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Pilot Study for a Brain-Muscle-Computer Interface Using the *Extensor Pollicis Longus* with Preselected Frequency Bands

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Abstract— **We are developing a new class of Brain-Computer Interface that we call a Brain-Muscle-Computer Interface, in which surface electromyography (sEMG) recordings from a single muscle site are used to control the movement of a cursor. Previous work in our laboratory has established that subjects can learn to navigate a cursor to targets by manipulating the sEMG from a head muscle (the *Auricularis Superior*). Subjects achieved two-dimensional control of the cursor by simultaneously regulating the power in two frequency bands that were chosen to suit the individuals. The purposes of the current pilot study were to investigate (i) subjects' abilities to manipulate power in separate frequency bands in other muscles of the body and (ii) whether subjects can adapt to preselected frequency bands. We report pilot study data suggesting that subjects can learn to perform cursor-to-target tasks on a mobile phone by contracting the *Extensor Pollicis Longus* (a muscle located on the wrist) using frequency bands that are the same for every individual. After the completion of a short training protocol of less than 30 minutes, three subjects achieved 83%, 60% and 60% accuracies (with mean time-to-targets of 3.4 s, 1.4 s and 2.7 s respectively). All three subjects improved their performance, and two subjects decreased their time-to-targets following training. These results suggest that subjects may be able to use the *Extensor Pollicis Longus* to control the BMCI and adapt to preselected frequency bands. Further testing will more conclusively investigate these preliminary findings.**

I. Introduction

General advances in technology are paving the path for rapid development of tools that allow communication between the brain and its external environment. Such tools, referred to as Brain-Computer Interfaces (BCI), have the potential to help severely paralyzed individuals and amputees gain some independence by using their brains to manipulate their physical surroundings. Thus far, BCIs have been primarily based on non-invasive electroencephalography (EEG) and invasive electrocorticography (ECoG) readings (measures of electrical activity from the brain recorded on the surface of the head and beneath the scull respectively) [1]. Individuals learn to use these devices through a combination of operant conditioning and machine adaptation [2]. Here we report continued findings from a novel BCI device based on non-invasive surface electromyography (sEMG) readings that we call a Brain-Muscle-Computer Interface (BMCI). BMCIs work by processing electrical signals that are transmitted from the brain to the muscle when a surface muscle is contracted. Essentially, we use a muscle site as an electrical signal generation device.

sEMG signals have been widely used as a basis for controlling prostheses, where sensors are placed at *multiple* intact muscle locations to control different aspects of a prosthetic device [3],[4]. Typically, one control channel is achieved per muscle. A major benefit of our device is that more than one simultaneous control channel can be obtained from a single recording site. Previous case studies in our laboratory have shown that subjects can learn to perform cursor-to-target tasks on a laptop screen by contracting the *Auricularis Superior* (AS) muscle located above the ear [5]. Learning was achieved through operant conditioning and machine adaptation comparable to standard BCI protocols. The AS muscle was chosen because it has no known function in humans (some animals use the equivalent muscle to orient the ear towards sound sources [6]) and therefore contracting it does not interfere with other important actions, such as speaking or directing eye-gaze. More importantly, the AS muscle is typically accessible even for individuals with the most severe neck-down paralysis – the main intended user group of BCIs. The results of the previous study established that subjects can be trained to achieve two-dimensional control of a cursor by manipulating the power in two frequency bands while contracting the AS. This skill is not required when ordinarily contracting a muscle, and is not dependent on a specific muscle movement. The frequency bands in our previous studies were identified following a series of correlations between powers within certain bands during a pre-training test, and hence differed for each individual subject [5].

In the present pilot study we used a newly developed portable Android mobile phone version of the BMCI system [7] to address two important questions: (i) is the process of identifying personalized frequency bands in fact necessary, or are individuals able to 'tune in' to any preselected bands within the sEMG frequency spectrum? and (ii) can other muscles of the body be used to control the BMCI? We aimed to answer these questions by training subjects to use frequency bands that were selected prior to testing rather than tailored to each individual. To address the second

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question we chose to record sEMG from *Extensor Pollicis Longus* (EPL), which is located on the wrist and is used to stretch the thumb. Although high paralysis patients would not use this specific muscle, hand amputees could potentially use it for hand prostheses. In terms of neurophysiological study, people generally have access to the EPL and it is easily accessible for recording.

II. METHODS

A. Human Subjects

Three students at the University of California Davis took part in the experiment (subject 1: male, age 19; subject 2: female, age 22; subject 3: female, age 18), all of which were right handed, able-bodied and had no prior experience with BCIs. The subjects provided written consent as approved by the Institutional Review Board of the University of California Davis (UC Davis IRB Protocol #251192-4) and received psychology course credits for participating.

B. Electromyography

We collected sEMG signals from the EPL muscle on the subject's dominant hand with two surface disposable Ag-AgCl snap electrodes (6.3 mm diameter) connected to a model Y03 preamplifier (www.motion-labs.com) with input impedance > 100 000 000 Ω, 15-2000 Hz signal bandwidth and a gain of 300. The electrodes were placed on the base of the subject's wrist along the axis of the muscle with approximately 1.5 cm inter-electrode distance (see Fig.1). One additional electrode was placed on the elbow as a reference. Prior to electrode application, the skin was cleaned with an alcohol wipe. The snap electrodes were of the type ConMed 1620 Pediatric Huggables Electrodes held in place with Clear NeoDerm tape.

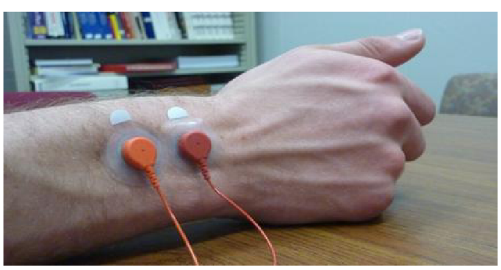

Fig. 1. Anatomical placement of sEMG electrodes. Two electrodes were placed on the *Extensor Pollicis Longus*. The electrodes give a single differential sEMG signal. The references electrode was placed on the elbow.

C. Signal Processing

Once the analog differential sEMG signal was measured and filtered (15-2000 Hz) at the amplifier, we fed the signal into a mobile phone device (HTC myTouch cell phone running the Android operating system) to create two control channel signals. 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. We sampled our sEMG signal at the standard available sampling rate of 8000 Hz and then down sampled to effectively sample at 4000 Hz. (Power spectrum analysis of our signal at the higher 8000 Hz sampling rate showed our sEMG bandwidth for the EPL muscle under 600 Hz, with negligible noise above 1000 Hz.) The signal processing needed to transform the single sEMG signal from one muscle site to two control channels (X-pos and Y-pos) is shown in Fig. 2 and Eqns. 1-2. 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 80-100 Hz (Band 1) and 130-150 Hz (Band 2). These bands were selected following visual inspections of the power spectra of an arbitrary contraction of the EPL muscle by previous subjects. The bands appeared to produce comparable powers and were separated by 30 Hz.

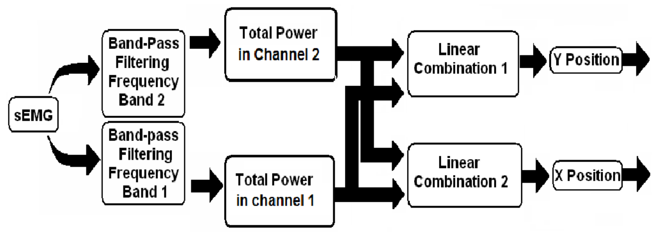

Fig. 2. Block diagram of system developed to generate two control signals from one sEMG signal at a single muscle site.

$$X_{POS} = \frac{1}{Effort_X}\left[1.75\left(\frac{Power\_Band\_1}{Max\_Power\_Band\_1}\right)\cdots\right. \quad (1)$$

$$\left. -0.75\left(\frac{Power\_Band\_2}{Max\_Power\_Band\_2}\right)\right]$$

$$Y_{POS} = \frac{1}{Effort_Y}\left[-0.75\left(\frac{Power\_Band\_1}{Max\_Power\_Band\_1}\right)\cdots\right. \quad (2)$$

$$\left. +1.75\left(\frac{Power\_Band\_2}{Max\_Power\_Band\_2}\right)\right]$$

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, then the cursor is placed on

(Xpos=1, Ypos=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. In the current experiment, the researchers adjusted the effort settings for one of the subjects once during training (but not during pre-test and post-test) when he appeared to develop persistent difficulties moving in one specific direction.

D. Testing Protocol

A Graphical User Interface (GUI) was developed to provide feedback cue information to the subjects about the position of the cursor on the mobile phone screen. The GUI was saved as an application consisting of a number of screens that the subjects were guided through one at the time. The first few screens allowed the raw signal to be visually inspected and calibration to be carried out.

Before training, subjects performed a "pre-test" of 30 trials (contractions). A black circular cursor was present on the screen, and the cursor's position was determined by the subject's muscle contractions. The cursor's starting point was the grey area in the bottom left corner (the 'rest area') and the cursor always returned to this position when the muscle relaxed. On each trial, a circular target (equivalent to 1% of the total size of the screen) appeared in one of three locations of the screen at random. Each target location was displayed 10 times. The subject was instructed to direct the cursor to the target, and if hit, the target turned yellow. The subject then relaxed to return to the rest area. If a target was not hit within eight seconds, the trial was terminated and the cursor was placed in the rest area. A trial was defined as successful if the target was hit within eight seconds and unsuccessful if the subject returned the cursor to the rest area without hitting the target or the trial timed out. Each time the cursor returned to rest, it froze for two seconds in order to enforce a short break between trials.

The training protocol was based on 'shaping' (a form of operant conditioning), in which subjects were required to hit gradually smaller targets (see Fig. 3). The three target sizes were large, medium and small (4%, 2% and 1% of screen size respectively). At the first stage of training, subjects learned the path to each target location one at a time. Initially the target was large, and the size decreased to medium when the subject hit the target successfully four times out of the last five trials. When the medium target was hit four times out of the last five trials, the target size decreased to small (equivalent to the size during pre-test). When the small target was hit four times out of the last five trials, training on the first target was complete and the subject performed the task for the remaining two targets.

The next stage of training used shaping as detailed above, but the targets were randomly presented among any of the three target locations. The target size started out large and became medium when the subject hit the target eight out of the last 10 trials. When the medium target was hit eight out of the last 10 trials, the target became small. Finally, the subject had to hit the small target 16 out of the last 20 trials to complete training. When this had been achieved, subjects performed a "post-test", which was exactly the same format as the pre-test (with 30 randomly presented targets at smallest size), to evaluate potential training benefits.

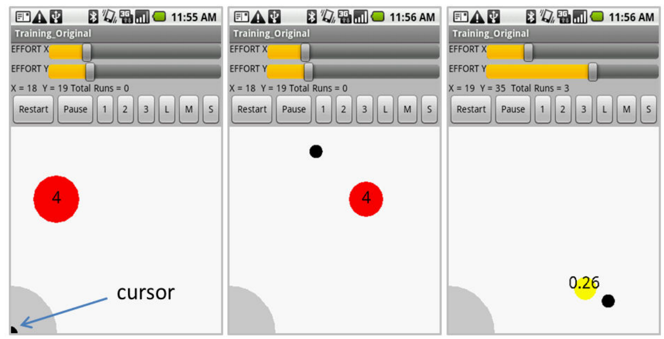

Fig. 3. Screen shots of the android phone. Left: large target in first target location. The number on the target signifies the number of times the target has to be hit before passing the level. The cursor is positioned in the grey rest area in the bottom left corner of the screen. Middle: medium target in target location two. Right: small target in target location three. The target has just been hit by the cursor and is therefore yellow. The number indicates the time-to-target in seconds.

III. Results

A. Hit Rates and Time-to-Target

Each subject's performance on the pre- and post-tests are summarized in Table 1. As can be seen in the second column, the subjects' pre-test performances were in the range of 50-67%. Subject 1 demonstrated a 16% increase in performance on the post-test compared to the pre-test, however the time-to-target (TT) increased by 0.9 s. Subject 2's performance was lower than that of Subject 1 on both the pre- and post-test. Performance did, however improve by 10% and TT decreased by 1.4 s. Subject 3 had a higher pre-test score than Subject 2, and improved her score slightly on the post-test. TT also decreased marginally, suggesting that she moved more efficiently to the targets following training, but overall learning appeared to be minimal.

B. Cursor Trajectories

Example cursor trajectories from post-test are shown for each subject in Fig. 4. The illustrated trials were all successful hits that had corresponding TTs within one standard deviation of the mean for each respective subject. Subjects 1 and 2, who demonstrated the highest performance scores, also seemed to produce the most direct trajectories. As can be seen in the middle plot, Subject 2 missed the top left target on her first try and then proceeded to drop the cursor over it. This appeared to be a common strategy among

TABLE 1. SUBJECT PERFORMANCE

Subject	Pre-Test Score (out of 30 trials)	Pre-Test TT (SD)	Post-Test Score (out of 30 trials)	Post-Test TT (SD)	Total no. of training trials	No. of final stage training trials[a]	Score during final training stage
1	67%	2.5 (1.8) s	83%	3.4 (2.6) s	112 (16 min.)	21	76%
2	50%	2.8 (2.3) s	60%	1.4 (1.5) s	209 (25 min.)	95	67%
3	57%	3.1 (2.7) s	60%	2.7 (1.7) s	144 (22 min.)	75	64%

[a]Final stage of training includes the smallest targets during stage two, presented at random locations and which the subjects had to hit 16 times our of the last 20 trials.

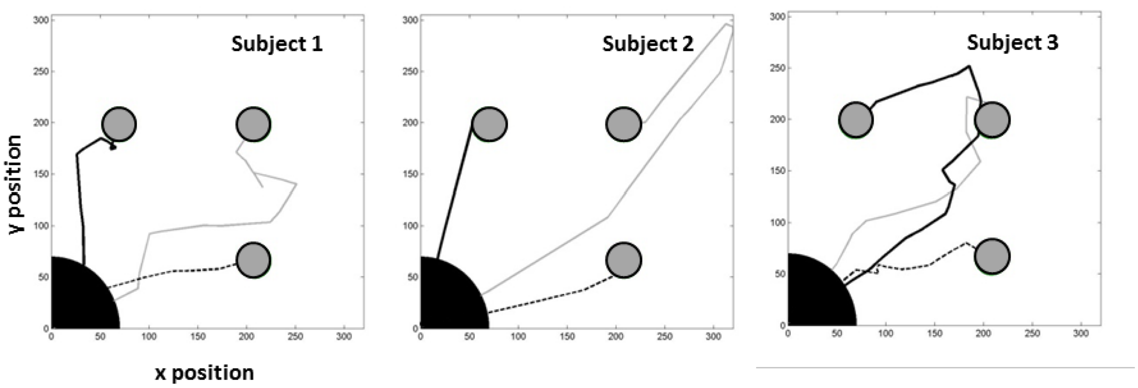

Fig. 4. Examples of cursor trajectories generated during post-test. All three target locations are shown on the same screen here, but during the experiment targets would appear one at a time on separate trials. The trials selected for display were all successful trials that had corresponding TTs within one standard deviation of the mean. Target size was 1% of the size of the screen.

subjects when targets were initially missed. Subject 3 appeared to exhibit a little less control of the cursor. This is noticeable in the path to the left-most target. Overall, however, the cursor trajectories seem to suggest that all three subjects moved the cursor with intentionality rather than hitting targets by randomly moving around the screen.

C. *Training*

Training time is provided in Table 1 and was defined as the number of trials it took each subject to complete the full training protocol. This number varied significantly between subjects; Subject 1 required the fewest trials followed by Subject 3 and Subject 2. Thus, this pattern shows that Subject 3, despite having the lowest performance scores, required fewer trials than Subject 2 to complete the training phase at the required 80% criterion. This questions whether or not the post-test score is an appropriate measure of stable task performance. Some subjects could experience more physical or mental fatigue towards the end of testing sessions causing a drop in performance. It is also possible that some of the subjects felt negative pressure knowing they were evaluated during the post-test. For these reasons, we decided to examine the accuracy scores and TTs for trials occurring during the last stage of training, for which the subjects had to successfully hit 16 out of the last 20 trials to pass. This last set of training trials all included small targets and corresponded to the task in the post-test. Subject 1 completed the last training level in 21 trials with an average score of 76%. Subject 2 completed in 95 trials with a score of 67% and Subject 3 completed in 75 trials with a final score of 64%. These numbers reveal that for Subject 2 and Subject 3, the average performance during the last stage of training was higher than during the post-test. Given that many more trials contributed to the average, it is possible that the training score is a more reliable measure of the subjects' actual abilities.

IV. DISCUSSION

The results of the present pilot study suggest that the three subjects could perform cursor-to-target movements on a mobile phone by contracting the *Extensor Pollicis Longus* and manipulating the power in two preselected frequency bands. Some abilities to use the BMCI seemed to be present at the start of the experiment, as evident by the subjects' relatively high pre-tests scores (50-67%). Also, the three subjects seemed to improve their performance after a training session of less than 30 minutes. The cursor trajectories indicate that the subjects moved the cursor to the target locations with intentionality.

The subjects' performances is encouraging considering that the target sizes for the pre- and post-test were only 1% of the size of the screen, requiring a high level of precision (by comparison, one EEG-based study used targets which were 4% of the screen size [8]). Our current training protocol was developed with the primary intention of demonstrating some levels of proficiency in target hitting without the requirement to complete more than, at the most, a couple of 1-hour long training sessions (all three subjects reported in this study completed training in less than 30 minutes). The four subjects from Perez-Maldonado et al. [5] underwent between 15-16 hours of training using the AS muscle and were able to achieve 87-98% accuracy with a target size of only 0.16% screen size. We assume that if more training was provided in the current study, our subjects would also demonstrate higher levels of learning.

One possible weakness of our design is that we set the criterion too low for passing training, so subjects had not reached a stable performance at 80% by the time they completed the post-test. This is presumably one reason why Subject 2 and 3 performed as low as 60% on post-test. Examination of the last stage of training revealed that these two subjects demonstrated higher performance levels just preceding post-test than during the post-test (67% and 64%). The numbers of trials contributing to the average training score were much higher compared to those contributing to the post-test score (95 and 75 versus 30) and therefore possibly represent more precise measures of the subjects' abilities. Furthermore, it cannot be ruled out that subjects were experiencing mental and/or physical fatigue toward the end of the session which could also have deflated the post-test scores. On a similar note, we are concerned that the format of our assessment procedure might have caused the subjects to feel unnecessary stress. In future protocols we plan to avoid a clear distinction between training and assessment in an attempt to remove the negative pressure we might have imposed on our subjects.

In future protocols we also intend to introduce a 'null-test', which will provide an estimate of subject's performance rate during random (i.e. non-target directed) cursor movement. Although inspections of the subjects' accuracy scores during pre-test seem to suggest some level of control even before training, it is difficult to make this assessment without any knowledge of how many targets the subjects are likely to hit when they move in a random fashion. We expect that if individuals have the general ability to maneuver a cursor (albeit not in a controlled manner), then they will be able to hit some targets – but the trajectories should be chaotic and TT higher compared to conditions under which they direct the cursor intentionally.

As the subjects appeared to move around the screen with relative ease, it was not necessary to adjust the X- and Y-effort settings more than once during training in this experiment. As explained above, the need to do so appeared when one subject developed difficulties moving to a specific target location during the first stage of training. It is unclear whether the adjustment was in fact necessary and if the subject would eventually have overcome his difficulties without system adaptation. There is some evidence to suggest that the power in the frequency spectrum shifts towards lower values during fatigue [9], [10] (later studies have disputed spectral shift as a general property of all fatigue [11]). If this shifting is the reason behind the sudden difficulty in reaching certain areas of the screen then it is surprising that it was only the subject who carried out the fewest trials that experienced it. Also, it is surprising that it happened so early in the experiment (10 minutes into training) and only once. An alternative explanation is that Subject 1 experienced some kind of learning interference [12] due to the format of the first stage of the training protocol. The concept of co-adaptation is generally well-known and accepted within the BCI research community [2] and one important aim for the future is to develop devices which achieve optimized co-adaptation from an automated procedure.

V. Conclusion

The pilot study reported here demonstrates that subjects may be able to learn to navigate a cursor to goal targets by manipulating the sEMG signal recorded from one single muscle site located on the surface of the *Extensor Pollicis Longus.* This finding suggests that muscles other than the *Auricularis Superior* may be used to control our BMCI. Furthermore, our results show that subjects may be able to adapt to using preselected frequency bands, suggesting a flexible learning system. The pilot tests also highlighted improvements we should implement in our current protocol for future investigations.

Acknowledgment

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References

[1] M.D. Serruya, and J.P. Donoghue,"Design Principles of a Neuromotor prosthetic device", in *Neuroprosthetics: Theory and Practice*, K.W. Horch, and G.S. Dhillon, Eds., Imperial College Press, 2004, pp. 1158-1196.

[2] D.J. McFarland, D.J. Krusienski and J.R. Wolpaw, "Brain-computer interface signal processing at the Wadsworth Center: mu and sensorimotor beta rhythms." Proj. Brain Res., vol. 159, pp. 411-419, 2006.

[3] K. Englehart and B. Hudgins, "A robust, real-time control scheme for multifunction myoelectric control," *IEEE Transactions on Biomedical Engineering*, vol. 50, pp. 848-854, 2003.

[4] M. Zeeca, S. Micera, M. C. Carrozza, and P. Dario, "Control of Multifunctional Prosthetic Hands by Processing the Electromyographic Signal," *Critical Reviews in Biomedical Engineering*, vol. 30, pp. 459-485, 2002.

[5] C. Perez-Maldonado, A.S. Wexler, and S.S. Joshi, "Two dimensional cursor-to-target control from single muscle site sEMG signals." *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 18, no.2, pp. 203-209, 2010.

[6] L.C. Populin and T.C.T. Yin, "Behavioral studies of sound localization in the cat," *J. Neurosci*., vol. 18, pp. 2147–2160, 1998.

[7] S. Vernon and S.J. Joshi, "Brain-Muscle-Computer Interface: mobile phone prototype development and testing." *IEEE Trans. Info. Tech. in Biomedicine*, Vol. 15, No. 4, pp. 531-538, 2011.

[8] J. Wolpaw and D.J. McFarland, "Control of a two-dimensional movement by noninvasive brain-computer interface in humans." *Proc. Nat. Acad. Sci.*, vol. 101, pp. 17849–17854, 2004.

[9] B. Bigland-Ritchie, R. Johansson, O.C.J. Lippold and J.J. Woods, "Contractile speed and EMG changes during fatigue of sustained maximal voluntary contractions." *J. Neurophysiol*., Vol. 50, pp. 313–324, 1983.

[10] J. Moxham, R.H.T. Edwards, M. Aubier, A. De Troyer, G. Farkas, P.T. Macklem and C. Roussos, C., "Changes in EMG power spectrum (high-to-low ratio) with force fatigue in humans." *J. Appl. Physiol*., Vol. 53, pp. 1094–1099, 1982.

[11] N.K. Vøllestad, "Measurement of human muscle fatigue." *J. Neuro. Methods*, Vol. 74, pp. 219-227, 1997.

[12] R. Shadmehr and T. Brashers-Krug, "Functional stages in the formation of human long-term motor memory." *J Neurosci*, Vol. 17, pp. 409– 41, 1997.