has been done over the past two decades exploring the development of smart wheelchairs. Despite several functioning prototypes, nothing has developed into a marketable product available to the general public.

Another option for persons unable to control traditional interfaces is “single switch scanning.” This offers directional control through a single switch. Yanco expresses a widely held opinion that single-switch scanning is the access method of last resort (Yanco, 1998). Her argument supporting this rests heavily on the navigational requirement for frequent course corrections to counteract drift. Because of its perception as the “access method of last resort,” combined with the learning curve required to master its use, single-switch control is often dismissed as a non-viable option for persons with severe physical limitations. While it by no means can replace the fluid control of proportional systems, switch based scanner control can offer many advantages over more traditional systems, especially for those with the most severe mobility limitations (Andreasen, 2006).

In addition to wheelchair navigation, persons with severe mobility limitations can use single-switch control with other technologies such as environmental control units which enable the user to dial and answer the phone, control infrared devices such as televisions, VCRs, CD players, etc., and control appliances such as lights and fans. However, the amount of independence realized by the user is often diminished by the need for a caregiver to assist in switching back and forth between two or more target applications (Felzer, 2007).

This paper presents a case study demonstrating the efficacy of using single switch control to navigate a power wheelchair, control power seating actuators, and operate a full featured Smartphone. The subject is a 44-year-old male with an advanced form of spinal muscular atrophy. Due to this condition he is paralyzed with only a surviving left pectoralis muscle and slight movement in his right thumb. The subject has a history of adapting proportional control mechanisms to accommodate his diminishing strength and range of motion. At the point where no further adaptation proved possible, single switch scanning was employed as a literal “option of last resort.” The necessity for numerous switch activations with minimal physical exertion was identified as paramount to making switch access viable. Electromyographic (EMG) switch activation addressed this need. This case study uniquely focuses on the benefits of using an EMG sensor to trigger the single-switch mechanism. A priority was placed on enabling the subject to independently switch between target technology applications. The aim was to leverage the single EMG sensor interface to optimally control multiple technologies. Functional scenarios are described which demonstrate benefits in terms of both independence and productivity.

3. Single EMG Sensor

Fig. 1: *Tinkertron Dual D-Box, Delsys EMG Sensor, Reference Electrode, and Stickers*

The switch used in this case study was a Tinkertron Dual D-Box (see Fig. 1, above). This box converts tiny electromyographic (EMG) signals near an active muscle into a standard switch closure output (Andreasen, 2005). A Delsys DE-2.1 EMG sensor is included with the Dual D-Box and is held on the skin using 2-slot adhesive interface stickers. A reference electrode is also needed to support the amplification of small signals in the presence of electromagnetic interference. This is placed away from the muscle being used to engage the EMG. In this case study, Kendall BioTac Cloth adhesive gel stickers were used to attach the reference electrode to the user. This sticker does not have to be removed daily because it has a snap interface with the reference electrode. The BioTac adhesive electrode sticker was changed every week while the Delsys sensor interface sticker was changed daily. No skin breakdown or irritation was observed over longterm use. However, trials with BioTac Ultra Foam stickers did result in skin irritation that was unacceptable.

The efficacy of the system was highly dependent on finding the optimal placement of the EMG electrode. Effort was given to ensure that placement was nonintrusive, comfortable and secure. While the EMG electrode should be placed near the movement site of an active muscle, movement is not required to trigger a switch closure. The Delsys sensor provides amplification of minute muscle activity detected on the surface of the skin, and a switch activation is triggered when a signal is detected that exceeds a user adjustable threshold. Susceptibility to signal interference could be reduced by adjusting position and orientation of the sensor around the chosen target area. Once the optimum placement is found, a photograph of the site can aid caregivers in providing consistent daily placement (see Fig. 2, below).

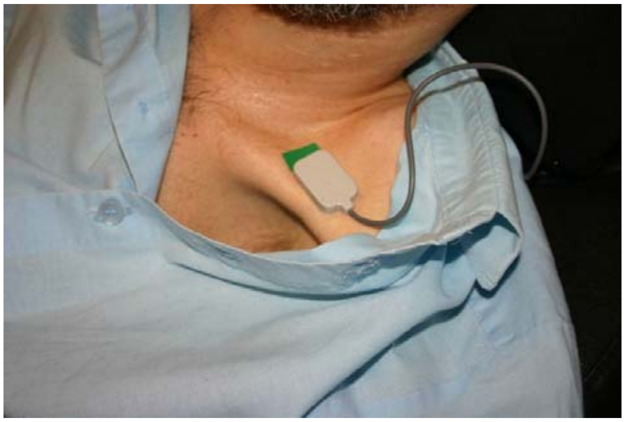

Fig. 2: *Delsys EMG Sensor Placement*

Another key factor influencing the system's performance was to find the user's optimum signal threshold. Threshold changes are made by turning a small knob on the front panel of the D-Box. Low threshold settings are more susceptible to false triggers because they require only a small surface signal to cause an activation. A "false trigger" is defined here as an inadvertent switch closure output resulting from electromagnetic interference or unintended movement. High threshold levels will minimize false triggers yet they require stronger muscle function to trigger a switch closer. In this case study, the lowest possible threshold was sought that avoided false triggers resulting from electromagnetic interference from the power wheelchair motors. Focus was placed on the subject learning to discipline active muscle use with regard to: 1) avoiding unintentional muscle movement while the power wheelchair's controller is on; 2) avoiding muscle exertion beyond what is required by the threshold setting. After approximately two days of practice associated with wheelchair navigation and seating controls, false triggers resulting from unintended movement were significantly reduced and no longer required conscious effort. After approximately one week, false triggers were inconsequential and the user experienced no fatigue or limitations with long periods of use.

Several D-Box features were added to the system in accordance to the subject's performance expectations. These parameters are adjustable through miniature programming switches internal to the D-Box unit. One such parameter is the *Relay-On-Time*. This setting allows the user to choose a switch closer duration of 100 or 200msec. Another available parameter is the *Click-Holdoff* which offers the choice between a 100 and 200msec delay before allowing another switch closer to be triggered. While some devices may require the 200msec duration to recognize the signal, the subject desired the shortest duration possible to increase system responsiveness. In this case study, all technologies involved could accept the user preferred setting of 100msec for both Relay-On-Time and Click-Holdoff. Especially as the subject's skills advanced, the ability to trigger multiple, rapid switch closures became significantly important for optimum performance.

The D-Box was further enhanced by a *Threshold-Full-Scale* parameter that enables the user to adjust the scale used for the threshold range. This range can be set to a maximum 300mV for persons limited to weaker signal activations, or it can be set to 600mV for those that can trigger stronger signals (it should be noted that the Delsys sensor provides a 1000mV gain to the muscular signal, thus, the actual scale maximums are 300uV and 600uV). Threshold changes are made by turning a small knob on the front panel of the D-Box. A turn of this knob with Threshold-Full-Scale set at 600mV will yield a larger increment then the same turn of the knob with a Threshold-Full-Scale set at 300mV. In this case study, having the Threshold-Full-Scale set to 300mV better facilitated the small incremental adjustments necessary to find the subject's optimum threshold setting.

Additional D-Box parameters are discussed in section 4c as they pertain to dual switch outputs.

4. Multi-Function Technologies

Having placed the EMG electrode and established the optimum signal threshold, focus was directed toward leveraging this single interface to control multiple technologies. In this case study, the single EMG sensor used by the Tinkertron Dual D-Box became an interface to navigate a Permobil C400 power wheelchair, actuate the power features of a Permobil Corpus seating system, and control an HP iPAQ 6925 Smartphone. System configuration and operational techniques are discussed in the following sections. Practical uses of the technologies and examples of increased independence and productivity are discussed in section 5, *Functional Scenarios*.

a) Wheelchair Navigation

In this case study, PG Drives Technology's Omni+ Module was used to interface the Dual D-Box with the Pilot+ Control System of a Permobil C400 power wheelchair. Through the Omni+ Single Switch Scanner mode a user can choose control functions from constantly scanning menu loops. For example, the initial Omni+ display for Single Switch Scanner mode shows a menu that cycles through FORWARD, RIGHT, REVERSE, LEFT, MENU and loops back to FORWARD. Contracting the active muscle beneath the EMG sensor will cause a switch closer that results in the selection of the menu item highlighted at that moment.

The wheelchair can be navigated from the Single Switch Scanner in either *momentary* or *latched* modes. In momentary mode, a switch activation will cause the wheelchair to move in the direction of the menu item highlighted. Maximum speed can be adjusted from the menu options when the wheelchair is stationary. Movement will continue until the switch is opened. With EMG sensor control, the active muscle must remain contracted to sustain movement within momentary mode. When the muscle is relaxed and the signal falls below the pre-set D-Box threshold, the chair will stop.

In latched mode, a short activation while the FORWARD menu item is highlighted will cause the wheelchair to move forward. The wheelchair continues to move forward even after the signal falls below the threshold. Subsequent switch activations with FORWARD highlighted will increase *stepped* speed. The maximum speed is equally divided into 5 steps. The user has the option to send several consecutive switch activations with FORWARD highlighted to increase stepped speed quickly, or FORWARD may be selected again after cycling through the other menu choices. Switch activations with REVERSE highlighted will decrease stepped speed. Likewise, selecting REVERSE while the wheelchair is stationary will cause the wheelchair to move backwards with stepped speeds. LEFT and RIGHT are always treated as momentary. A typical latched mode driving scenario is a culmination of consecutive *muscle contractions* associated with scanner *menu selections* that result in specific *wheelchair movement* (see Table 1, below).

Muscle	Menu	Movement
3 short contractions	FORWARD	Forward at 3rd stepped speed
2 short contractions	LEFT	Veering right correction
1 long contraction	RIGHT	90 deg. right turn on-the-fly
2 short contractions	REVERSE	Reduce forward speed
1 moderate contraction	LEFT	45 deg. Left turn
1 short contraction	REVERSE	Stop

Table 1: *Typical wheelchair driving scenario with EMG sensor*

This scenario begins with 3 short muscle contractions while the FORWARD menu item is highlighted. This causes the wheelchair to move forward, gradually accelerating to its third step which is 60% of its maximum speed. Figure 3, below, shows the Omni+ navigation display with the maximum speed parameter set at 4 and the stepped-speed indicator at the third step. Two short muscle contractions with LEFT highlighted are soon needed to compensate for the wheelchair veering too much to the right. After cruising for a matter of seconds, one long muscle contraction with RIGHT highlighted is performed to cause the chair to make a 90 degree right turn while moving forward. The subject relaxes the muscle contraction at the point that the turn is complete, and the wheelchair continues moving forward. Two short muscle contractions with REVERSE highlighted will reduce forward speed to step 1. A moderately sustained muscle contraction with LEFT highlighted will produce a 45 degree left turn to avoid an obstacle in the driving path. Finally, one short muscle contraction with REVERSE highlighted will bring the wheelchair to a stop.

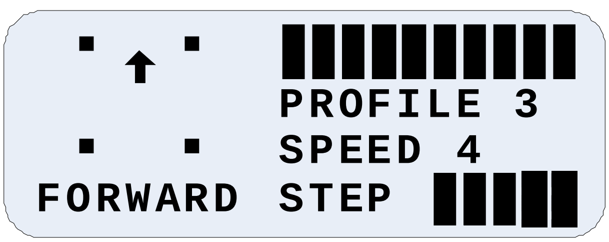

Fig. 3: *Omni+ Single Switch Scanner Display*

Those capable of using a joystick enjoy the advantage of having fluid access to acceleration, deceleration and turning. Scanning navigation is quite the opposite. However, significant ease of use, precision driving capabilities, and high speed control was demonstrated within multiple environments by exploiting the customizable Omni+ configuration settings and drive profiles. The scan rate can be adjusted within a range of 0.25sec to 4.75sec. In this case study, an initial rate was set at 0.75sec. Thus, each menu item changed every 0.75 seconds. This scanning rate was increased to 0.50sec after two days of practice. After four weeks, the rate was increased to the maximum of 0.25sec. After several months of continuous use, menu selection became quite intuitive to the subject and a faster rate seemed desirable. As the scanning rate increased, the subject was able to drive the wheelchair at faster speeds safely and with precision. Even with a scan rate of 0.25sec, a user may wait a full second before the desired menu item is highlighted. This is a significant delay when driving at higher speeds, thus, minimizing this wait time was of utmost importance.

Another important configuration setting is the *Switch-Long.* This option sets the minimum time the switch can be open before the Omni+ goes into sleep mode. In practice, this parameter determines how long a muscle contraction can be sustained before the Omni+ sleep mode terminates wheelchair movement. In this case study, Switch-Long was placed at its maximum setting of 2.5sec to enable the subject to make 90 degree turns while moving forward. Placing this parameter at its minimum setting of 0.50sec would cause the system to time-out before the turn was complete. This option is only relevant to latched navigation and does not limit switch activations relevant to momentary control.

The Omni+ system also offers user-defined drive profiles which are sets of parameters that can be tailored to accommodate various environments. Three types of drive profiles gradually emerged from the subject's routine navigational situations. These are titled *Cruise, Proximity* and *Crawl* and are defined by their parameter settings in Table 2 below.

Profile	**#1**	**#2**	**#3**	**#4**	**#5**
Title	*Cruise*	*Proximity*	*Cruise*	*Crawl*	*Crawl*
Mode	*Latched F*	*Momentary*	*Latched F/R*	*Momentary*	*Latched F/R*
Acceleration	10	10	10	10	10
Deceleration	20	60	20	60	20
Fwd. Speed Max.	90	40	90	25	25
Fwd. Speed Min.	38	10	38	25	25
Rev. Speed Max.	50	40	50	25	25
Rev. Speed Min.	25	10	25	25	25
Turn Acceleration	20	20	20	20	20
Turn Deceleration	20	60	20	60	20
Turn Speed Max.	20	30	20	30	20
Turn Speed Min.	5	10	5	10	5

Table 2: *Customized Omni+ drive profiles for single EMG sensor navigation.*

Cruise (#3) is the primary profile used for traveling distances indoors or outdoors. This profile offers stepped latched control for both forward and reverse. A second profile (#1) was made as a slight variation of the Cruise profile offering stepped latched control for forward and momentary control when moving in reverse. This offered some advantages when navigating the wheelchair backwards into tightly defined spaces. The Proximity profile (#2) offers momentary control in all directions. Short muscle twitches move the wheelchair inch by inch in the chosen direction. Sustained muscle activations will cause slow speed acceleration, but movement will sharply stop when the muscle is relaxed. The Crawl profile (#5) has significantly dampened speed to allow precision navigation. In our case study, this profile was designed to give the subject the precision driving capability to independently negotiate his van's wheelchair lift and tie-down system (see section 5a for detailed description). A second version of this profile (#4) offers the same dampened speed with momentary control. Thus, the three essential types make up five functionally defined drive profiles that were customized to the subject's driving needs within various situations and environments. Their numbered ordering was determined by frequency of use and efficiency in changing from one to another (e.g. changing from Cruise to Crawl before van entry).

The importance of a *cutoff* switch accessible to the user cannot be overstated. Activating the cutoff switch (sometimes called a “kill switch”) will kill the power to the Omni+ and bring the wheelchair to an immediate stop. A second activation of the same switch will restore power with the Omni+ displaying its initial drive menu. Beyond the obvious safety hazards, engaging the system without a user accessible cutoff switch requires the user to exercise extreme anticipation with regard to path and obstacles. In this case study, a Tash Microlite switch was used with the subject’s right thumb. The thumb muscle could not support the numerous activations necessary for wheelchair navigation but was quite suitable for occasionally pressing the cutoff. A future option will be to use a secondary EMG switch for a cutoff at a site independent of the muscle being used to trigger menu selections. With the Tash Microlite switch in place, the subject drove more naturally and aggressively (i.e. at higher speeds) without fear of losing control. This was especially important during the early stages of adjusting to single switch scanning control.

Based on her single switch driver performance research, Yanco plainly states, “Single switch scanning is the access method of last resort for powered wheelchairs, primarily because drift is a significant problem.” (Yanco, 1998) “Drift” refers to the inevitable veering of the wheelchair to the left or right due to uneven terrain and performance variance between the two drive motors. A single switch user has to monitor the menu display and select RIGHT or LEFT to compensate for drift. However, recent advances in power wheelchair technology give cause to reevaluate Yanco’s conclusions. Permobil offers what they call ESP (Enhanced Steering Performance) technology on most of their Front Wheel Drive (FWD) chairs that monitors the actual direction of travel. This component is able to compare “intended” directional signals provided by the user with real time directional data and make automatic course corrections that are transparent to the user. With the ESP technology, the wheelchair can automatically maintain a straight course of travel on most any terrain (e.g. side slopes, loose gravel, etc.). Thus, a single switch user can travel over long distances without having to make the constant course corrections.

Initial trials of the EMG sensor control were conducted without an ESP module. FWD chairs unintentionally turn “uphill” on side slopes making course correction difficult and requiring long signal durations to compensate. In such instances, the signal duration required could easily exceed the Switch-Long parameter setting and (to the user’s consternation) unintentionally stops the wheelchair. Changing to an ESP equipped chair significantly improved the subject’s navigational experience (see section 5a). In addition to preventing the chair from turning “uphill” on side slopes, the ESP module also counteracted “fishtailing” when navigating steep downgrades.

b) **Seat Actuators**

In addition to wheelchair navigation, power seating features are controlled through the Omni+ scanning menus. In this case study, a Permobil Corpus seating system equipped with actuators to control *tilt-in-space, backrest recline, footrests elevation, headrest angle,* and *seat elevator* was manipulated via the same EMG sensor. When ACTUATORS is selected from the MODES sub-menu, the user can select any one of the five seating features. For

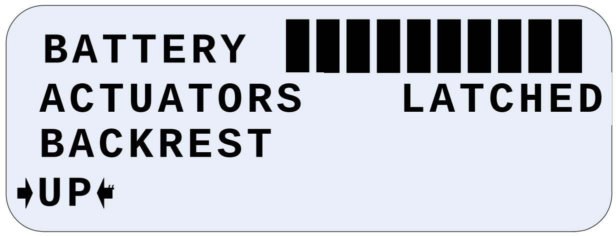

Fig. 4: *Omni+ Seating Actuator Control*

example, choosing BACKREST will display a sub-menu which cycles through UP, DOWN, and EXIT. Choosing DOWN will cause the backrest to recline backwards. Choosing UP will cause the backrest to move upright (see Fig. 4, left). Choosing EXIT will exit the sub-menu and return to the menu of actuator choices. Seating actuators may be controlled in either momentary or latched modes. Momentary control requires a sustained switch activation to change seating positions. For example, executing a sustained switch activation when DOWN is displayed from the HEADREST sub-menu will cause the headrest to move in a tipping motion at the neck. Actuator movement will continue until the switch returns to an open state (e.g. the EMG signal falls below the activation threshold). Latched control requires a switch activation to begin movement and a second activation to stop. For example, selecting UP from the SEAT sub-menu will cause the seat elevator to begin rising. Menu cycling is frozen until the system receives another switch activation which stops actuator movement.

In this case study, momentary actuator control was initially chosen because it gave the subject a greater sense of control. The subject's active muscle was capable of delivering prolonged switch activations. However, muscle strain was observed when sustaining an activation long enough to raise the seat elevator from its extreme positions, an action requiring over 15 seconds. Within two weeks the subject's comfort with the system reached a level where latched actuator control was preferred over momentary. Actuator limit sensors were adjusted to ensure a safe and comfortable range of movement among all the seating actuators. Furthermore, the Omni+ cutoff switch will stop actuator movement when needed.

c) **Smartphone**

In addition to controlling wheelchair navigation and power seating actuators, the same EMG sensor was used to access all features of an HP iPAQ 6925 Smartphone. Control of this device was completely independent of the Omni+ system. To leverage user capabilities, the first generation Tinkertron D-Box was enhanced to include dual switch outputs. *SINGLE* or *DUAL* switch output mode and switch *Rollover-Time* are designated via miniature programming switches internal to the D-Box. In this case study, the D-Box was used in *DUAL* switch output mode with a *Rollover-Time* of 4 seconds. This means that a switch activation sustained for 4 seconds will cause the currently inactive switch output to become active. The *Rollover-Time* must be set long enough so as not to engage a rollover during sustained switch activations associated with wheelchair navigation. Furthermore, using *DUAL* switch output mode may conflict with momentary control of seat actuators. For example, moving the seat elevator from its extreme positions using momentary control would cause the D-Box to rollover to the alternate switch before the seating function was completed. This resulted as a non-issue when latched control became the subject's preference for controlling seat actuators. Momentary mode navigation seldom involved sustained activations longer than 4 seconds.

Fig. 5: *iPAQ & RS232 Cable*

The D-Box's second 3.5mm switch output jack interfaced with the mobile device through an adapter cable which attaches to the iPAQ's RS232 serial port (see Fig. 5, left). Each switch closure is recognized by a mobile device application called nohandcom. This software, developed in Switzerland, offers numerous options for single switch control of devices running Windows Mobile operating system. Nohandcom's most proficient method of control is through its "crosshairs" mode where the user can virtually "tap" any position on the device screen via three switch activations. The red crosshairs symbol in the bottom-right portion of Figure 6a, above, indicates that nohandcom is in locked crosshairs mode. The first switch activation causes a horizontal bar running the width of the display to pan downward from top to bottom (also shown in Fig. 6a). A second switch activation will cause the horizontal bar to hold its position, and a vertical bar running the height of the display begins to pan from left to right (see Figure 6b). The third switch activation will cause the vertical bar to hold its position, and a "tap" is issued where the two lines intersect. Thus, in Figure 6c, the third activation engaged the Wi-Fi icon.

Fig. 6a: *horizontal bar panning*

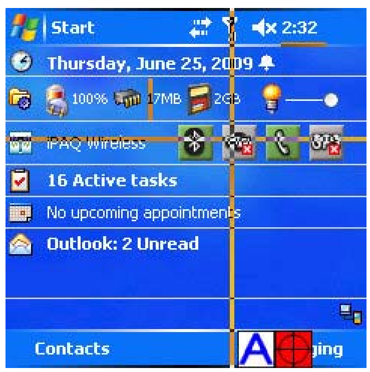

Fig. 6b: *vertical bar panning*

Fig. 6c: *IPAQ with Wi-Fi active*

Nohandcom has a Crosshairs Writing mode that reduces the scanning field to the size of the onscreen keyboard. Typing can then be performed within any device application by selecting alphanumeric targets. Figure 7a, below, shows the character "m" being selected as the subject typed the word "swimmer." Figure 7b shows the subject selecting "swimmer" from the device's predictive word completion. Figure 7c shows the completed writing sample (132 characters, including spaces) which took 6 minutes and 37 seconds for the subject to complete, yielding a 20 character-per-minute typing rate.

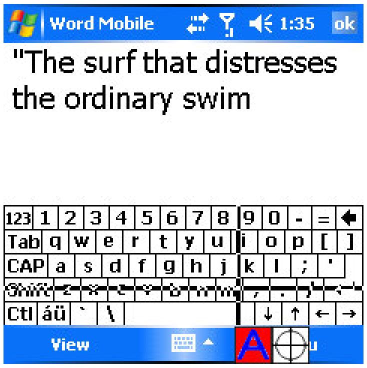

Fig. 7a: *alphanumeric selection*

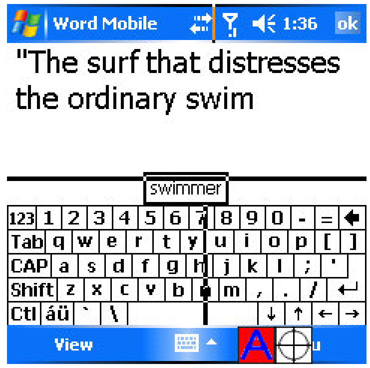

Fig. 7b: *predictive word completion*

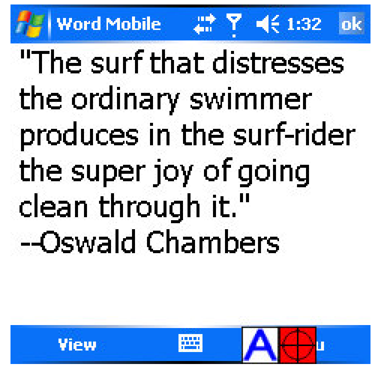

Fig. 7c: *132 character writing sample*

The requirement of three switch activations for a single alphanumeric character or device action underscores the importance of finding the optimum EMG signal threshold. Consistent with wheelchair navigation performance, the lowest signal threshold possible while still avoiding false triggers is desired. This allows the user to execute numerous switch triggers with negligible fatigue. The D-Box *Relay-On-Time* and the *Click-Holdoff* parameters were both set to 100msec to provide maximum responsiveness when needing to execute rapid switch activations. For example, in the nohandcom crosshairs mode, three rapid switch activations in sequence will drop down the Windows Mobile Start menu located in the upper-left corner of the display (see Figure 8, below). Other nohandcom input options are available with scanned icons that appear on the lower border of the screen (see Figures 9a and 9b, below). These modes enable the user to execute direct mouse movements, issue context clicks, and perform specific device functions (i.e. answering incoming call). EMG control of specific iPAQ features and Windows Mobile applications is discussed in section 5c.

Fig. 8: *Start menu drop-down*

Fig. 9a: *Mouse Mode icons*

Fig. 9b: *Actions Mode icons*

Fig. 10: *iPAQ & Kydex Mount*

In this case study, a Kydex plate was fabricated to mount the iPAQ adjacent to the Omni+ display (see Fig. 10, below). The Kydex plate was attached to the Omni+ display using industrial Velcro, and the iPAQ in similar fashion is held to the plate with standard Velcro. The standard Velcro can easily support the 6oz device while allowing for easy removal of the device from the Kydex plate. In conjunction with the switch interface, the adapter cable was spliced and modified to accept the iPAQ car charger allowing for a continuous power supply from the wheelchair batteries. The charger/wheelchair interface was accommodated through a PowerStream 10A 24V to 12V DC/DC converter.

5. Functional Scenarios

Technical aspects of implementing the single EMG sensor interface to the multiple technologies used in this case study has thus far been described. How these technologies increased the subject's independence and productivity is addressed in the sections that follow. Focused efforts were made to investigate pragmatic applications to enhance mobility, communication and job performance. Techniques to improve ease-of-use and efficiency were developed and documented throughout the case study.

a) Wheelchair Navigation

In this case study, D-Box and Omni+ parameter settings were optimized to mimic, as much as possible, the fluid control of proportional navigation. The EMG signal threshold was lowered to trigger a switch activation with the slightest muscle impulse while still avoiding false triggers (see section 3). The menu scan rate was increased over a four week period to the highest level commodious to the user. Thus, the lowest effective signal threshold combined with the maximum scan rate offered the optimum system responsiveness for fluid-like navigation.

Table 3: *Navigational Skill Development*

Time (days)	Milestone
1	Scan Slow
1	Stop to Turn
7	Scan Medium
7	Fluid Turn
14	Precision
21	No Stop Entry
28	Scan Fast
56	Intuitive

The subject's navigational skills and commensurate scan rate steadily increased over a period of four weeks (see Table 3, left). Introduction to the system began with familiarization of the Omni+ menu trees. Initially, there was a significant cognitive load requiring the subject to simultaneously focus attention on the menus and on the path being traversed. By the end of the first day he was able to negotiate basic navigation at a scan rate of 0.75sec ("basic navigation" being defined in this case study as navigation requiring the user to come to a full stop when making turns). Within one week, the subject was comfortable with increasing the scan rate to 0.50sec and was able to make fluid, 90-degree turns without stopping. By the end of the first month the subject was comfortably using the maximum scan rate of 0.25sec, could perform no-stop doorway entries, and demonstrated precision navigation skills utilizing all five Omni+ drive profiles (see Table 2, section 4a).

As the subject's skill level increased, menu selections became a quasi unconscious cognitive process. Quick glances at the menu display replaced the subject's initial need to track the menu cycle. Sustained switch activations for turning and veering correction became intuitive. Cognitive and muscular fatigue associated with using the system steadily diminished, becoming insignificant even after extended periods of navigation. Introduction of the Permobil ESP module (see section 4a) significantly curtailed muscular fatigue by reducing navigational switch activations by an estimated 50% of that without automatic veering correction. This was best observed by the subject's experience attempting to navigate the Kansas City zoo prior to the ESP module's integration into the system. Side-sloped terrain throughout the walking trail required the subject to make continuous course corrections leading to unacceptable muscle fatigue. The gradient often required compensatory switch activations that exceeded the *Long-Stop* parameter setting (see section 4a). This caused the wheelchair to unintentionally stop which further exacerbated his difficulty traversing alongside his comrades. This event is in stark contrast to the subject's experience traversing the St. Louis zoo a year later with an ESP equipped Permobil wheelchair. While both zoos share very similar topography, the ESP module allowed the subject to enjoy unfettered navigation over the most severe gradients. No fatigue was experienced throughout the entire day of navigation. The subject observed his ability to remove his focus from the menus and visually appreciate his surroundings while navigating; similar to prior times using joystick control. As the day wore on, his comrades had difficulty keeping up with him (this included his 10-year-old son).

Fluid-like navigation was best realized by the subject's "door trick" scenario. This sequence involved navigating house porch, reducing speed on approach to the front door, pushing the unlatched exterior door open, no-stop doorway entry, making a 180-degree pivot, pushing the exterior door closed, bringing the chair to a stop when the door becomes latched, making another 180-degree turn and preceding onward. While this scenario did require an environment with significant open space, it clearly demonstrated the performance potential of single EMG sensor navigation.
(See video at http://www.youtube.com/watch?v=9DPiTdm2k1U)

Precision navigation was demonstrated by the subject's ability to independently navigate onto his wheelchair lift platform, make van entry through a narrow doorframe, pivot within a small area within the van, and maneuver the wheelchair into an EZ-lock tie-down system The Crawl and Proximity drive profiles were tailored to streamline this scenario. The full speed range of the latched Crawl profile is utilized while gaining entry and making the initial interior pivot. The momentary Proximity drive profile is then used to approach and engage the tie-down lock. Interaction between the wheelchair's rear wheel casters and ridges in the van floor posed a significant navigational obstacle. This issue was resolved by increasing the turning speed on the Proximity drive profile to add sufficient "bite" to the wheelchair's turning ability. Without this modification, maneuverability within the van was extremely difficult. It should be noted that the cutoff switch played a significant role by allowing the subject to stop precisely where the interior pivot needs to take place.
(See video at http://www.youtube.com/watch?v=qKQ9QYhBcN4)

b) **Seat Actuators**

A unique benefit of the EMG sensor control is that all seating and positioning considerations can focus on stability and comfort. Such considerations are typically constrained by the need to maintain access to the drive mechanism. With the EMG electrode stuck to the surface of the skin, the user enjoys nearly full freedom of movement while maintaining access to the system interface. Thus, shearing or shifting from using seat actuators and/or driving over rough terrain did not pose threats to the subject's ability to control navigation.

In this case study, the subject could move the full range of all seating actuators and independently return to a driving position. For example, the subject could easily recline the backrest and elevate footrests to position himself in a completely horizontal position (see Fig. 11, below). The subject could then independently return to an upright position and begin navigating the wheelchair. The subject's ability to independently change seating positions and regain maneuverability was a newfound level of independence.

Fig. 11: *Seating System Fully Reclined*

The combined navigation and positioning capabilities offered the subject robotic-like functionality. This was first realized by the subject's ability to activate a microphone on/off switch mounted underneath his computer desk. The subject could use the Proximity drive profile (see Table 2, section 4a) to position the wheelchair footrests underneath a switch plate and then elevate the footrests until his foot depressed the switch. This scenario enabled him to independently reset or turn on/off the microphone associated with his speech recognition.

(See video at http://www.youtube.com/watch?v=edoUTNTtskA)

Another robotic-like function was demonstrated by the subject being able to move the tilt-in-space actuator so as to position his footsteps low enough to the ground to allow his two-year-old grandson to step aboard. He then could engage the tilt-in-space to elevate the footrest, thus moving the child's weight safely against his legs and proceeded to navigate slowly across a room or yard. This scenario closely mimicked the ability to pick up and carry his grandson. *(See video at http://www.youtube.com/watch?v=fF_zoSf366Q)*

The subject's ability to control the headrest, backrest, tilt-in-space and footrests actuators dramatically reduced risks of pressure sores, and decreased dependence on caregivers for periodic repositioning. Having the ability to independently shift to a supine position significantly reduced anxieties related to his atypical dysreflexic blood pressure condition. The subject also performed range of motion exercises with the footrests actuator to reduce aching and spasticity in his legs. In addition to the freedom of navigational mobility, the ability to change positions and shift weight according to the subject's own timing and discretion significantly increased overall self efficacy. These observations were consistent with Buning's findings which suggest that the use of powered mobility devices enhance occupational performance, competence, adaptability and self-esteem for persons with severe mobility impairments (Buning, 2001).

c) **Smartphone**

An HP iPAQ 6925 was chosen for this case study because it was one of the most feature rich Smartphones on the market, and it offered a RS232 serial port to interface with the D-Box switch output. While the iPAQ does offer Wi-Fi capabilities, the cellular plan used in this case study offered unlimited data so as to support efforts to exploit all potential uses of the phone such as text messaging, Internet browsing and GPS use.

Significant advantages were quickly seen with having the iPAQ mounted within the user's constant vision (i.e. adjacent to the Omni+ display). While most users rely on ringtones and other (sometimes disruptive) auditory cues, the subject found it advantageous to rely mostly on visual feedback from the device. The visual cueing combined with the virtually transparent EMG interface resulted in a very subtle tool for communication and information access. For example, the subject could send and receive text messages while in a small group meeting without anyone's awareness. Similarly, the subject had anytime/anyplace access to his digital library, personal contacts and Google searches. This enabled the user to actually multi-task in similar fashion to non-disabled peers. The subject routinely used travel time in his van to review email, concurrently carry on a text messaging conversation, as well as give positive verbal cues to his wife's conversation (received skeptically).

A substantial advantage the subject enjoyed over the average Smartphone user was the benefit of having a continuous power source from the wheelchair (see section 4c). Conserving battery power is a serious concern for most Smartphone users and many features and techniques exist to trade functionality for longer battery life. Some of these include: standby sleep mode, decrease screen brightness, turn off Bluetooth and Wi-Fi when not in use, and plug device into external power whenever possible. These tradeoffs became a non-issue for the subject. The power pulled for the Smartphone was inconsequential to the 24V power supplied by the wheelchair's batteries. Thus, the subject enjoyed full screen brightness and continuous use of any and all features without constraints.

ActiveSync via Bluetooth was a key feature contributing to the subject's ability to independently use the device to its fullest. ActiveSync is a Microsoft program that synchronizes data and performs file transfers between a desktop computer and a mobile device. Bluetooth is a wireless protocol facilitating data transmission. Using ActiveSync via Bluetooth circumvented the need to physically place the device into a docking cradle that connects to the desktop via USB. Thus, the subject could utilize his desktop to compose narrative, perform extensive Internet searches, build his electronic library, and then independently transfer the information to his Smartphone. Considering that data entry for EMG sensor control is approximately 20 characters per minute (see section 4c), it was important to leverage the advantages of desktop synchronization. The subject quickly learned to make abbreviated Calendar, Contacts and Tasks entries on the device. These entries could then be synchronized with Microsoft Outlook on the desktop, expanded with complete information and desired annotations, and synchronized again to update the device. This quickly resulted in a useful store of data accessible from the device and backed up on the desktop computer.

In this case study, focus was placed on finding ways to use the device to promote independence, communication and productivity. Specific functional scenarios supporting these goals are discussed below.

i. **Phone**

Fig. 12: *Phone with Speaker*

Fig. 13: *Phone Contacts*

Using nohandcom in crosshairs mode, the subject could easily choose from his Contacts list and place calls independently using the iPAQ's speaker phone capabilities. Likewise, answering incoming calls and activating the speaker can be performed quickly enough to receive incoming calls in a normal fashion. A Jawbone Bluetooth headset allowed the subject to control call connections from the phone without requiring him to press any headset buttons. The Jawbone headset improved clarity and provided privacy for most phone usage, while the speaker capability ensured access to the phone at all times. The subject also enjoyed using the call-in feature to listen to news stories from National Public Radio's mobile website. A summary of stories can be reviewed from the iPAQ's Internet browser at http://m.wunc.npr.org/. The call-in feature provided instant audio of the stories without any download delays associated with streaming audio.

ii. **Text Messaging**

Fig. 14: *Typing Text Msg.*

Due to diminished pulmonary function, the phone was not the subject's preferred means of communication. Text messaging was found to be quite advantageous in both home and work environments. This medium offered him a quick, convenient means to make progress checks with colleagues, give direction to employees, and even send an occasional warm fuzzy to his wife. The subject's condition also required approximately two mid-day hours to be spent on a non-invasive ventilatory machine. During this time he is unable to speak and was thus rendered unproductive because of his reliance on speech recognition. Access to the iPAQ significantly changed this, allowing the subject to check email, read journal articles, browse the Internet, etc. without the use of speech. Text messaging became his sole means of communication when the subject was receiving ventilatory support.

iii. **Outlook Mobile**

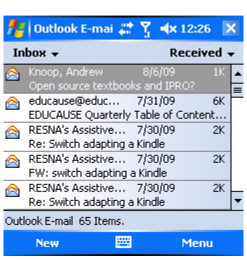

Fig. 15: *Outlook Inbox*

Outlook Mobile was used to synchronize, review and respond to email. The subject primarily used this to review email during otherwise unproductive time away from his desktop workstation, saving emails within the Inbox that required lengthy responses that would be more conducive to speech recognition. Because of the subject's need for an adapted workstation, he could not access email via any available workstation at various work sites. Having email access always available via the iPAQ enabled the subject to give and receive timely communication. For example, when on campus he could receive emails with meeting time changes and/or agenda updates.

The subject also benefited from Outlook Mobile access during several extended hospital stays. In addition to staying up-to-date on work assignments, he utilized email to communicate with physicians, healthcare providers and insurance case managers. The ease of use and constant availability of this mode of communication significantly increased his participation and self-determination in his healthcare. For example, the subject emailed questions to his pulmonary specialist in the evenings and would have a response to share with other attending physicians during rounds the next day.

iv. **Mobipocket Reader**

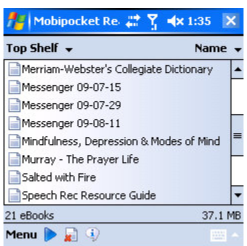

Fig. 16: *Mobipocket Library*

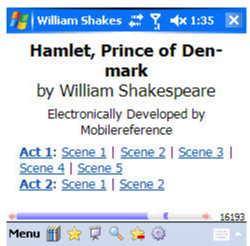

Fig. 17: *Mobipocket eBooks*

Mobipocket Reader was used to organize, read and annotate electronic books and documents. The subject could easily download eBooks, journal articles and other text files from his desktop workstation, systematically convert them into Mobipocket format, and synchronize with the Mobipocket device reader. Various techniques were identified to minimize switch activations for repeated processes. For example, Mobipocket will assign a default bookmark name according to the first three words of the top line displayed. Thus, the subject quickly learned to use the automatic scroll to position text headers at the top of the display before setting a bookmark. This gave the bookmark a meaningful name without requiring any alphanumeric data entry. Furthermore, Mobipocket's user-defined library categories, "Find in text" feature, embedded dictionary, and customizable toolbars saved much time and many switch activations when reviewing large documents.

The iPAQ supported a virtually limitless text library on a 2 gigabyte mini SD card. This enabled the subject to build a personal digital library that provided reading and reference materials for both business and personal use. As a result of a cooperative agreement between the subject and his church publisher, periodicals, books and other denominational publications were provided via email in a format easily converted to Mobipocket. This digital library quickly grew into a valuable resource which permitted the subject a first-time experience to independently browse reading material during a meeting, in a waiting room or when traveling in a vehicle. The level of independence achieved was noted by the subject's ability to easily engage in or disengage from the activity at will without assistance.

v. Word Mobile

Fig. 18: *Word Outline*

While alphanumeric character input is easily accomplished through the nohandcom software, it was clearly recognized in this case study as an inefficient method of data entry (see section 4c for typing speed discussion). Chief advantages of Word Mobile were seen in the subject's ability to take brief notes during business meetings, construct outlines, and exchange documents with colleagues via Bluetooth. The subject found it beneficial to transfer meeting agendas to his device and add short phrases and/or action items to the document during and following business meetings. The same document could later be transferred to his adaptive desktop workstation and thoughts expanded using voice recognition. The subject also enjoyed the ability to construct document outlines during windows of opportunity when away from his adapted desktop workstation.

vi. Excel Mobile

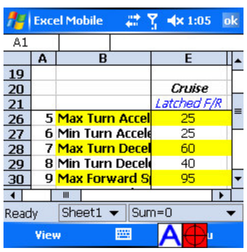

Fig. 19: *Excel Spreadsheet*

Mobile access to Excel spreadsheets allowed the subject quick and easy access to files used for tracking data. For example, he could review or modify equipment inventories on-site, or make changes to budget items during group meetings. While these are typical uses of pocket PCs and notebook computers, the subject's ability to participate in social interactions while having easy access to the technology proved quite propitious. The ability to transfer Excel documents from the iPAQ to another device or desktop computer via Bluetooth was another convenience that supported his productivity.

vii. Internet Explorer

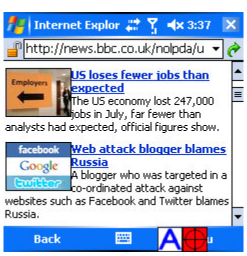

Fig. 20: *Browsing BBC News*

Fig. 21: *Google Search*

Fig. 22: *Reading Web Article*

The iPAQ has a 75mm square display making serious Internet browsing less than ideal. The subject found it most useful for quick informational Google searches, Google book search and reading, reading news and monitoring weather. A common scenario might find him googling the search term "healthcare robotics" to help guide a brainstorming session on robotics research. Having ready access to such ubiquitous technology significantly increased the subject's participation and effectiveness in such meetings. His transparent use of the device with the EMG sensor also made it shamefully useful to come up with answers to most any trivia question.

viii. Calendar

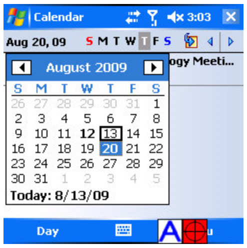

Fig. 23: *Month Display*

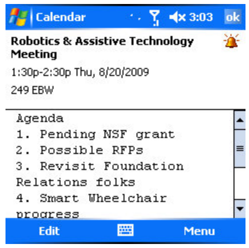

Fig. 24: *Appt. Display*

Adding calendar appointments and setting reminder parameters was easily achieved through alphanumeric data entry with nohandcom. In this case study, the Calendar feature was synchronized with the subject's desktop Outlook client. This allowed him to use speech recognition to enter agenda items and notes related to specific meetings. He could then review and add comments to appointment notes as needed during and following such meetings.

ix. Tasks

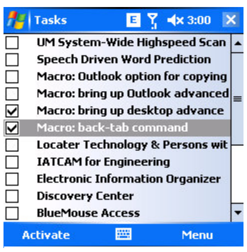

Fig. 25: *Tasks List*

Alphanumeric data entry with nohandcom was reasonable for creating task items and setting reminder parameters. The subject found it beneficial to create a subset of repeated tasks that could easily be changed between active and inactive status. Similar to the Calendar feature, the subject leveraged his speech recognition system to create task templates and expand narrative as needed.

x. GPS

Fig. 26: *GPS & Google Maps*

Fig. 27: *Favorite Locations*

The iPAQ's integrated GPS receiver offered the subject access to real-time navigational assistance via Google Maps. This was especially useful during out-of-state business trips. For example, prior to leaving, the subject added addresses corresponding to his planned itinerary into Outlook Contacts using his desktop speech recognition. Once these contacts were synchronized with the mobile device, they could easily be added to Google Maps' list of favorite destinations. During the trip he could easily select from the favorites list and provide navigational assistance to his driver. Google search results from the device could also yield driving directions for unplanned destinations requiring minimal switch activations. The subject also found Google Maps satellite view feature beneficial when at crowded outdoor events. Such situations can be difficult for persons at wheelchair eye level. The satellite view was able to zoom-in close enough to enable the subject to orient himself to the infrastructure of the grounds.

xi. Camera

Fig. 28: *Photos Taken from IPAQ Camera Via EMG Sensor Control*

The iPAQ Smartphone has a built-in 1.3 MP camera capable of capturing photos and moving video. A slot was cut into the Kydex mounting plate to allow for the camera lens. The subject could aim the camera as desired by pivoting the wheelchair and using the seat elevator and tilt-in-space features. This process clearly demonstrated the benefits of the combined functionality of the technologies being controlled via the single EMG sensor. For example, at a business conference the subject volunteered to take the pictures of the exhibit booth and send them to the department's public relations unit. Table 4 below shows each sub-task performed and the corresponding technology employed.

Table 4: *Single EMG Sensor Photography*

Sub-Task	Technology Employed
Point camera	Wheelchair navigation
	Tilt-in-space seat actuator
	Seat elevator
Capture photos	PhotoSmart Camera
Review photos	PhotoSmart Mobile
Send photos	Outlook Mobile

The subject navigated the wheelchair to several different positions. At each position he would pivot the wheelchair to bring the photo target horizontally into the camera's visibility. The subject then used the seat elevator and tilt-in-space actuator to bring the photo target vertically into range. The PhotoSmart Camera software enabled him to zoom-in for photographing portions of the equipment displays and zoom-out for capturing broader views of the booth. PhotoSmart Mobile software allowed the subject to review the photographs from the device and choose a subset of preferred photos. These photos, along with a brief message, were then sent to colleagues via Outlook Mobile.

xii. Pocket E-Sword

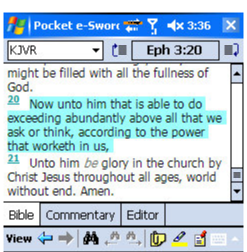

Fig. 29: *Bible Resource*

Pocket E-Sword is a device application that the subject used to access multiple Bible translations and commentaries. Pocket E-Sword combined with his Mobipocket digital library, enabled the user to independently reference and annotate text information within group settings. The subject went from having someone sit beside him to turn the page of his Bible or Sunday School quarterly during church services to having independent access to a 2 gigabyte digital library at the twitch of his pectoralis muscle. In many respects the subject gained an advantage over his peers because of the ready access he had to a large data store with text searching capability for information retrieval.

xiii. Calculator

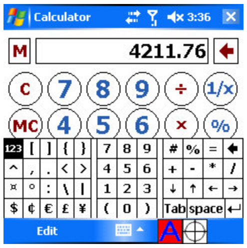

Fig. 30: *Calculator & Keypad*

The calculator was not heavily utilized, but was beneficial by merit of its ready availability to the subject. For example, without any foreknowledge or setup, the subject could compare volume pricing on products while in the shopping isle. Using the onscreen numeric keypad for input was far more efficient than panning the entire screen with the crosshairs to target calculator icon keys.

xiv. Games

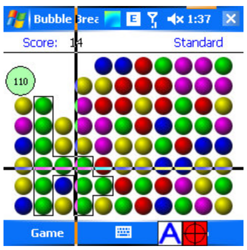

Fig. 31: *Bubble Breaker*

Fig. 32: *Chess Mobile*

The comprehensiveness of nohandcom to access mobile device features was seen in the subject's ability to play games such as Chess, Sudoku and Bubble Breaker. For example, the game Chess Mobile would not allow a user to move pieces by simply tapping locations on the board. The subject was able to use the Actions menu (see section 4c) to control directional movement of the chess pieces. The built-in Solitaire game proved to be a formidable test to nohandcom's input options because the mouse control lacks the ability to "drag" an icon. This feature is planned to be incorporated in nohandcom's next update (personal communication, April 27, 2008). Such capability would clearly enhance nohandcom's overall utility. For example, selecting text within device applications is somewhat tedious and currently requires the use of onscreen keyboard shortcuts.

xv. ActiveSync Remote Display

Fig. 33: *PC Control of Device*

ActiveSync Remote Display is part of Microsoft's Windows Mobile Developer Power Toys collection of utilities. This utility displays Pocket PC applications on a desktop or laptop computer. It also allows a mobile device to be controlled from a PC mouse and keyboard. Thus, the subject was able to further leverage desktop assistive technology to provide expedient data entry. For example, setup and customization of the mobile operating system and specific applications was accomplished with ActiveSync Remote Display active. This allowed him to independently enter all data using speech recognition without being constrained by the slow typing rate with nohandcom. This also offers an alternative to synchronizing Contacts with an Outlook desktop client. With Remote Display active, the subject could enter contact, calendar and task information via speech recognition directly to the device applications. This combined control also supported the subject's initial learning curve with mobile technology. He could use desktop keyboard/mouse control to browse device applications and read help files which significantly accelerated adoption of new applications. A secondary benefit of Remote Display was facilitating demonstrations of the EMG controlled iPAQ. The remote display window on the desktop correspondingly changes with the menus, messages, and backgrounds of the mobile device. Nohandcom crosshairs panning was likewise displayed on the desktop screen with only a slight time delay.

6. Discussion

The physical demands of using single EMG control were inconsequential from the onset. Cognitive load and skills development were focal points of this study. As described in section 5a, cognitive load decreased and navigational skills increased steadily over the first eight weeks of using the system. Cognitive load was further relieved by the addition of the Permobil ESP module. This technology significantly improved the subject's navigating experience by no longer requiring constant visual focus on the menus. A Permobil Head/Tail/Signal Light Package was also controlled by the subject through the Omni+ system. This provided further independent maneuverability of indoor and outdoor environments.

Variations of the methods used during this case study could offer support for the varying needs of single EMG users. For example, users that fear unexpected propulsion from unintentional muscle movement can create profiles that yield limited wheelchair movement. A pre-defined profile could easily restrict navigation to simply pivoting the chair. A profile could also be reserved for seating actuator movement only. Thus, someone that does not feel ready for independent EMG navigation can still control seating features and even pivot the wheelchair without placing themselves outside their comfort zone. The Omni+ has further capacity to support an Alternate Communications Module (ACM) which gives menu control of eight additional switches. While this was not investigated as part of the case study, its potential as a ready interface for wireless environmental controls is noteworthy. PG Technologies' next generation controller is the R-net. While this controller is currently available for most drive systems, its single-switch control capabilities are still under development. Among its expanded capabilities, the R-net controller will offer customizable menu text, programmable speed and limits for seating actuators, and Bluetooth mouse emulation for desktop computing.

Utility of the Smartphone increased as the subject's knowledge of mobile applications increased. Several potentially useful applications that are yet to be explored include:

i) Using the device camera with Microsoft Tag to access mobile content from print advertising, product packages, and billboards;
ii) Using PowerPoint Mobile to control a projected desktop presentation via Bluetooth;
iii) Expanding the digital library to include video lectures accessed through Windows Mobile Media Player

Two obstacles currently exist for making single-switch Smartphone access available on a larger scale. Chief among these is fabricating the adapter cable which interfaces a switch with the RS232 port of the mobile device. The formidable part of this issue is the dwindling number of Smartphones supporting RS232 serial communication. The industry standard has moved almost exclusively to mini USB making the device interface unable to detect switch activations. A potential upcoming alternative is USB OTG (On-The-Go) which would allow a serial converter to interface with the USB port. However, few devices seem to have USB OTG and device manufacturers show no signs of making any commitment to this standard. All other alternatives would involve significant software modifications and/or developing an USB Host enabled switch. While the nohandcom software does support Bluetooth switch activation, field tests during this case study were unfavorable. Reliability in maintaining the Bluetooth connection was lacking, and the slight delay between switch activation and device response was quite undesirable to the subject. A lesser but significant issue with regard to nohandcom implementation is the availability of the nohandcom device software within the United States. The Switzerland-based developer is currently transitioning support of nohandcom to an assistive technology foundation that promises to expand global availability. Fabricating adapter cables can likely become part of the support of any US distributor, and future software revisions will have to address switch interface options.

7. Conclusions

Can single EMG users navigate safely and independently? How does single EMG control compare to proportional control? Does it offer the precision driving capabilities required for indoor environments? Does it allow the user to negotiate the varied topography of outdoor environments? Are there navigational situations that arise which dictate the use of attendant control? Is the user's mobility restricted due to the physical and/or cognitive demands of using the system? Does the user have to weigh his desire to mobilize against his apprehension of using the system? These are all worthy questions to be considered when evaluating the overall efficacy of single EMG control.

Several performance capabilities were observed during the first 12 months of using the system that are strong indicators of overall navigation effectiveness:

i) The subject was capable of keeping up with non-disabled pedestrians during guided tours. On several occasions the subject independently traversed through various facilities maintaining the natural pace of the guide and group. No path alterations were made that would not have been necessary for any power wheelchair user.

ii) The subject independently maneuvered up and down the steep incline associated with using his 5-foot portable ramp over steps. Stability of the EMG control mechanism was maintained at slopes as steep as 20 degrees. The subject's ability to countervail the wheelchair's natural tendency to fishtail on steep downgrades was noteworthy.

iii) The subject exercised precision maneuverability when boarding public transportation. Without deferring to attendant control, the subject gained access to an Amtrak passenger car, a city bus, and various van shuttles, each requiring unpracticed entry and tie-down positioning within extremely limited spaces.

iv) The subject could recline the backrest and elevate footrests to position himself in a completely horizontal position and then independently return to an upright position and begin navigating the wheelchair. The subject's ability to significantly change seating positions and regain maneuverability without assistance was a newfound level of independence.

Assuming there are significant benefits associated with single EMG navigation, as evidenced in this case study, when is it time to abandon proportional control? The subject gained significant functionality and independence with EMG control that he had not enjoyed with proportional control for over 15 years. One must conclude that there was an earlier time where the benefits of EMG control outweighed the benefits of proportional control. In other words, the subject spent many years with reduced mobility and functionality as a result of clinging to the concept (not the benefits) of proportional control. Evidence from this case study reveals the need to identify the optimal transition time for moving to single EMG control, as opposed to pursuing less effective control systems through a chain of forced transitions.

Several distinct factors contributed to the Smartphone's impact on the subject's productivity:

i) ***The capacity of the mobile device*** made it such that the subject had extensive resources available to him through a single interface. The breadth of this capacity is easily recognized in the numerous features touted by the iPAQ Smartphone. The depth of the iPAQ's capacity was best exemplified by its 2 gigabyte mini SD card which supported access to a virtually limitless digital library.

ii) **The *anywhere, anytime, all-the-time* availability of the mobile device** extended the subject's productivity far beyond the reach of his adaptive desktop workstation. With the mobile device mounted beside the Omni+ display, the subject had continual visual access to the device. His ability to independently alternate between switch outputs made it always amenable to engage the device. Because the mobile device drew its power from the wheelchair, the subject enjoyed full screen brightness and continuous use of any and all features without constraints.

iii) **The negligible fatigue associated with repeated EMG switch activations** resulted in the subject using the mobile device frequently and spontaneously. Three switch activations are required for each screen tap using nohandcom's crosshairs mode. Thus, a 30 character text message would require more than 90 switch activations and take approximately one and one-half minutes. The subject could perform this action without any muscle fatigue.

Based on these observations and the scenarios described in section 5, several conclusions can be safely drawn:

a) Single EMG control is a viable means for persons with severe mobility limitations to independently navigate a power wheelchair.
b) Single EMG sensor control of seating actuators can significantly increase independence and improve quality of life for persons with severe mobility limitations.
c) Single EMG sensor control of a Smartphone can significantly increase independence and productivity of persons with severe mobility limitations.
d) Persons with severe mobility limitations can leverage a single EMG sensor interface to successfully control multiple technologies supporting independence and productivity.

8. References

Richard C. Simpson, Edmund F. LoPresti and Rory A. Cooper. “How Many People Would Benefit From A Smart Wheelchair?” Journal of Rehabilitation Research and Development, 45(1):53-72,2008.

Holly A. Yanco and James Gips. “Driver Performance Using Single Switch Scanning with a Powered Wheelchair: Robotic Assisted Control Versus Traditional Control.” In Proceedings of the Annual Conference of the Rehabilitation Engineering and Assistive Technology Society of North America, Minneapolis, Minnesota, 26-30 June 1998. RESNA Press, 1998, pp 298-300.

Dinal S. Andreasen and Darren L. Gabbert. “Electromyographic Switch Navigation of Power Wheelchairs.” In Proceedings of the Annual Conference of the Rehabilitation Engineering and Assistive Technology Society of North America, Atlanta, Georgia, 22-26 June, 2006. RESNA Press, 2006.

Torsten Felzer and Rainer Nordmann. “Consolidating Computer Operation and Wheelchair Control.” In Proceedings of the Annual Conference of the Association for Computing Machinery Special Interest Group on Accessible Computing, Tempe, Arizona, 15-17 October, 2007. ACM Press, 2007, pp 239-240.

Mary Ellen Buning, Jennifer A. Angelo and Mark R. Schmeler. “Occupational Performance and the Transition to Powered Mobility: A Pilot Study.” American Journal of Occupational Therapy, 2001, 55, 339-344.