University of Alberta

The Development of a Myoelectric Training Tool for Above-Elbow Amputees

by

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Abstract

Above-elbow myoprostheses aim to restore the functionality of amputated limbs and improve the quality of life of amputees. By using electromyography electrodes attached to the surface of the skin, amputees are able to control motors in myoprostheses by voluntarily contracting the muscles of their residual limb. An advance in myoelectric control called targeted muscle reinnervation (TMR) reinnervates severed nerves into healthy muscle tissue and increases the number of muscle sites available for use in control purposes. In order to improve rehabilitation after TMR surgery, an inexpensive myoelectric training tool has been developed in collaboration with the Glenrose Rehabilitation Hospital that can be used by TMR patients for biofeedback applications. The training tool consists of a robotic arm, signal acquisition hardware, controller software, and a graphical user interface. This dissertation describes the design and evaluation of the training tool and its use as a research platform for testing novel controllers.

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List of Symbols and Abbreviations

2D	Two-dimensional
3D	Three-dimensinoal
AC	Actor-Critic
ANN	Artificial Neural Network
API	Application Programming Interface
BOM	Bill of Materials
COM	Component Object Model
CMRR	Common Mode Rejection Ratio
CNS	Central Nervous System
DAQ	Data Acquisition
DoF	Degree of Freedom
EMG	Electromyography (after 2.2 any use of EMG refers to sEMG)
FES	Functional Electrical Stimulation
GUI	Graphical User Interface
GRH	Glenrose Rehabilitation Hospital
HREB	Health Research Ethics Board
iEMG	Intramuscular Electrmyography
LDA	Linear Discriminant Analysis
LLGMN	Log-Linearized Gaussian Mixture Network
MCETS	Myoelectric Control and Evaluation Trainer System
MAV	Mean Absolute Value
MTT	Myoelectric Training Tool
NI	National Instruments
PCI	Peripheral Component Interconnect
RL	Reinforcement Learning
RLAI	Reinforcement Learning and Artificial Intelligence
SENIAM	Surface EMG for a Non-invasive Assessment of Muscles

SVM	Support Vector Machines
TD	Temporal Difference
TMR	Targeted Muscle Reinnervation
UofA	University of Alberta
UVa-NTS	UVa-Neuromuscular Training System
VB	Visual Basic
VRML	Virtual Reality Modelling Language

Chapter 1

Introduction

1.1 Motivation for the Research

Upper limb loss is a worldwide problem affecting an estimated 41000 people in 2005 in the United States alone [1]. Amputees must live with reduced motor function, which can negatively impact the type of activities they are able to perform. The goal of upper limb prostheses is to increase the level of functionality closer to the original pre-limb loss level. Myoelectric prostheses in particular use muscle signals voluntarily generated by amputee patients to control powered robotic prostheses [2].

A significant problem with the application of myoelectric prostheses is that as the amputation level increases, the number of muscle sites that can provide relevant control information decreases. To address this problem a new technique called targeted muscle reinnervation (TMR) has been developed that reinnervates severed nerves into healthy muscle tissue and increases the number of muscle sites available for use in control purposes [3].

The Glenrose Rehabilitation Hospital in Edmonton, Alberta, Canada, recently started performing TMR surgeries and is looking for tools to help train patients to use myoelectric technology in advance of receiving their final prostheses. Training is an important part of the fitting process and can potentially decrease prosthesis rejection rates in children [4], increase learning rates, and allow patients to reach a higher functioning level more quickly. The Glenrose's current training method involves having the patient imagine moving their phantom limb in various exercises and leaves some room for improvement.

A number of studies have surveyed amputees' opinions on design considerations for future upper-limb prostheses [5–7]. Improving the functionality of myoelectric prostheses has ranked highly in importance in all studies. Specific improvements suggested by the studies include life-like function, proportional control as well as increased number of movements, movement range, adaptability and reliability. These design goals can be achieved by improving and developing new myoelectric controllers.

1.2 Problem Statement

The first objective of the project is to design an inexpensive myoelectric training tool to help above-elbow amputees learn how to use myoelectric prostheses. The myoelectric training tool maps the muscle contractions on an above-elbow amputee patients' residual limb to the degrees of freedom of a robotic arm using surface electromyography (EMG) electrodes (a non-invasive means of measuring the physiological signal corresponding to muscle force). The purpose of the tool is to train amputees in using myoelectric technology in advance of receiving their actual myoelectric prostheses.The second objective of the project is to use the myoelectric training tool as a research platform for testing new myoelectric control schemes that can be potentially used in future prostheses.

1.3 Scope of Thesis

The scope of this thesis includes:

- The design of the research and clinical prototypes of the myoelectric training tool;
- The fabrication of a functioning research prototype that includes all of the desired core features; and,
- The implementation and testing of a reinforcement learning method on the research prototype of the myoelectric training tool in collaboration with the Reinforcement Learning and Artificial Intelligence Group in the Computing Science department.

1.4 Thesis Organization

The content of this thesis has been divided into six chapters. The background information pertinent to the research topics and the groundwork for the rest of the thesis is included in chapter 2. A description of the EMG signal and commercial myoelectric prostheses along with brief literature reviews for TMR and EMG controllers are specific sections included in this chapter. An in depth literature review for myoelectric training systems is included in chapter 3. The development of the myoelectric training tool research prototype including sections for research and problem definition, detailed design, manufacturing, and evaluation is detailed in chapter 4. Please note that chapters 3 and 4 have been submitted as journal papers to the Journal of Electromyography and Kinesiology and the IEEE Transactions on Neural Systems and Rehabilitation Engineering, respectively. The design of the clinical prototype highlighting the key similarities and differences to the research prototype is covered in chapter 5. The development of a novel myoelectric control method using reinforcement learning is described in chapter 6. The overview of how the controller works along with the results and discussion from initial tests are also included in this chapter. Finally, an overall summary of the results and future work are described in chapter 7.

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Chapter 2

Background

This chapter will provide a brief background in topics relevant to the remainder of this dissertation. The sections covered include a description of muscle anatomy and physiology, EMG signals, the current state of above-elbow myoelectric prostheses, conventional myoelectric control methods, targeted muscle reinnervation, and pattern recognition based control methods.

2.1 Muscle Anatomy and Physiology

A muscle is comprised of several muscle fibers comprised of smaller tubules called myofibrils as seen in Figure 2.1. Each myofibril consists of an array of sarcomeres. The sarcomeres contain myofilaments (thick and thin) and titan as seen in Figure 2.2. During a muscular contraction a message is sent from the central nervous system to the muscle via neural pathways traveling from the motor cortex down through the spinal cord and finally to the muscle as illustrated in Figure 2.3. The neurons that connect to the muscle fibers are called motoneurons and together with the muscle fibers they innervate are called motor units. An action potential, which depolarizes the sarcolemma and creates a measurable electric field, then travels down the muscle fiber away from the motoneuron. The action potential sets off a number of molecular events in the myofibrils, which in turn cause the thin filaments to contract towards the thick filaments generating tension. The motor unit action potential finally terminates at the tendons of the muscle. For a more detailed description of the anatomical and physiological processes of muscular tissue please see chapter 10 of [1].

The overall level of tension developed in muscles is controlled through the number and size of motor units recruited and by the frequency at which these muscles are contracted (rate coding). A single muscle fiber contraction is called a twitch and is illustrated in Figure 2.4. A short latent period occurs due to the time required for the propagation of the action potential and molecular interactions to initiate the muscle twitch. This latent period is

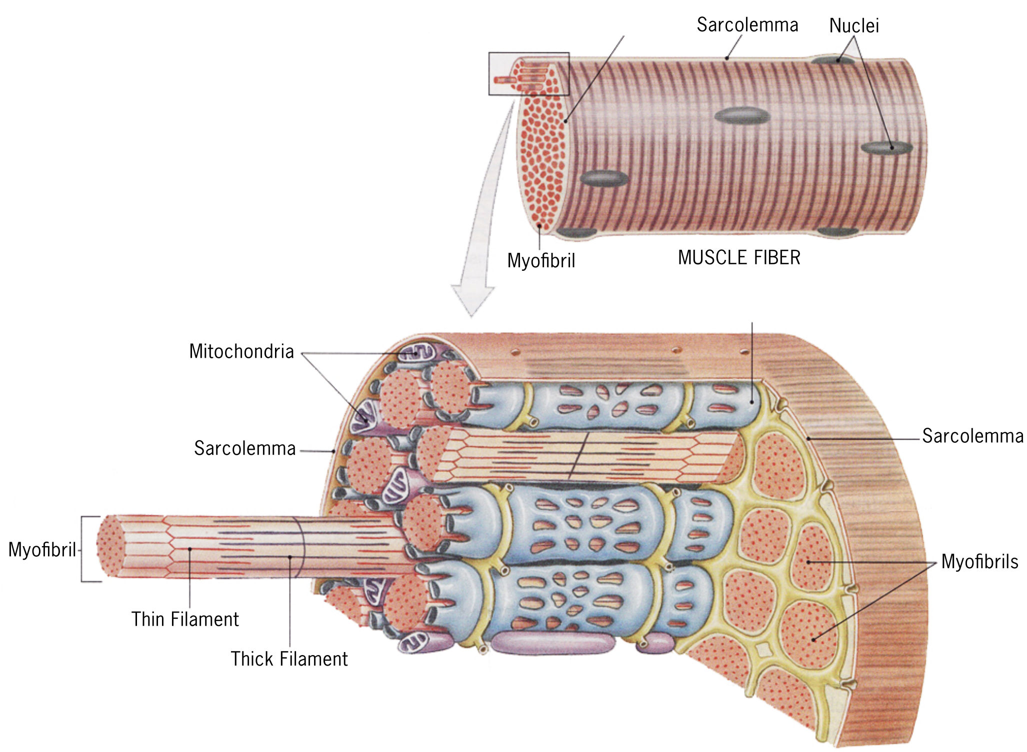
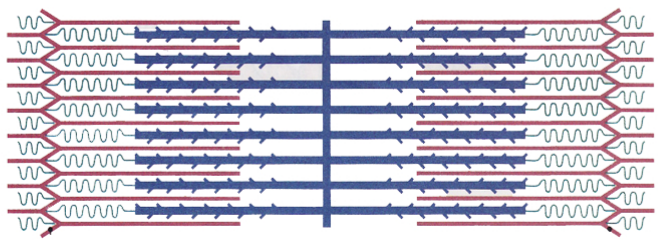
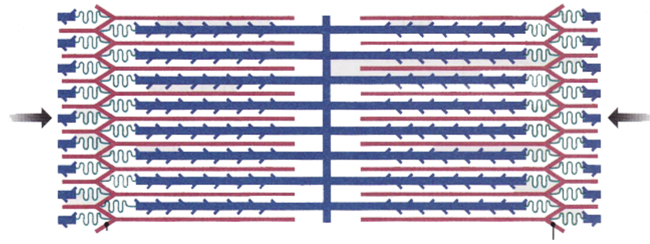


Figure 2.1: Basic anatomy of skeletal muscle (adapted from p.287 of [1])



(a) Sarcomere at rest



(b) Contraction and filament sliding

Figure 2.2: Sarcomeres and muscle contraction (adapted from p.292 of [1])

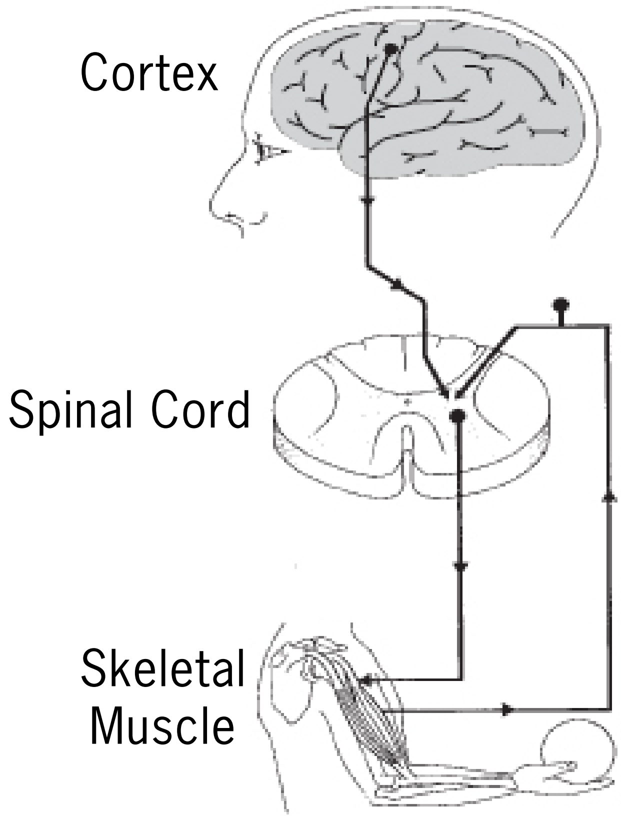


Figure 2.3: Basic physiology of motor units (adapted from p.3 of [2])

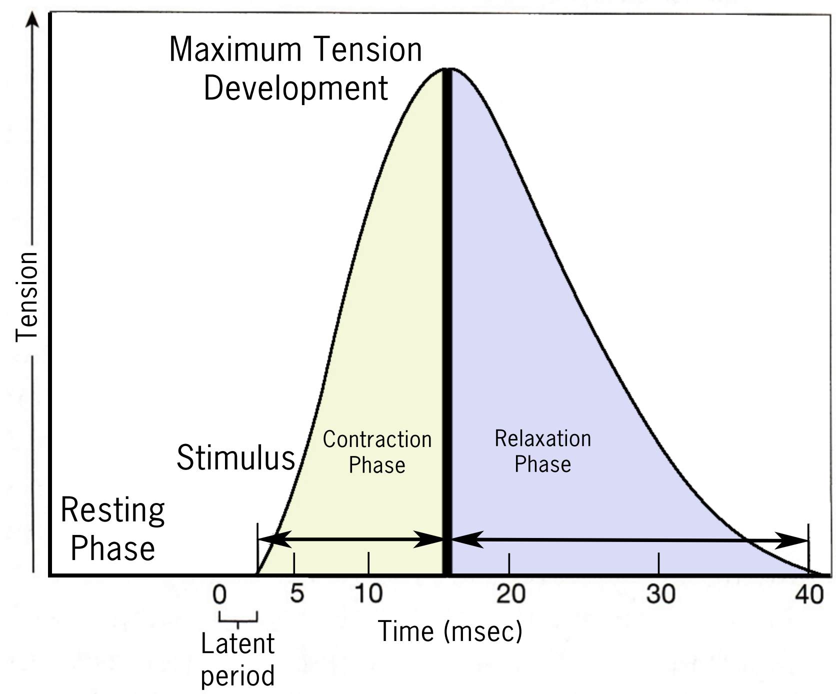


Figure 2.4: Tension versus time of a single muscle twitch (adapted from p.302 of [1])

then followed by a contraction phase where the maximum tension is developed and then a relaxation phase where the tension drops back down to zero. To increase the overall tension stimuli can be sent at higher frequencies, which result in the effect of wave summation as seen in Figure 2.5. Wave summation involves an additional stimulus being received before the relaxation phase of the previous muscle twitch has completed. Eventually the muscle tension will reach a maximum level called tetanus and a further increase in activation frequency will no longer result in an increase in tension. According to the size principle developed by Henneman [1], motor units are recruited from smallest to largest size (where size refers to the number of muscle fibers in the motor unit). Small motor units are used for fine motor movement and larger motor units are used for movements that require a large amount of tension. For more detailed information on the expected behavior of muscular tissue to excitation of the central nervous system please see [1, 2].

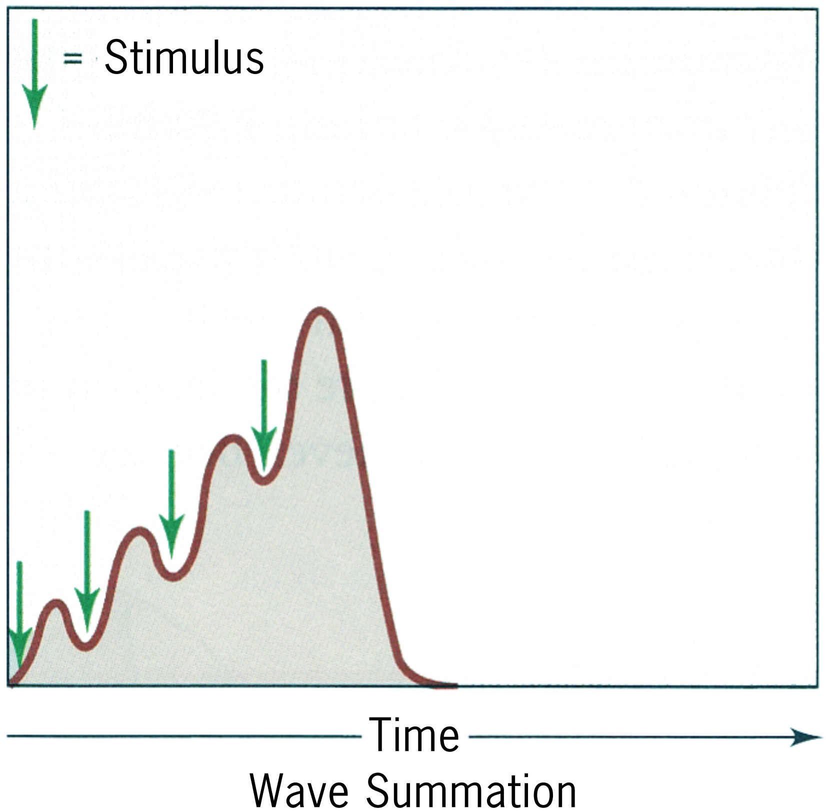


Figure 2.5: Tension versus time of subsequent muscles twitches resulting in wave summation (adapted from p.303 of [1])

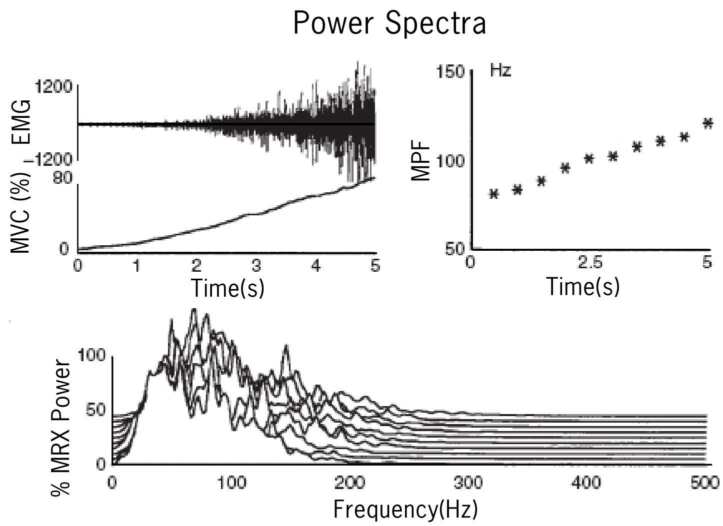


Figure 2.6: Relationship between increasing sEMG amplitude and mean voluntary contraction (adapted from p8 of [2])

2.2 EMG Fundamentals

The importance of muscular tissue lies not only in its function of actuation in the human body, but also in the rich information that can be recorded directly and indirectly from these muscles. Electromyography is the study of the electrical signals emitted by the muscles of the body. An electromyogram is a recording of muscle activity in the form of changing voltage over time. An example of information that can be extracted from EMG readings includes the signal amplitude, which roughly corresponds to the number of motor units recruited and their activation frequency as shown in Figure 2.6. Two major types of electromyography exist including intramuscular electromyography (iEMG) and surface electromyography (sEMG).

iEMG uses needle electrodes, which penetrate the skin and most of the subcutaneous tissue reading the electrical signal directly from inside the muscle tissue. The importance of the iEMG method is that the electrical response of individual motor units can be recorded and studied improving the understanding of how muscle tissues function [3]. This information can then be used to help detect potential muscular disorders [4]. A disadvantage of this method is that it is invasive and thus the risk of potential infection and the loss of mobility while wearing the electrodes are present.

sEMG uses surface electrodes, which are placed on the surface of skin and indirectly read the sum of electrical signals generated by the individual muscle motor units. The importance of the sEMG method is that the electrodes are noninvasive. The sEMG signal can

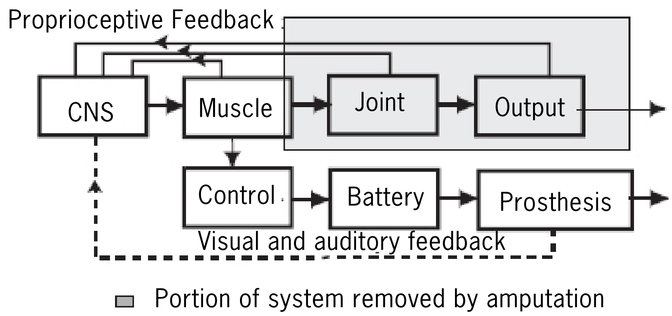


Figure 2.7: Block diagram of how a myoelectric system interfaces with an Amputee (adapted from p.454 of [6])

be processed and used as a control input for prostheses and teleoperated robotics. sEMG is also used often in biomechanical studies as an indicator of muscle activity when humans are performing different motions [5]. A disadvantage of sEMG is that the spatial and temporal information of motor units that are firing cannot be easily recovered [6].

2.3 Above Elbow Myoelectric Prostheses

Myoelectric prostheses are limb prostheses that interpret muscle signals that are voluntarily generated by an amputee to control the robotic actuators of the prostheses. The objective of myoelectric prostheses is to improve the lives of amputees by restoring function in a manner closely resembling that of the original limb. A block diagram showing the functions that are removed by amputation and restored through myoelectric prostheses can be seen in Figure 2.7. The main systems lost in amputation as shown in the figure are the actual physical joints, the force and velocity output of the arm, and any sensory feedback. For the purposes of this dissertation the type of myoelectric prostheses that will be considered will be limited to those that take in sEMG inputs for above-elbow amputees and from now on when EMG is used in the text it means sEMG.

Some myoelectric prostheses that are currently commercially available are Liberating Technologies' Boston Elbow [7], Motion Control's Utah arm [8], and Otto bock's Dynamic Arm [9] as seen in Figure 2.8. These elbow prostheses are typically modular providing up to 3 myoelectrically controlled degrees of freedom (DoF) including elbow flexion/extension, wrist rotation, and hand open/close as seen in Figure 2.9. Recent versions of these myoelectric prostheses have included the ability to control multiple DOF simultaneously. The cost of these prostheses is in the tens of thousands of dollars with the elbow joint costing around 30000 dollars alone [10]. In academia and industry, current research is focused on increasing the mobility of myoelectric prostheses with humeral rotation [11] (see Figure 2.9) as well as increased dexterity in the hand [12].

Figure 2.8: Otto Bock's Dynamic Arm combined with myoelectric wrist rotator and prehensor (adapted from [9])

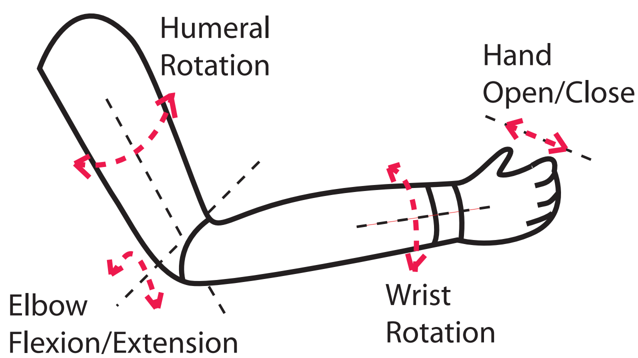


Figure 2.9: An illustration of the 3 common DOF's available on current commercial prostheses along with the humeral rotation of future prostheses

2.4 Conventional EMG Control

Using EMG for control purposes (myoelectric control) was first studied in the 1940s. Over time, with advances in microprocessors and battery technologies, EMG prosthetic devices have become more and more viable as alternatives to body powered and passive prosthetics. However, in commercial myoprosthetics the main type of control scheme has changed very little over the last thirty years. The conventional method of controlling myoprosthetics uses the rectified mean absolute value (MAV) of a single sEMG signal measured off of a single muscle group. When the amputee voluntarily increases or decreases the level of contraction in their muscle it results in a measurable increase or decrease in the value of the MAV. When the MAV increases above a threshold level it can control a single function on the myoelectric prosthesis (i.e. elbow flexion, hand open, hand close, ect). A typical control setup for an amputee patient as seen in Figure 2.10 with an active myoelectric hand would include 2 channels: one placed over the bicep to control hand opening and one placed over the triceps to control hand closing. The amputee patient is then limited in the number of functions they can perform with the myoelectric arm by the number of discrete muscle sites available for sEMG readings. This type of controller is known as a two-state amplitude modulation controller [6].

While this type of controller is often used to simply control an actuator in an on/off fashion with a fixed velocity, it can also be extended to proportionally control the angular or linear velocity of each actuator. This effect is achieved by introducing a second maximum threshold and using a linear proportional mapping between the minimum and maximum thresholds to the minimum and maximum angular velocities of each actuator. By increasing the strength of their muscular contraction a patient can then for example increase the speed at which their myoelectric hand opens. For a typical controller setup, see Figure 2.11.

An advantage of conventional EMG controllers is that they are simple and easy to implement on the embedded hardware typical of myoelectric prostheses. They are also relatively easy to setup and configure by prosthetists and provide acceptable performance for enough amputees to warrant commercial ventures. A disadvantage of these controllers is that they require two discrete muscle sites for each myoelectric degree of freedom on a myoelectric prostheses. These discrete muscle sites must also be far enough apart in order to prevent crosstalk where the signals tend to overlap and interfere with each other. This problem increases as the amputation level increases and the amputee is left with less muscle sites available for use as control inputs. In the case of shoulder-disarticulation amputations these types of controllers do not work at all. For above elbow amputations the controllers are often non-physiologically relevant since the available muscle sites, biceps and triceps, are typically used to control the hand open/close degree of freedom on the robotic limb. This

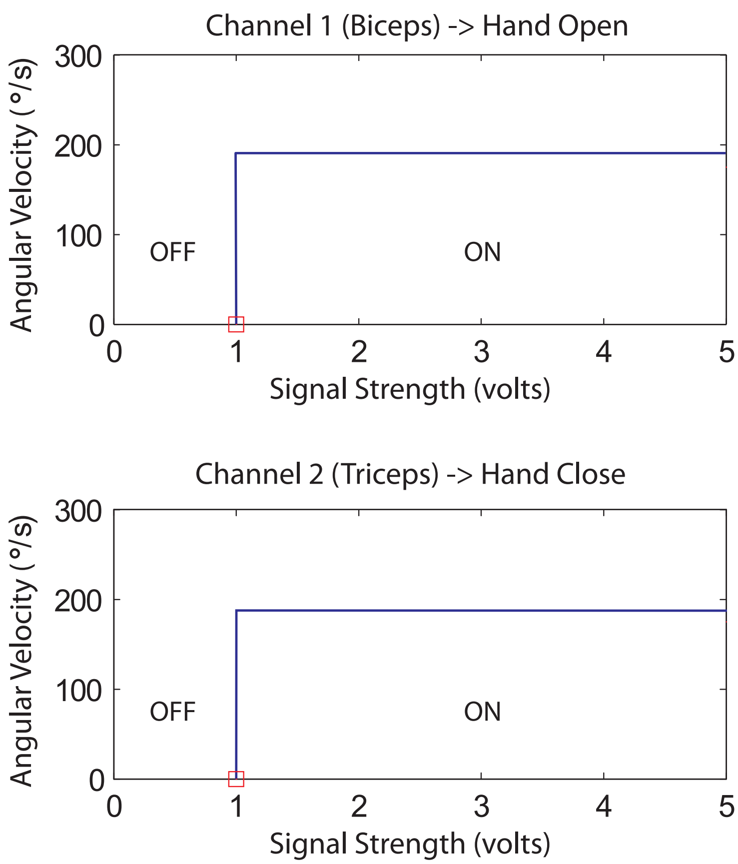


Figure 2.10: A functional representation of the control mapping in a two-state amplitude modulation controller

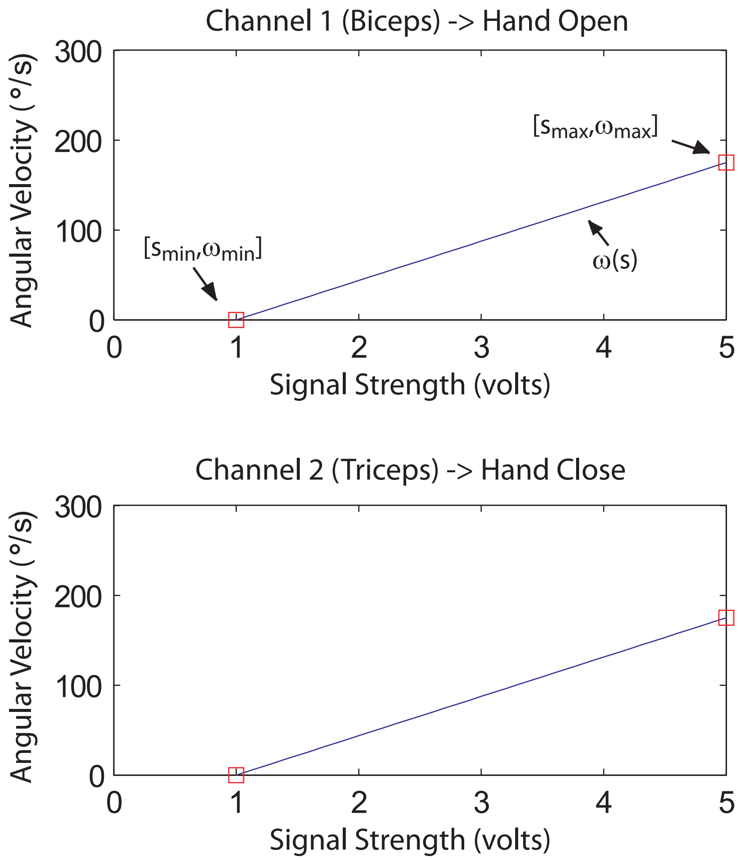


Figure 2.11: A functional representation of the proportional control mapping in a two-state amplitude modulation controller. ω(s) is the angular velocity as a function of signal strength. ω_{min} and ω_{max} are the minimum and maximum angular velocities. s_{min} and s_{max} are the minimum and maximum signal thresholds. Before s_{min} the actuator is turned off and after s_{max} the angular velocity remains constant at its maximum value.

can cause the controller to be un-intuitive for patients to learn and increase the difficulty in training. Additionally, with proportional controllers the averaged EMG signal still contains substantial noise, which can translate into velocity jitter in the actuators.

Many other variations and extensions of these types of amplitude modulation controllers exist, but they all share similar qualities to the conventional controller described above. For example, to achieve more functionality, sometimes a switch is used to select sequentially between DoF (i.e. between hand open/close and elbow flex/extend). The switch can be implemented through such means as a third myoelectric channel (if available), a foot switch, or co-contraction of the original two myoelectric channels. In depth reviews of conventional EMG controllers can be found in the literature. [13, 14].

2.5 Targeted Muscle Reinnervation

Targeted muscle reinnervation (TMR) is a surgical procedure that reinnervates the severed nerves in the residual limbs of amputees into de-innervated healthy muscle tissue where they can be used to generate physiologically relevant control inputs for use in myoelectric prostheses. The procedure was pioneered by Todd A. Kuiken of the Department of Biomedical Engineering, Northwestern University in collaboration with the Rehabilitation Institute of Chicago. Initial studies were performed as early as 1995 and showed promising results on rat models [15]. Subsequent work analyzed the feasibility of the procedure for use in the myoelectric application [16] and eventually led to the first human trial in 2004 [17]. The initial procedure was performed on a patient with bilateral shoulder disarticulation amputations. The residual nerves of the patient including the musculocutaneous, median, radial, and ulnar nerve were reinnervated into the upper pectoralis major, middle pectoralis major, lower pectoralis major, and pectoralis minor muscles respectively as seen in Figure 2.12. Following a five month recovery period after the surgery, three of the four connections had successfully reinnervated. The patient was able to voluntarily generate muscle contractions and control up to two DoF simultaneously on a myoelectric prostheses. In addition to reinnervating the muscles, subcutaneous fat tissue was removed in order to facilitate the reading of EMG signals from the new muscle sites on the pectoralis. Further clinical trials were performed and documented on additional amputee patients at the transhumeral level [18, 19], as well as further results from patients at both amputation levels [20]. From these studies a slightly different reinnervation scheme was developed for transhumeral amputees: The median and distal radial nerves were re-mapped to the medial biceps and lateral triceps muscles respectively.

Due to the initial success and promise of the TMR surgery several other offshoot research

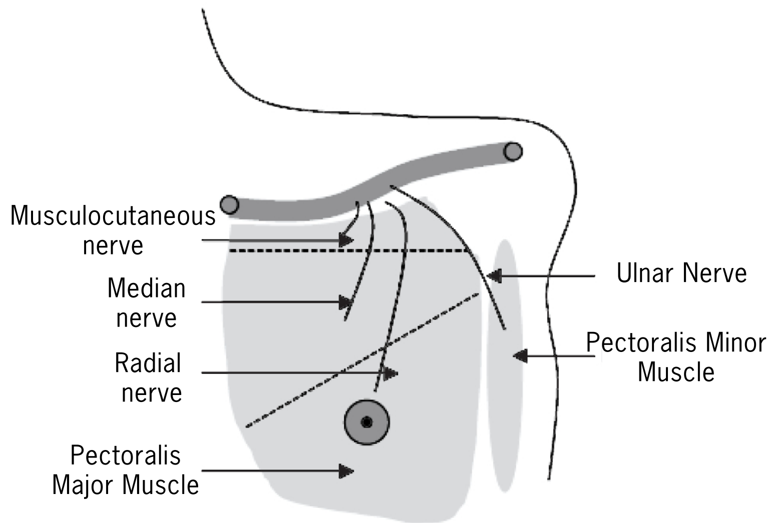


Figure 2.12: Diagram of reinnervated nerves and their respective target muscles (adapted from p7 of [18])

studies have been performed in various areas in order to improve its application in myoelectric prosthetics. Signal processing research related to TMR has focused on issues such as using high density surface EMG recordings [21], removal of electrocardiogram contamination from the heart [22], electrode configuration studies to determine the optimal placing of electrodes over the reinnervated muscle [23], and the use of different types of spatial filtering amplifiers in EMG electrodes [24]. Myoelectric control research related to TMR includes studies related to the use of conventional EMG control methods [25] and pattern-recognition methods [26–28]. An interesting development has occurred through the discovery of target sensor reinnervation [29], which is the reinnervation of the skin over the muscles such that when you touch for example the appropriate area on the pectoralis muscle it would feel to the patient like their hand was being touched. Several studies have been performed in order to investigate using this effect to provide sensory feedback to the patients when they are using their myoelectric prostheses [30–32]. Post-operative occupational therapy protocols have also been researched with the intended effect of improving clinical outcomes for TMR patients [33]. This work highlights the importance of post-operative signal strengthening training prior to prosthesis fitting. The current method involves having the patient simply imagine moving their phantom limb in order to practise generating signal contractions in their newly reinnervated muscle. As previously mentioned, improvements in training during this time serve as a major motivation for this dissertation.

A major advantage of the TMR surgery is that it can provide more control information to control more DoF in a myoelectric prostheses. With traditional myoelectric schemes for above-elbow amputees the patient is limited to at most controlling one degree of freedom at a time that they may be able to switch through sequentially with other DoF. With TMR an above-elbow patient can control two or more DoF simultaneously to create more natural motions. With TMR the control information is also more physiologically relevant (i.e. using your radial nerve to control the wrist rather than your bicep/triceps) and correspondingly can be become more intuitive for the patient to use and learn. The reinnervation of the skin is also an advantage in that it can help provide useful sensory feedback to the patient in addition to the visual feedback, to which traditional methods are limited. A disadvantage of TMR is that it does require an invasive surgery that does include some risks. Also currently the surgery is still rare and has strict eligibility guidelines, only being performed at a few rehabilitation hospitals across the world such as the Rehabilitation Institute of Chicago and the Glenrose Rehabilitation Hospital in Edmonton, Alberta, Canada. Hopefully over time the TMR surgery will become more widespread and be able to reach more patients.

2.6 Myoelectric Control using Pattern Recognition Methods

Another method that exists for mapping from user intent to the measured sEMG signal is the use of pattern recognition or machine learning. Machine learning is a facet of artificial intelligence that involves training a learning algorithm with examples. In general, these algorithms use optimization equations with different weightings to make output decisions based on the input information. Several different kinds of learning algorithms exist and the main differences between them are the methods of optimization, the conditions under which they accept examples, and whether they train online or offline [34].

In myoelectric applications, the input of the learning algorithm is the feature set. The feature set represents the information contained in the myoelectric signal. Typical features that are used in myoelectric applications are MAV, zero-crossings, as well as several frequency domain features that can be extracted using the fast Fourier or wavelet transforms. The example features and their corresponding example outputs (i.e. hand open/close, elbow flexion) are then passed onto the learning algorithm, which is called a classifier. The classifier groups the examples into labels and is then able to be used in real-time as the experimental/computational mapping between user intent and prosthesis function. See Figure 2.13 for a block diagram of the above learning algorithm procedure. Several learning algorithms and feature sets have been studied in the literature for various myoelectric control applications and can be found in [35–37].

The advantages of machine learning algorithms are that they resemble the actual method of motor learning and can potentially be more intuitive for amputees to control. They can also

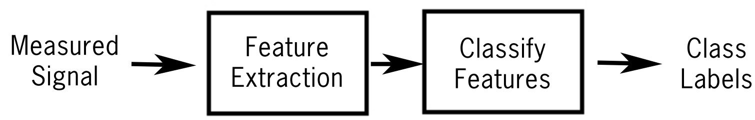


Figure 2.13: Learning algorithm flow chart for myoelectric prosthesis (adapted from p464 of [6])

provide more functions from less muscle sites and electrode channels. A general disadvantage of learning algorithms is that they tend to work well over the range in which they were trained, but conversely do not always work well outside of their training range. Additionally, due to the non-stationary nature of the EMG signal, classifiers need to adapt, which is difficult to achieve in practise. Another option is for the classifier to be retrained over time, but this is cumbersome to achieve logistically in clinical applications. In addition to adaptability, proportional and simultaneous control are also difficult to implement using pattern recognition methods and are the subjects of current and future research in the literature.

Review papers provide in depth coverage on the current state of myoelectric control research [38, 39].

2.7 Conclusion

The background information contained in this chapter was foundational and will be refered to and built upon in future chapters.

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Chapter 3

Review of Myoelectric Training Systems

3.1 Introduction

Upper limb loss is a worldwide problem affecting an estimated 41000 people in 2005 in the United States alone [1]. Amputees must live with reduced motor function, which can negatively impact the type of activities they are able to perform. The goal of upper limb prostheses is to increase the level of functionality closer to the original pre-limb loss level. Myoelectric prostheses in particular use muscle signals voluntarily generated by amputee patients to control robotic powered prostheses.

The conventional method of controlling myoprosthetics uses the rectified mean absolute value (MAV) of a single surface electromyography (EMG) signal measured off of a single muscle group. This measure corresponds to an estimation of the signal strength and is the method most commonly employed in commercial myoelectric prostheses. When the amputee voluntarily increases or decreases the level of contraction in their muscle it results in a measurable increase or decrease in the value of the signal strength. When the signal strength increases above a threshold level it can control a single function on the myoelectric prosthesis (i.e. elbow flexion, hand open, hand close, ect). A typical control setup for an amputee patient with an active myoelectric hand includes 2 channels: one placed over the bicep to control hand opening and one placed over the triceps to control hand closing. The amputee patient is then limited in the number of functions they can perform with the myoelectric arm by the number of discrete muscle sites available for EMG readings.This type of controller is known as a two-state amplitude modulation controller [2]. Three-state controllers are similar to two-state controllers except that they control two functions with one muscle site by using two threshold points (i.e. a medium contraction closes the hand, and a strong contraction opens the hand). More advanced myoelectric controllers in development in the literature use pattern-recognition techniques to map between the patient's intent and the movement of the robotic prostheses [3–5]. It would appear from the literature that these pattern recognition methods are not yet available in commercial myoelectric prostheses.

The clinical application of myoelectric prostheses can include an initial patient evaluation, purchasing of the prostheses with funding often provided by government or charitable agencies, fitting of the prosthesis to the patient by a prosthetist, training of the patient by an occupational therapist, and finally the use of the prosthesis by the patient in daily living accompanied by periodic maintenance [6]. Myoelectric training in particular involves training adult or adolescent patients in how to wear and operate their myoelectric prostheses. Various myoelectric training protocols are covered in the literature and focus on methods for evaluating and improving the patient's performance over time [7, 8]. The clinical significance of myoelectric training is that it can potentially help increase a patient's competence and confidence in using their myoelectric prostheses. Correspondingly, this increase in comfort may also help increase the acceptance rates of myoelectric prostheses. In the literature, training is emphasized as playing a key role in successful fittings of myoelectric devices in children [8–11]. A few studies have shown that training did not have a significant effect on the acceptance rates in adults [12, 13]. These studies found that other more predominant factors such as the amount of time between amputation and prostheses fitting had a greater effect on acceptance rates in adults. The literature is lacking in clinical studies showing the specific effect of training tools on patient performance and acceptance rates.

Typically, myoelectric training is composed of 3 phases: signal, control, and functional training. Signal training involves using myoelectric testing devices, which display the patient's signal levels in real-time, to teach the patient how to activate, relax, and isolate their individual signals. Isolation of individual signals in conventional controllers is important in order to avoid co-contraction, which can cause undesired movements of the prostheses. Control training is the next level of training, which uses more advanced myoelectric training systems, such as prostheses simulators, video games, or robotic arms. These training systems teach the patient how to generate signals for conventional controllers and can also be used in the initial evaluation phase of the fitting in order to help gauge whether the patient is suitable for myoelectric fitting. Functional training is usually performed with the actual myoelectric prostheses and helps the patient learn how to perform tasks for daily living. These tasks can start with basic motor skills such as grasping an object and move up to more advanced tasks such as recreational activities and basic hygiene. [14]

The objective of this review is to describe the myoelectric training systems that have been developed in the literature and commercial industries. The scope of this review will focus on training systems that provide myoelectric training at the control or functional levels.The results of this review will identify common features in the training systems and areas for future improvement.

3.2 Search Methods

A systematic search was performed on the literature in order to find suitable papers for review. The primary database used was Scopus, but Compendex, Medline, and Pubmed were also cross-referenced. The following keywords were used in the search: training, learning aids, amputee, simulation, and virtual reality. These keywords were combined in searches with either 'myoelectric' or 'EMG' as additional keywords. Some examples of searches included: myoelectric training, EMG learning aids, and so on. Papers found in these searches were also cross-referenced checking for additional papers by each author and other relevant papers using the 'cited by' feature in Scopus. The criteria for inclusion in this review are that the paper at least describes the development and testing of a system that the authors mention can be used in myoelectric training applications and was published by the cutoff date of October 1st 2010. The commercial training systems were found by searching the websites of the relatively small number of myoelectric prostheses manufacturers. Under this criteria 12 papers and 3 commercial training systems were selected and are reviewed in the following section.

3.3 Review of Literature

3.3.1 Literature

Lovely et al. from the Institute of Biomedical Engineering at the University of New Brunswick in Canada, published their first work on a myoelectric training system in 1988 [15]. The main improvements of this first system over the commercial EMG signal display devices and toys available at the time were that it easily allowed the therapist to adjust the control settings via a liquid crystal display and was adaptable to new control strategies. In 1990, a second followup training system for children was described that connected to an IBM computer and allowed the patient to practise signal training by playing a video game [16]. The video game involved positioning a pointer over a target and then shooting it. After successfully shooting the target a new one would appear at a random location on the screen. The horizontal movement of the pointer was controlled via conventional two or three state EMG controllers using up to two EMG electrodes. The vertical movement and the shooting was controlled with a PC joystick. Using the EMG control on the residual limb and the joystick with the sound limb allowed the patient to practise coordinating their limbs together simultaneously. Both the joystick and EMG electrodes were connected to the computer via custom hardware board. The system also included a performance database that stored the patient's information and results over multiple trials. Results from limited trials at the Institute's Prosthetics Research Center, Fredericton showed positive reactions from children less than 10 years old.

In 1994, Dupont et al. from Queen's University in Canada published details about their MCETS (Myoelectric control and Evaluation Trainer System) [14]. The MCETS was implemented as a computer program that simulated the opening and closing of a myoelectric hand viewed in two dimensions from the side. The MCETS interfaced with an existing EMG acquisition system developed at the Hugh Macmillan Rehabilitation Centre in Toronto. The goal for the patients was to open or close the hand until it matched a target image. Three difficulty settings were available to the patient with the highest difficulty setting corresponding to the smallest leeway in matching the controlled hand to the target image. The program included evaluation and assessment features such as saveable patient information and results from multiple training sessions. The system used two bipolar surface EMG electrodes placed over the antagonist muscles in the wrist and a conventional two-state myoelectric controller to map the patient's signal strength to the hand opening/closing velocity. A study with able-bodied participants was performed and analyzed statistically to validate the effectiveness of the training tool. The learning curves and analysis of user error generated by the study showed that the participants improved over the course of the trials.

Fukuda et al. from Hiroshimi University in Japan published a work on their myoelectric training system in 1999. The system was developed in order to help patients train to use a myoelectric control system based on a pattern recognition method [17]. EMG signals were recorded by four electrodes on the forearm and two on the upper arm. The signals were then acquired by a computer via a data acquisition system. The signals were interpreted using a log-linearized Gaussian mixture network (LLGMN) in order to control the movements of a robotic arm. The motions discriminated by the robotic arm were hand open/grasp, wrist supination/pronation, and elbow flexion/extension. The system provided three different training modes for the patient. Muscular contraction training involved having the patient practise holding the signal strength within various target bands for a certain length of time. Cooperation training involved training the LLGMN classifier by having the patient perform the combined muscle contractions corresponding to the various movements previously mentioned. In the timing training mode the patient was able to practise using the motions in various combinations for certain lengths of time. The control method was validated using an experiment with an amputee patient. The results of the experiment showed that the discrimination ability of the patient increased over a five day period of using the training system.

In 2003, Soares et al. from the Federal University of Uberlandia in Brazil published a work describing the development of a virtual myoelectric prosthesis to be controlled by a pattern recognition method [18]. The identified applications for the virtual prosthesis were studying new control methods and myoelectric training for patients. The pattern recognition method employed was an artificial neural network (ANN) with autoregressive coefficients. Five EMG electrodes were placed over the bicep and tricep muscles of the upper arm and read into a computer via a data acquisition card. An analog bandpass filter with cutoff frequencies of 20Hz and 1kHz was used to filter out unwanted noise. The output of the ANN were the following four class labels that were used to control the movements of the virtual prostheses: elbow extension, elbow flexion, wrist supination, and wrist pronation. The virtual simulation was created using the virtual reality modelling language (VRML) in a Java application. The simulation provided visual feedback to the patient in the form of a three dimensional virtual person moving their arm with the desired motions. A study was performed using the virtual prosthesis with the ANN and the author reported classification accuracies of between 95-100%.

A virtual reality training system was developed by Pons et Al. of the Instituto de Automatica Industrial in Spain in 2005 for use in training the MANUS hand prosthesis developed by the same research group [19]. The study proposed a control method based on a 3-bit language. This control method works similar to the three state-controller except the patient would perform three successive commands with the values of 0,1, or 2 which would correspond to movements of the hand prosthesis. This method supports up to 18 output commands for the hand. For example a 1-0-0 pattern (medium contraction followed by relaxation) would output the stop command. Another example would be a 2-1-0 pattern (strong contraction, followed by a medium contraction and then a relaxation) which corresponds to the command that rotates the hand to the left. The system included EMG electrodes that recorded the muscles signals, which were then passed onto a computer via a data acquisition system. The virtual reality training included features that allowed the user to calibrate EMG parameters and map 3-bit commands to output movements on the virtual prosthesis. The virtual prosthesis was represented as a three-dimensional hand. Additional features of the training platform included a database for holding patient data and the ability for a patient training at home to send saved clinical data to a therapist via email. A study was performed on 15 amputee patients and the results showed they were able to learn to use the 3-bit language to a satisfactory level using the training platform.

In 2007, Hauschild et al. from the University of Southern California reported on a virtual reality environment [20]. The primary applications of this system were for it to be used as a tool in designing neural prosthetic limbs and to test control algorithms for functional electrical stimulation (FES). A secondary application was for the system to be used as a tool for patient training. The system included a motion capture system and a three dimensional head mounted display for the patients. A data acquisition card was used to acquire EMG signals and other sensory data into a real-time computer running Matlab's xPC software. The real-time computer contained the controller software and was connected to the visualization computers, which provided visual feedback to the patient. A full three-dimensional dynamic model of an arm was created in order to accurately model the movement of an actual or robotic limb. In initial EMG tests, a virtual myoelectric hand was successfully controlled using a conventional two-state proportional controller.

Takeuchi et al. from Kagawa University in Japan described a training system for myoelectric prosthetic hands [21] in 2007. The training system worked by having the patient control a myoelectric hand in a virtual environment. The system included two EMG electrodes, which acquired the EMG signals into a computer for interpretation. The angular velocity of virtual hand was controlled via a method similar to conventional EMG control. The grasping force was also controlled in order to help the patient maintain their grasp on objects. The task in the study was for the patients to grasp a virtual object without breaking it. The goal of the study was to test a method for virtually assisting the patient with training by changing the task difficulty to match their current skill level. The task difficulty was adjusted by increasing or decreasing the strength of the virtual object. The study was performed on able-body participants and the results showed that their skill at using the EMG control significantly improved with the virtual assist training method.

A virtual reality system modeling a below-shoulder three dimensional arm was reported by Al-Jumaily et al. from the University of Technology, Sydney in Australia in 2009 [22]. The system was used to test out a pattern recognition based method using fuzzy wavelet packet based feature extraction. The authors mentioned that the system could also be used in training applications. The controller output and virtual arm included the following ten classes of movements: forearm pronation/supination, wrist flexion/extension, hand ball grab/release, hand open/rest, and wrist radial/ulnar deviation. EMG signals were acquired via 16 electrodes placed over the upper arm. The virtual environment was created using VRML in Matlab's virtual reality toolbox.

In 2009, De La Rosa et al. from the University of Valladolid in Spain described their UVa-Neuromuscular Training System (UVa-NTS) [23]. The UVa-NTS was designed to be portable and included a virtual arm and myo-pong computer game. The system contained two modules: a custom hardware signal-conditioning unit which acquired and processed the EMG signals and a PC computer, which interprets the signals and runs the training tools. In the myo-pong game two paddles were controlled via EMG signals produced by two separate muscles such as the biceps and triceps. The game used methods similar to conventional EMG controllers whereby when the signal strength exceeded or fell below a threshold the paddle moved towards the bottom or top of the screen respectively. The difficulty of the game was adjusted by controlling the speed of the ball and the size of the paddle. Several parameters were used for evaluating the patient such as success rate (ratio between successful hits to total number of misses) and admissible speed (maximum speed of ball to maintain a desired success rate).

The development of Air-Guitar Hero was reported in 2008 by Armiger et al. of John Hopkins University [24]. Their system used custom hardware and a pattern recognition based myoelectric controller to interface with the popular Guitar Hero video game. The suggested application for their system was for performance evaluation of pattern recognition based EMG controllers. They also identified patient training of pattern-recognition based controllers as a potential barrier to their implementation and suggested that their system could help improve the training process by making it more engaging and fun. Six to eight differential EMG electrodes were placed over the forearm and acquired into a computer using a data acquisition card. A virtual integration environment developed in Matlab was used as the software platform for the controller. An experiment was performed testing the system on able-bodied participants. Results from the experiment showed the participants were able to increase their accuracy by the third trial. A similar followup work by the same research group was performed in 2010 with their development of the WiiEMG system [25]. The WiiEMG system interfaced with the Nintendo Wii controller to allow EMG control of Wii games via the same general architecture as described in their Air-Guitar Hero study. The main difference was in the hardware interface connecting the EMG electrodes to the controller and how the EMG signals were interpreted into accelerations that the Wii controller could understand. In their initial experiments they had able-body participants test the system by playing Wii Tennis. Results from the experiments showed that the participants were able to improve their average scores over the course of the trials.

3.3.2 Commercial Training Systems

Touch Bionics' BioSim software gives the ability to adjust various features and control options in their i-Limb myoelectric hand. The software comes in versions that can be used by both the prosthetist and the amputee patient. The software connects to the i-Limb using a wireless interface and can be used to record and evaluate the patient's EMG signals in real-time [26].

Myolab II EMG Tester is a training system that was developed by Motion Control to help prosthetists fit and train patients who use myoelectric prostheses such as Motion Control's Utah Arm. The training system includes a portable myoelectric signal testing device. The device allows the patient to see their own EMG signals visually and also provides audio feedback. The system acquires the patient's EMG signals via Motion Lab's EMG preamplifiers, which are sold separately [27].

Otto Bock's MyoBoy is a training system for helping patients learn to use Otto Bock's myoelectric hand prostheses. The system includes 2 Otto Bock EMG electrodes with built in preamplifiers and filters, MyoBoy training software, a robotic training hand, and a portable myoelectric signal testing device that can display the patient's EMG signals. The training software includes the ability to configure and test various conventional control schemes, a real-time moving graph display to visualize the patient's EMG signals, a virtual prosthetic hand, and an EMG-controlled computer game. In the computer game the patient has to navigate a car through openings in the walls by modulating the strength of their EMG signals. The software also has functionality for recording patient information including changes in their signal strength over time [28].

3.4 Discussion

A summary of the training systems found in the literature can be found in Table 3.1. The Pub. Year column refers to the publication year and is organized chronologically. An explanation of each remaining column and the general trends in the literature are given below.

The application column lists each study's primary and secondary applications. When a study has a primary training or research application it means that the system focused mainly on the development of either a training system or research platform for testing new EMG controllers respectively. The systems in the academic literature tended to have a strong emphasis on research while the commercial systems focused entirely on training. Another potential application for these training systems beyond training for prostheses is in the area of phantom limb pain. Recent work has started to investigate whether controlling a virtual arm using EMG inputs can help amputees reduce their phantom limb pain [29].

The movement column refers to the types of prostheses movements that the training system helps the patient practise. Over time the amount of functionality in the training systems has generally increased, which reflects on the advancement in commercial and experimental myoelectric prostheses since the 1980s. The primary focus in the literature is on training systems for hand prostheses and relatively little work has been done for multi-function prostheses at the above-elbow level. With the recent advent of targeted muscle reinnervation (TMR), which reinnervates severed nerves into healthy muscle tissue and increases the number of muscle sites available for use in control purposes [30], multifunction above-elbow prostheses have started to become more common and training systems will need to eventually be designed to help accommodate TMR patients' training needs.

The channels column refers to the number of EMG electrodes used in the system. Systems that use conventional controllers typically use two electrodes while systems that use pattern recognition methods will use four or more. Most systems also include some sort of data acquisition system with filters to bring the EMG signals into a control computer.

The controller column refers to what type of controller the training system supports. Some of the pattern recognition papers that use prosthesis simulators mention that their systems could be adapted to use conventional controllers for training purposes, however none of these papers have yet followed up on this line of research. While creating training tools for novel pattern recognition methods is important for research purposes, unfortunately it is not yet clinically relevant because the commercial prostheses amputees are currently using all employ conventional control schemes.

The training methods column refers to the type of training method used by each system. Since the 1980s the academic literature has shifted away from devices that just display the signal strength to more advanced training techniques such as EMG control of video games, simulators, and robotic arms. It should be noted that most of these more advanced training methods also include options for basic training based on the display of signal strength. Two of the commercial devices still mainly just display signal strength while Otto Bock's MyoBoy has a multipronged approach for training myoelectric hands including all of the above mentioned training types. The advancement of dynamic models in three dimensional virtual reality simulators will eventually allow patients to perform functional training in addition to signal and controls training.

The experiments column briefly describes what kind of experiments (if any) the papers performed to validate their methods. Most of the papers performed tests on able-bodied participants and only a few used amputee patients. The type of results reported varied from most commonly using qualitative analysis to a few that used statistical analysis. While some of the papers mentioned possibly performing additional studies to link their training system to improved clinical outcomes, no papers have followed up on this. In order to establish the importance of training systems, future work in the literature needs to be directed towards investigating the effect of these training tools on clinical outcomes. Possible methods for measuring clinical outcomes in studies could come from qualitative surveys of patients, prosthetists, and occupational therapists and also from quantative measures such as prostheses acceptance rates, learning rates, and patient performance on motor learning tasks.

3.5 Conclusion

In conclusion, the author has identified several obstacles that need to be addressed before advanced myoelectric training systems can see widespread use. Firstly, they must be inexpensive, portable, and reliable so that they can be accessible and affordable to rehabilitation centres. Ideally, the rehabilitation centres would be able to afford multiple training systems and be able to send them home with the patients to train remotely. The systems should also be designed so that they are adaptable to current and future control schemes. They should be flexible to accommodate patients at different amputation levels who will be eventually using above or below elbow prostheses. In order to promote their use and reduce the amount of motivation required to use them they should be fun and easy to use by prosthetists, occupational therapists, and patients. Multiple training methods should be employed in the different training phases such as signal strength display and EMG control of simulators, robotic arms, and video games. The training methods should include functionality for measuring and recording the performance of the patient throughout their training period. Finally, studies need to be performed in order to definitively establish a relationship between these training systems and clinical outcomes in amputee patients.

Table 3.1: Summary of the training systems found in the literature

Pub. Year	Reference	Application(s)	Movements	Channels	Controller	Training Method(s)	Experiments
1988	Lovely et al. [15]	Training, Research	Hand open/close	2	Conventional	Display signal strength	Preliminary testing with amputee patients
1990	Lovely et al. [16]	Training, Research	Hand open/close	2	Conventional	Video game	Preliminary testing with amputee patients
1994	Dupont et al. [14]	Training, Research	Hand open/close	2	Conventional	2D simulator	Statistical trials with able-bodied participants
1999	Fukuda et al. [17]	Research, Training	Hand open/close, Wrist supination/pronation, Elbow flexion/extension	4	Pattern recognition	Robotic arm	Single trial with amputee patient
2003	Soares et al. [18]	Research, Training	Wrist supination/pronation, Elbow flexion/extension	5	Pattern recognition	3D simulator	Controller performance
2005	Pons et al. [19]	Research, Training	Multiple hand gripping modes, Wrist supination/pronation	1	3-bit language	3D simulator	Controller performance
2007	Hauschild et al. [20]	Research, Training	multiple hand, wrist, elbow and shoulder movements	2	Conventional, Pattern Recognition	3D simulator	Preliminary tests
2007	Takeuchi et al. [21]	Training, Research	Hand Open/Close	2	Conventional	3D simulator	Statistical trials with able-bodied participants
2008	Armiger et al. [24]	Training, Research	N/A	6-8	Pattern recognition	Video game	Trials with able-bodied participants
2009	Al-Jumaily et al. [22]	Research, Training	10 forearm movements	16	Pattern recognition	3D simulator	controller performance
2009	De La Rosa et al. [23]	Training, Research	Hand Open/Close	2	Conventional	Video game	N/A
2010	Oppenheim et al. [25]	Training, Research	N/A	6-8	Pattern recognition	Video game	Trials with able-bodied participants
N/A	Biosim [26]	Training	Hand movements	2	Conventional	Display signal strength	N/A
N/A	Myolab [27]	Training	Hand open/close	2	Conventional	Display signal strength	N/A
N/A	MyoBoy [28]	Training	Hand open/close	2	Conventional	Virtual hand, Video Game, Robotic hand	N/A

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Chapter 4

Development of the MTT Research Prototype

4.1 Introduction

This chapter describes the development of a myoelectric training tool (MTT) for upper limb amputees that will help them learn how to use myoelectric technology in advance of receiving their actual myoelectric prosthesis. After presenting some background information the next several sections summarize the design and evaluation process that was used during the development of the MTT. The final sections summarize the results of the evaluation and the future work required to clinically realize the MTT.

Myoelectric prostheses are robotic prostheses that are controlled via electromyography (EMG) electrodes attached to the residual muscles of amputee patients. The patient is able to control the velocity of the prosthesis actuators by voluntarily contracting their residual muscles. The objective of myoelectric prostheses is to restore some functionality to the patient and by doing so help improve their quality of life.

Part of the difficulty in learning to use myoelectric prostheses comes from how they are normally controlled. The conventional control methods currently employed in myoelectric prostheses map an estimate of the signal strength from a single surface EMG signal measured off of a single muscle group to the velocity of a single actuator on the robotic prostheses. The patient is required to modulate their signal above a threshold value after which the velocity of the actuator can be controlled in an on/off or proportional manner. For example an above elbow patient could use their biceps to control hand opening and their triceps to control hand closing. In the literature this type of controller is known as a two-state amplitude modulation controller [1]. Since the patient is limited by the number of muscle sites available and higher level amputees have less muscle sites only a limited number of degrees of freedom (DoF) on an actuator can be controlled at a time. To circumvent this problem, switches are added to the control scheme that can allow a patient to cycle through available functions sequentially. These switches can be controlled by an additional EMG channel or a linear displacement transducer. Unfortunately, these control methods are somewhat unintuitive since they require the patients to modulate muscles individually and sequentially instead of groups of muscles simultaneously. More advanced myoelectric controllers in development use combined muscle signals via pattern-recognition techniques to control the movement of the robotic prostheses [2–4]. It appears that these pattern recognition methods are not yet available in commercial myoelectric prostheses.

A surgical development called targeted muscle reinnervation (TMR) reinnervates residual nerves into healthy muscle tissue and creates more muscle sites that can be used for control purposes [5]. Without this surgery above-elbow amputees are typically limited to controlling one DoF sequentially using two or three muscle sites. After the TMR surgery the patients can get as many as five muscles sites, which can potentially allow them to control two DoF simultaneously while still having one muscle site available for switching. The Glenrose Rehabilitation Hospital (GRH) in Edmonton, Alberta, Canada has recently started performing these surgeries and needs a myoelectric training system with increased functionality in order to accommodate the TMR patients. Through discussion with prosthetists at the GRH it was revealed that the current method of training TMR patients involves having them imagine moving their phantom limb and leaves much room for improvement.

In consultation with the GRH and the MTT design team the objectives and scope of the project were defined. The first objective of the MTT is to help upper limb amputees (both TMR and non-TMR) learn to use myoelectric technology in advance of receiving their actual myoelectric prostheses. Within this objective the MTT will also be useful as an evaluation tool to determine whether a myoelectric prostheses will be a good fit for a patient in advance of them starting the wheels going on the funding process. The second objective is for the MTT to be used as a research platform for testing new pattern-recognition controllers. This objective will be tackled in collaboration with the Reinforcement Learning and Artificial Intelligence group (RLAI) from the Computing Science (CS) department at the UofA. The scope of the project will include the design, manufacturing and testing of an initial proof of concept MTT prototype, which meets the core requirements outlined in the following subsections.

4.1.1 Electrical Safety Standards and Guidelines

A review of safety standards and guidelines was performed. In Canada the main standard for the requirements of medical electrical devices relating to basic safety and essential performance is CAN/CSA-C22. No. 60601-1, which is based off of the international standard IEC 60601-1. Additional standards for medical devices include ISO 13485 - Quality Management Systems, ISO 14971 - Application of risk management to medical devices and ISO 14155 - Clinical Investigations. Considering that these standards are geared more towards commercial products and that the safety risk of the proposed device is very low, it was determined that these stringent standards need not be strictly followed during the development of the initial research prototype of the MTT. However, future MTT prototypes that will be used in a clinical setting should more closely conform to the above mentioned standards.

The SENIAM (Surface EMG for a Non-invasive Assessment of Muscles) guidelines were released in 1999, with the aim of trying to standardize EMG measurement methodologies across research groups [6]. The SENIAM guidelines make recommendations pertaining to the design of EMG electrodes, their positioning, and EMG signal processing and acquisition. The relevant parameters were extracted from the SENIAM guidelines and used as design requirements for the electrical subsystems of the MTT.

4.1.2 Review of Training Systems

A review of existing training systems in the literature and commercial industries was performed in order to determine the strength and weaknesses of current systems and areas for improvement that could be included in the MTT. In terms of significance, training in general was found to be an important factor in successful fittings of children [7–9]. However, for adults training was not found to have a significant impact on acceptance rates [10, 11]. Their is a gap currently in the literature between showing a patient is able to learn with a training system and showing that training actually helps improve their clinical outcome. Future clinical studies that focus specifically on training systems need to be performed in order to determine whether these devices can be linked to improved clinical outcomes.

The training systems in the literature included the following types of devices: signal strength displays [12] myoelectrically controlled video games [13–16], robotic arms [17], and computer simulations [18–23]. The devices in the literature were found to have a strong emphasis on being platforms for researching new myoelectric control methods rather than a training focus on helping patients learn to use the conventional control schemes commonly used in commercial prostheses. The systems with a training focus were typically limited to controlling only a single degree of freedom on a myoelectric hand (i.e. hand open/close) using two EMG electrodes.

The training systems available commercially included signal display devices [24, 25], and Otto Bock's Myoboy [26]. The MyoBoy included functionality for signal display, a simple

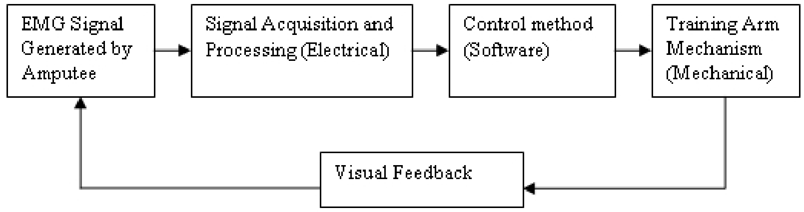

Figure 4.1: Simplified flow chart of a myoelectric control system

video game, and a myoelectrically controlled hand available as both a 2D simulator and an actual physical robotic hand. The application focus for these commercial systems was found to be exclusively training to use each company's myoelectric prostheses and all devices were limited to controlling a single degree of freedom using two EMG electrodes.

From the review of these devices several key requirements and improvements have been identified. Firstly, training systems should be affordable, portable, and reliable with features to evaluate and record patient performance that can be used at a rehabilitation center or remotely by the patient. The systems should also be designed so that they are adaptable to current and future control schemes. They should be flexible to accommodate patients at different amputation levels including TMR and non-TMR patients. In order to promote their use the devices should be fun and ergonomic. Multiple training methods should be included as options such as signal strength display and EMG control of simulators, robotic arms, and video games.

4.1.3 Design Specifications

A design specification matrix was compiled using all of the information gathered from the initial research. The requirements were broken up into the following subsystems: mechanical, electrical, and software. A simplified diagram illustrating the different subsystems and how they relate to each other can be seen in Figure 4.1. Some of the key requirements are given below. The overall system cost was specified to be $6000. For the full specification matrix see Appendix A.1.1.

In the mechanical section the key specifications were for the robotic arm, which needed to be approximately half scale, anatomically correct, and weigh about five to ten pounds. The robotic arm should include five DoF which mimic the DoF of below and above elbow prostheses available on the market. The target cost for the robotic arm was $1000.

The electrical subsystem included requirements for the robotic arm actuators and the EMG acquisition hardware. In order to mimic commercial prostheses the actuators needed to be velocity controlled and to include positional feedback for implementation in safety features. Five EMG electrodes and a data acquisition (DAQ) system with at least five differential analog input channels were specified by the GRH. A decision was made to specify that the electrodes should run off of DC battery power on this prototype in order to minimize the risk associated with improper patient isolation. Future clinical prototypes that follow the ISO and IEC standards may not have this requirement and instead use medical grade power supplies and AC power. The target cost of the electrical subsystems was $5000.

In the software subsystem specific requirements related to processing the acquired EMG signal, controlling the robotic arm, and displaying all of the necessary information to the patient via a graphical user interface (GUI). The desired conventional control scheme was specified by the GRH with a delay time of 0.200 seconds or less. The core features for the GUI were also specified and having a 3D simulator was noted as a desirable feature. The software development environment for the EMG controller was chosen at the outset of the project to be MATLAB's xPC Target real-time prototyping environment in order to support conventional and novel controllers. This development environment was chosen because of the compatible hardware already available to the author at no cost as well as previous design experience from other projects. The environment includes pre-made plug and play driver blocks for many DAQ cards and a signal processing toolbox that can be used to save development time on low level software and EMG signal analysis respectively. Using a real-time environment also helps avoid some of the delays and complexities associated with threading on non real-time computers.

4.2 Methods

The design of the MTT research prototype and the experimental methods used to evaluate its performance are described in this section. The overall system flow diagram can be seen in Figure 4.2. A detailed bill of materials (BOM) for the entire MTT system can be found in Appendix A.1.3. When possible the least expensive components still meeting the design requirements were chosen in order to reduce the system costs. The overall cost of the MTT prototype was $5400 coming in slightly below the target cost of $6000. The next few subsections describe the components selected and development work for each subsystem in detail.

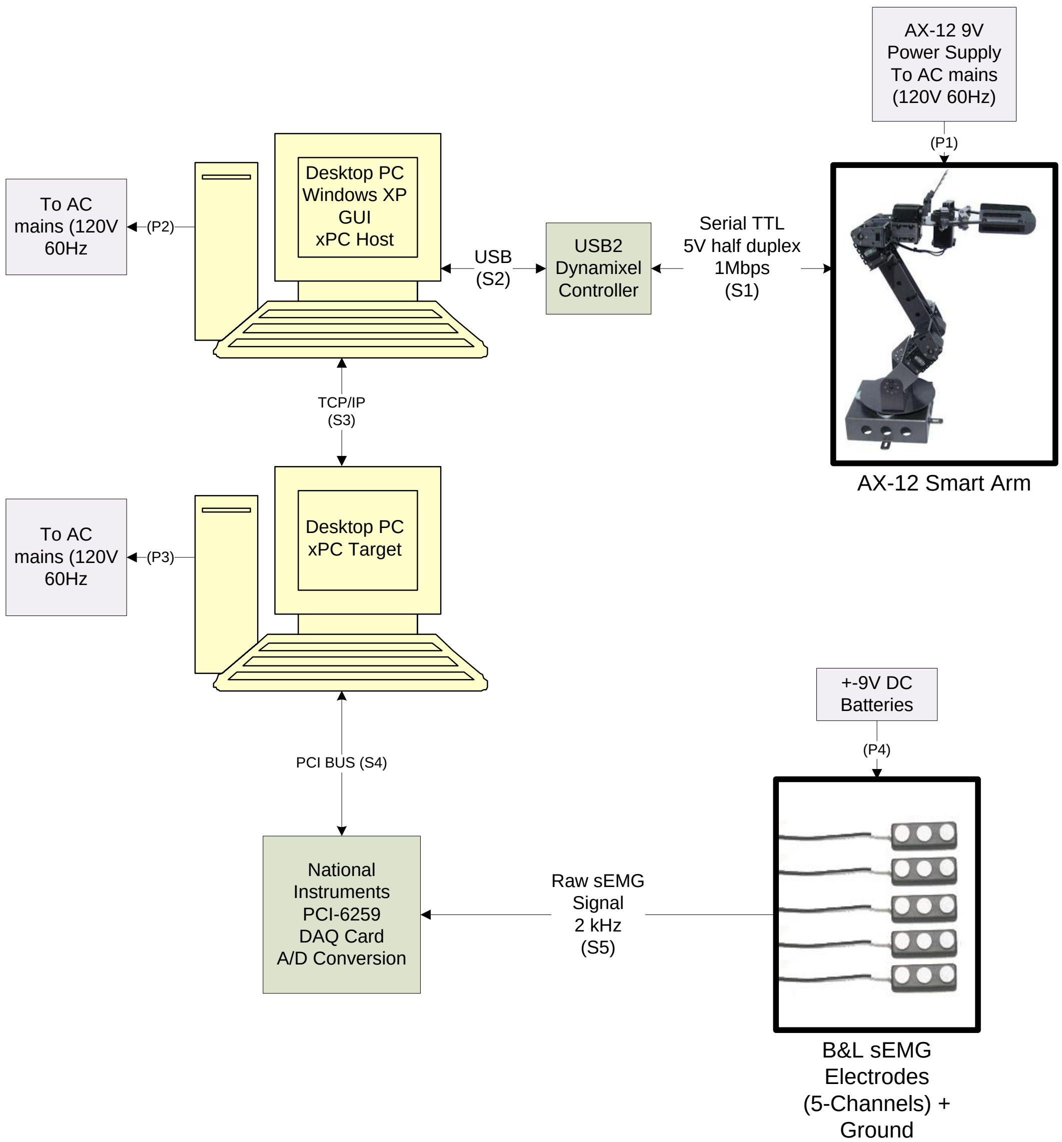

Figure 4.2: System flow diagram of the MTT research prototype.

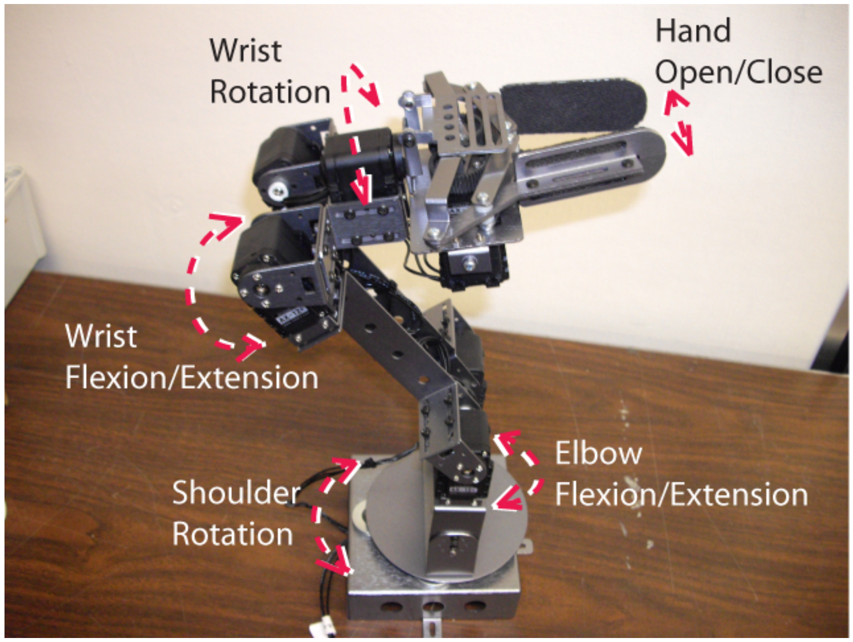

Figure 4.3: Crustcrawler's AX-12 Smart Arm and its available degrees of freedom including: shoulder rotation, elbow flexion/extension, wrist flexion/extension, wrist rotation, and hand open/close.

4.2.1 Mechanical Subsystems

The main mechanical components are the links and joints of the robotic arm. The AX-12 Smart Arm kit, developed by Arizonan robotics company Crustcrawler, was selected as the robotic arm for the MTT. Figure 4.3 illustrates the AX-12 Smart Arm and its available degrees of freedom including: shoulder rotation, elbow flexion/extension, wrist flexion/extension, wrist rotation, and hand open/close. The brackets are made from 5052 brushed aluminum with an anodized finish. The AX-12 Smart Arm meets all of the desired specifications except some of the relative link proportions are not quite anatomical. Another advantage of choosing this off-the-shelf solution is that it will be easier to procure more hardware in the case of additional robotic training arms being required. The robotic arm is secured to a table using adjustable clamps. The kit included detailed assembly instructions and took about four hours to fully assemble. Figure 4.4 shows the 3D CAD model of the AX-12 Smart Arm that was created in PROE Wildfire 4.0 for use in the MTT simulator.

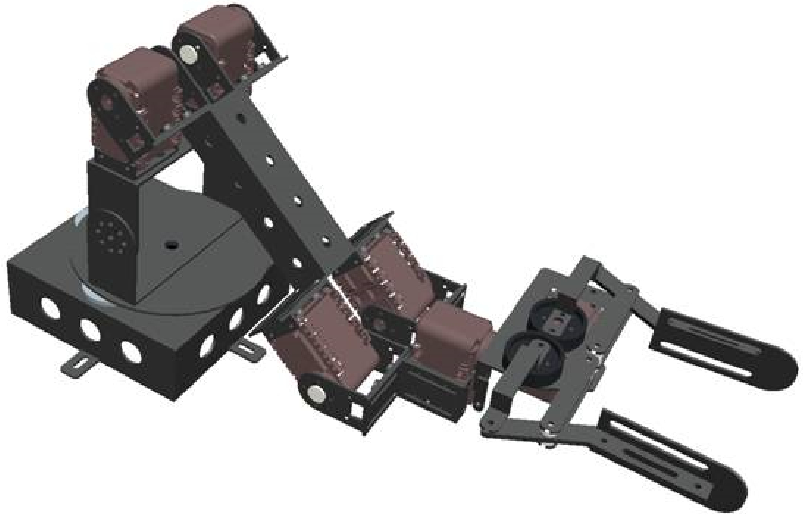

Figure 4.4: Image of the 3D CAD model of the AX-12 Smart Arm.

4.2.2 Electrical Subsystems

The actuators used in the AX-12 Smart Arm are the AX-12 Dynamixel servomotors as seen in Figure 4.5. Seven motors provide the required degrees of freedom with the flexion/extension DoFs using two servos because they are the most heavily loaded. Each servo has positional or velocity control along with positional, velocity, temperature, and load feedback. In the event of the temperature or load becoming too high the servos will automatically shut down providing a valuable safety feature. The positional restraints can be set within the internal servo controller in order to prevent the arm from swinging back towards the patient. The actuators are daisy chained together and controlled by the target embedded computer via the USB2Dynamixel controller through a USB interface. Power is supplied to the AX-12 servos via an off-the-shelf power harness and power supply kit, which runs at 9V up to a max current draw of 6A.

The BL-AE-N surface EMG electrodes developed by Californian company B+L engineering were selected for the MTT and closely follow the SENIAM guidelines. The BL-AE-N electrode can be seen in Figure 4.6. The stainless steel electrodes are arranged in a single differential configuration and include a built in pre-amplifier with a gain of about 330 that helps scale the acquired EMG signal close to the desired $\pm$5V range of the DAQ system. The electrodes have a common mode rejection ratio (CMRR) of 95dB, which helps reduce noise in the acquired signals. The input impedance is greater than 100Mohms and helps to prevent current from leaking back into the patient in fault conditions. The bandwidth of the

Figure 4.5: Image of the Dynamixel AX-12 Servomotor.

electrodes is 12 to 3000Hz with a 3dB roll off. The EMG electrodes are powered by two 9V DC batteries via a custom powering harness and are secured to the residual limb of the patient using wrist bands or velcro straps. For details of the custom powering harness see Appendix A.2.

The EMG signals are sampled at 2kHz by a National Instrument (NI) PCI-6259 DAQ card with 16-bit resolution. The EMG electrodes connect directly to a shielded NI SCB-68 connector block as seen in Figure 4.7, which pass the signals onto the PCI-6259 via an off-the-shelf cable. The PCI-6259 is connected to the target computer via a PCI slot and the target computer is connected to the host computer via a TCP/IP connection and standard ethernet cable. The target and host computers are standard desktop computers running on the dedicated xPC Target kernel and Windows XP operating systems respectively. Detailed connection diagrams for the electrical hardware can be found in Appendix A.2.

Figure 4.6: Image of the Bl-AE-N electrodes.

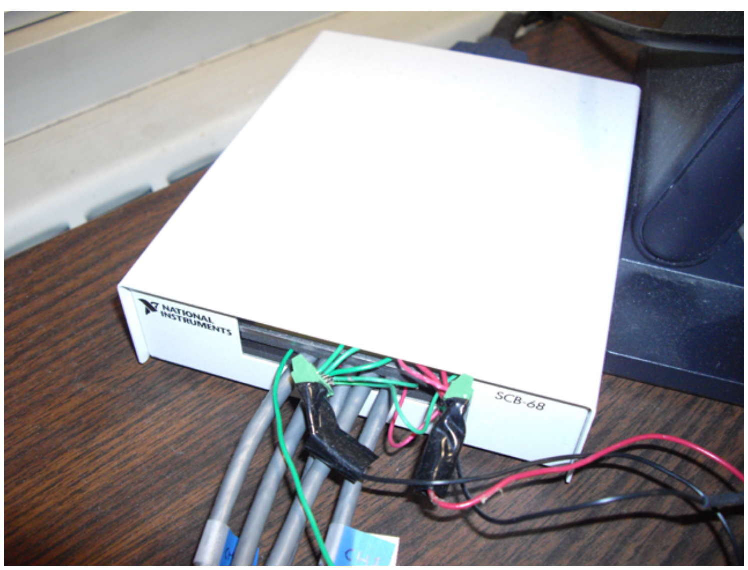

Figure 4.7: Image of the NI SCB-68 connector block

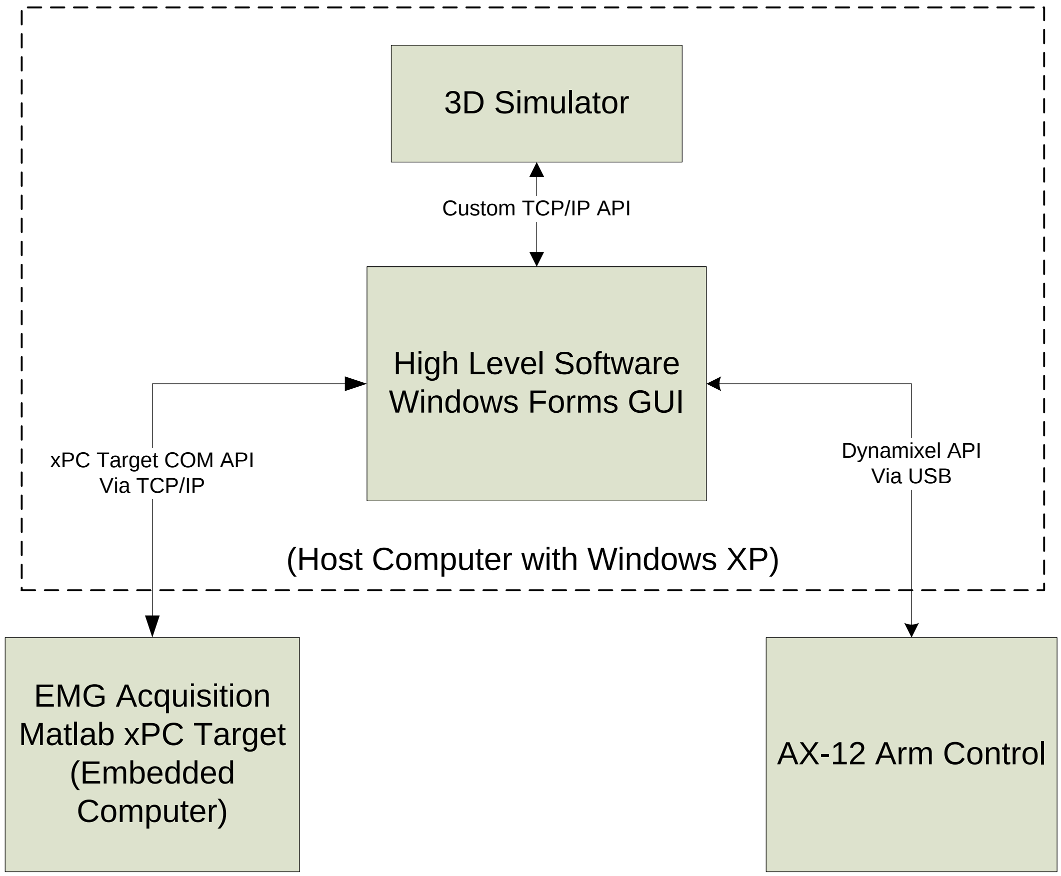

Figure 4.8: A block diagram showing the overall software architecture of the MTT.

4.2.3 Software Subsystems

The overall software architecture can be seen in Figure 4.8. The software was broken down into the following subsystems: EMG Acquisition and Control, GUI, Robotic Arm Control, and the MTT simulator. Whenever possible software subsystems were connected to each other through existing application programming interfaces (API) in order to save on development time. The EMG Acquisition and Control subsystem connects to the GUI via the xPC target COM API available in MATLAB and the Robotic Arm Control subsystem connects to the GUI via an existing Dynamixel API developed by Agave Robotics [27]. The simulator connects to the GUI via a custom API created by the MTT simulator design team.

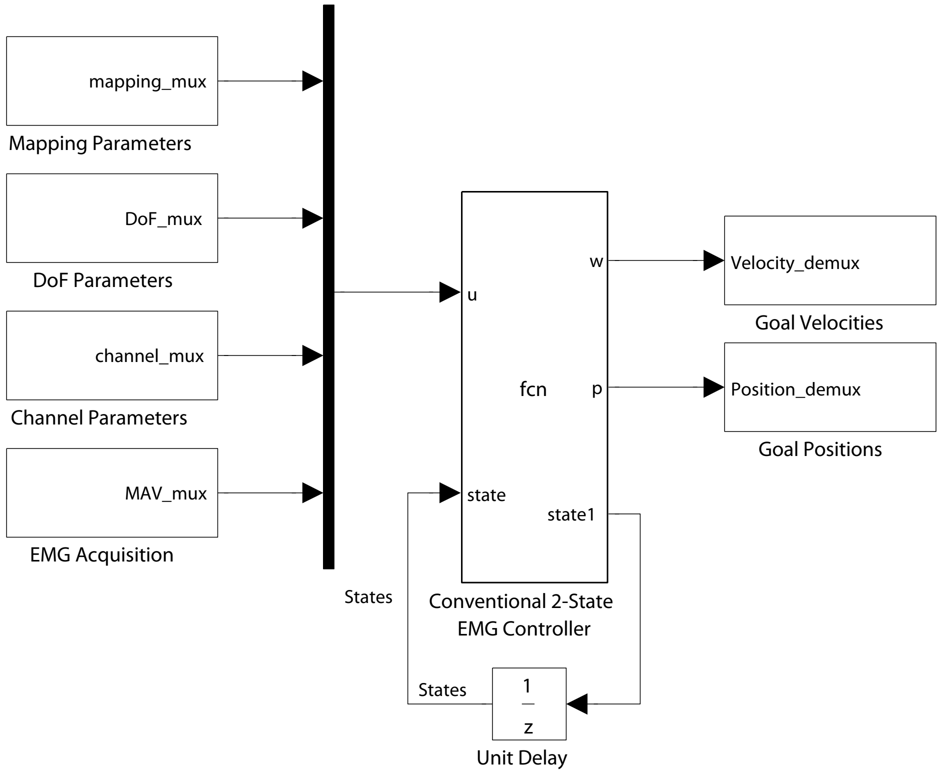

Figure 4.9: The top level block diagram of the EMG Acquisition and Control software.

EMG Acquisition and Control

The EMG Acquisition and Control software was created in the MATLAB R2009b simulink environment using the xPC target and signal processing toolboxes. An overview block diagram of the software can be seen in Figure 4.9. The timestep of the software is 0.0005 seconds, which corresponds to the 2kHz sampling rate of the DAQ card. This sampling rate was chosen in order to be at least twice the nyquist frequency, which was recommended to be 500Hz in the SENIAM guidelines. The software is compiled using the Visual C++ compiler from Visual Studio 2008 and can be loaded directly onto the target computer using the xPC Target embedded option. Within the xPC Target environment the software runs under hard real-time conditions, which means that if all the required operations cannot be completed within this timestep then the software will not execute at runtime. The software was also designed to be modular so that different conventional or pattern recognition controllers could be easily swapped in or out.

A graphical representation of the EMG acquisition subsystem can be seen in Figure 4.10.

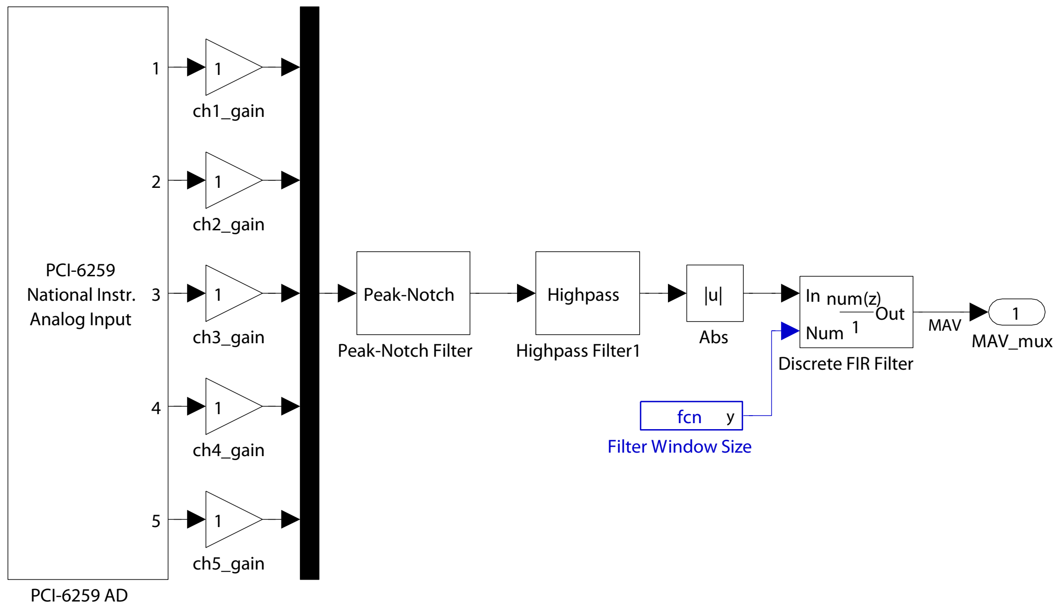

Figure 4.10: A block diagram of the EMG acquisition subsystem.

The PCI-6259 driver block outputs the raw EMG signals for each channel. The signals are amplified by a digital gain, which can be controlled by the patient or therapist through the GUI. A notch filter at 60Hz removes power line noise and a high pass filter with a cutoff frequency of 10Hz removes motion artifacts. The next step is to estimate the signal strength by extracting the mean absolute value (MAV) as described in [1]. In order to do this the signal is rectified and averaged using a moving average filter that uses 400 points. This corresponds to a 0.200 second delay between when a patient initiates a contraction and when the level stabilizes at the increased amount. This delay effect is illustrated from simulation results in Figure 4.11. The trade-off is that decreasing the delay causes the output signal to become less smooth. Several different delays were tested and a 0.200 delay was finally chosen in order to get the maximum smoothness of the MAV within the constraints of the design requirements.

The conventional 2-state EMG controller was designed as per the GRH's requirements in order to mimic controllers available on commercial prostheses. The controller uses four EMG channels measured from four separate muscle sites to control up to two DoF simultaneously on the robotic arm. Figure 4.12 shows s visual representation of how the linear proportional mapping is achieved for a single EMG channel. Each degree of freedom is controlled by an antagonistic pair of muscles on the forearm or upper arm. When possible control schemes are setup so that the mappings are as intuitive as possible for the patient.

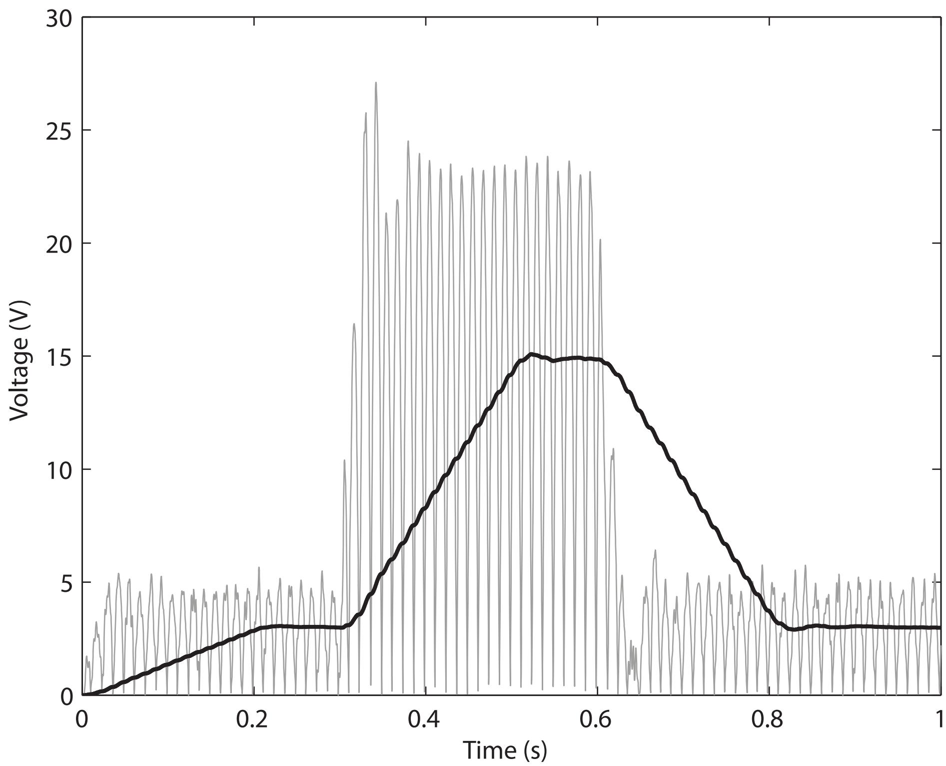

Figure 4.11: Signal Amplitude versus Time (seconds) of a simulated EMG signal. The grey signal (thin line weight) is the rectified signal and the black signal (heavy line weight) is the mean absolute value.

For example the biceps and triceps could control the elbow flexion and extension DoF on the robotic arm. A fifth channel is also available in order to switch sequentially through a list of DoF on one of the channel pairs. The mapping, DoF, and channel parameters are specified in the GUI and allow the therapist to customize the control scheme for each patient. The mapping parameters specify which DoF on the robotic arm that the EMG channel pairs are mapped to as well as the switching list if enabled. The DoF parameters specify the minimum and maximum angular velocities, ω_{min} and ω_{max}, and the positional constraints, p_{min} and p_{max}, for each DoF on the robotic arm. The channel parameters specify the maximum and minimum signal thresholds, s_{min} and s_{max}. When the MAV is below s_{min} the robotic arm does not move and holds its position. Above s_{max} the angular velocity is held constant at the maximum allowed amount, ω_{max}. Since a given DoF can only move in one direction at a time a "first past the post algorithm" was created in order to give preference to the movement corresponding to the channel that first reaches s_{min}. The outputs from the controller include the desired angular velocities and directions of rotation for each servo for each timestep. It should be noted that the paired servos for elbow and wrist flexion face away from each other and need to be rotated in the opposite directions.

Graphical User Interface

The GUI of the MTT software subsystems can be seen in Figure 4.13. The GUI was designed in Microsoft Visual Studio 2008 using Microsoft Visual Basic (VB) and the Microsoft .NET 2.0 framework. VB was chosen as the programming language since it is supported by all of the existing and custom APIs.

Starting from the top-left in Figure 4.13 and moving downwards: the controls in the EMG Acquisition - Communication Settings group box allow the user to specify the communication settings to connect to the target computer and to start and stop the control program. The EMG parameters described in the EMG controller can be adjusted using the EMG Acquisition - Parameters group box. The MAV of each channel is also displayed graphically using a bar graph. In the Robotic Arm - Parameters group box the user can adjust the DoF parameters of the robotic arm. Using the controls in the Robotic Arm - Communication Settings group box the user is able to adjust the communication settings with the robotic arm and start and stop the servos. A control is also supplied to allow the user to reset the servos in the case they have overloaded and shutdown. The only way to otherwise reset the servos is to cycle their power. The feedback group box allows the user to see the angular position, velocity, and load of each DoF. In the Simulator - Communication Settings group box the user can launch the simulator and connect or disconnect from it. Through the file menu the user is able to save or open profile files that record all of the GUI settings. It

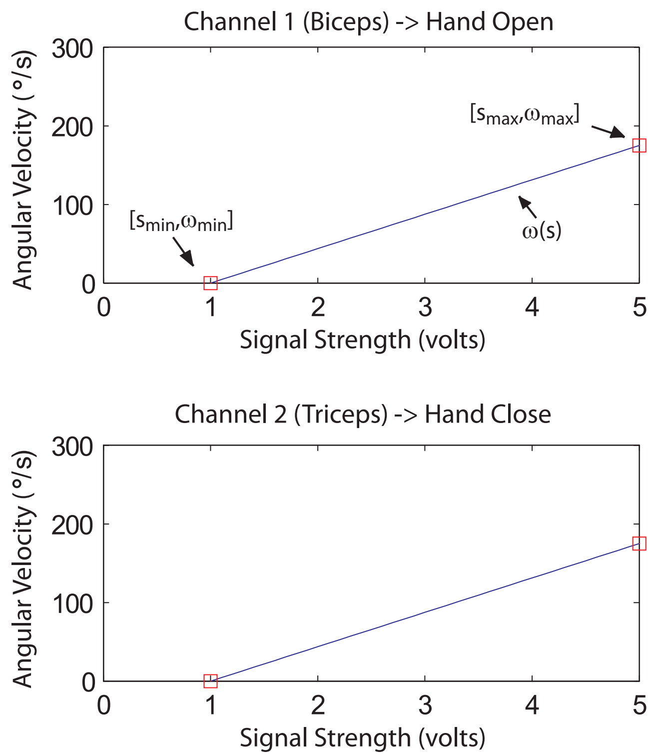

Figure 4.12: A functional representation of the proportional control mapping in a two-state amplitude modulation controller. ω(s) is the angular velocity as a function of signal strength. ω_{min} and ω_{max} are the minimum and maximum angular velocities. s_{min} and s_{max} are the minimum and maximum signal thresholds. Before s_{min} the actuator is turned off and after s_{max} the angular velocity remains constant at its maximum value.

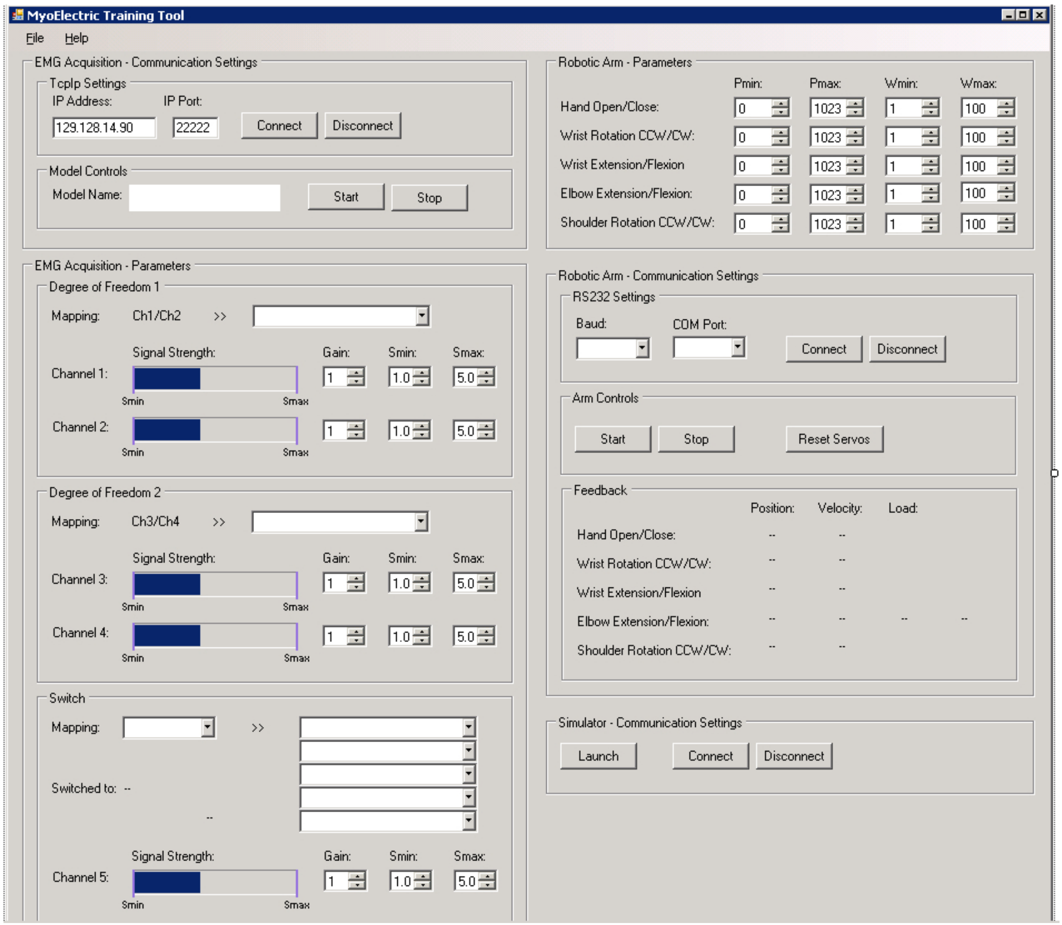

Figure 4.13: A screenshot of the MTT GUI.

should be noted that this is the research version of the GUI and that future versions for therapists and patients will have reduced features and simplified controls.

Robotic Arm Control

Behind the scenes the GUI works by sampling the desired angular velocities and rotation directions from the target computer every 30 ms via the xPC Target COM API and then passing the signals onto the Dynamixel bus using the Dynamixel API. The AX-12 servos are controlled using a serial communication protocol that operates at 1Mpbs on a half duplex multi-drop serial bus. Commands can be sent to each servo one at a time or in some cases broadcast to all the servos at once in a single packet. In order to save on the amount of messages that need to be sent in this application the broadcast method was used to send the velocity and position commands to the servos. For querying feedback from the servos the individual command method had to be used.

Simulator

The first objective of the simulator is to provide a training option for patients in situations where using the actual physical robotic arm are infeasible. The second objective of the simulator is to be used for evaluating new experimental myoelectric controllers as an intermediate step before trying them on the physical robotic arm. The software features included a 3D visual representation of the robotic arm, recording and playback options, a modular structure in order to allow for future improvement, and an API for interfacing with the GUI. The current version of the simulator is limited to biofeedback tasks and is implemented via a kinematic model with rigid and massless links. The simulator was designed in the java environment and is platform independent. An illustration of the simulator can be seen in Figure 4.14.

4.2.4 Preliminary Testing

Each subsystem in the MTT was first tested individually to make sure it worked as expected. A stage one prototype was then constructed in order to test the subsystems all functioning together. The stage one prototype was limited to controlling one DoF at a time using two EMG electrode channels with switching performed in the GUI using a mouse. In these preliminary tests the robotic arm was used to perform a simple ball movement task as seen in Figure 4.15.

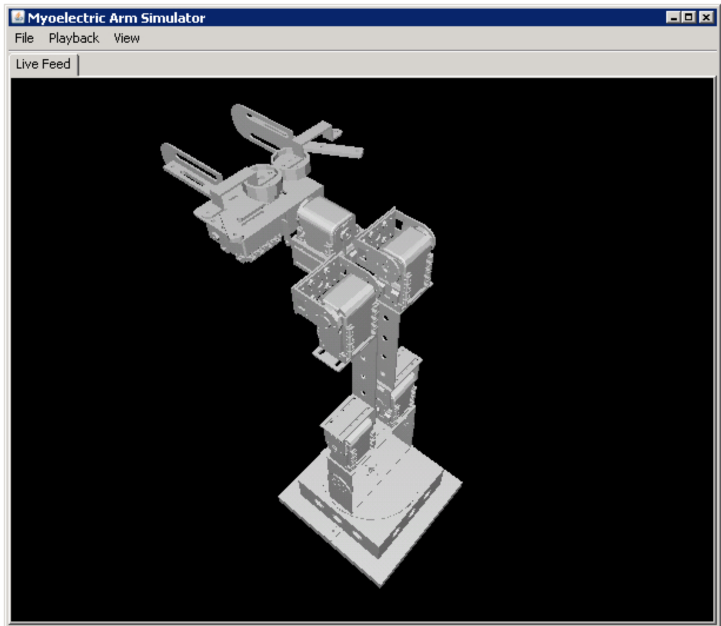

Figure 4.14: A screenshot of the MTT GUI.

Figure 4.15: The stage one MTT prototype being used to perform a simple ball movement task.

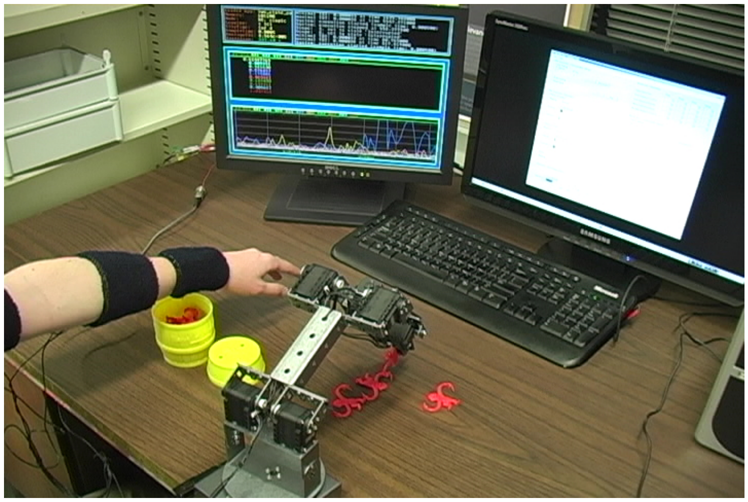

Figure 4.16: The stage two MTT prototype being used for a more advanced motor learning task.

The next step was to upgrade the prototype to be able to control two DoF simultaneously using four EMG electrode channels with a fifth channel used for the switch. Figure 4.16 shows the tests of the state two prototype performing a more advance motor learning task. During testing, any identified issues with the MTT in either the mechanical, electrical, or software subsystems were corrected.

4.2.5 Experimental Evaluato

Experimental trials were performed by five able-bodied subjects using the EMG controlled robotic arm to perform a basic motor-learning task. The objectives of this study were to show that people could learn to use the MTT using a standard training program and to gain qualitative insight into the strength and weaknesses of the system in order to identify areas for future improvement. The study was approved by the the Health Research Ethics Board (HREB) of the UofA and the subjects participated as volunteers with informed consent. The final version of the subject consent form can be found in Appendix A.3.

The task selected for this study was a modified version of the standard box and blocks task [28]. Modifications were necessary in order to adapt the size and shape of the boxes to the fixed elbow joint and limited workspace of the robotic arm. In addition, instead of moving as many blocks from one box to another in 60 seconds, the subjects in this study were required to move five balls from one box to another as fast they could with the performance indicator being the recorded time. This change was implemented in order to better resolve incremental improvements since pre-trials showed that subjects would only be able to move one to three blocks in 60 seconds. An illustration of the experimental setup including the

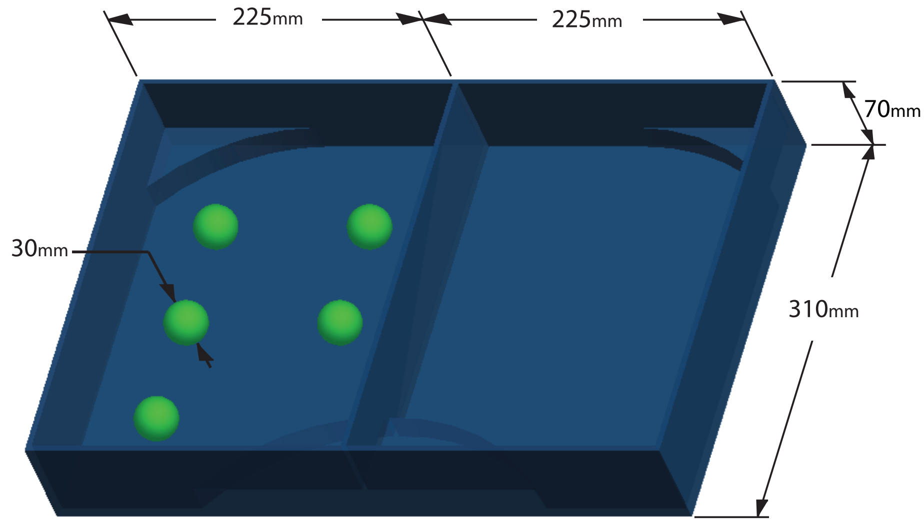

Figure 4.17: Image of the experimental setup including boxes and balls.

boxes and balls can be seen in Figure 4.17. A towel was placed in the bottom of the boxes in order to help prevent the balls from moving around and the areas in the box that were outside of the range of the robotic arm were blocked off. Five compressible plastic balls were placed into the left box in predefined locations. The subject starts with the arm in a default position pointing vertically upwards and may begin moving the balls to the right-hand box after the timer starts. The timer stops when the last ball touches the floor of the right-hand box. Subjects must pick up one ball at a time and move it completely into the plane of the right-hand box before releasing it. Under any foul condition the trial was marked incomplete and the subject was required to redo the trial. An example of a foul condition would be to cause the servos to overload by pushing the robotic arm too heavily into the floor of the boxes.

Before using the MTT the subject was given the opportunity to try the task with their actual left arm in ten timed trials. The subjects were then connected to the MTT and a calibration procedure was performed in order to adjust their gain and signal thresholds to a comfortable level. After calibration each subject was given approximately five minutes of time in the simulator to practise the basic control scheme and demonstrate they could control the arm safely before moving onto the actual robotic arm. The control scheme used in this study was for the subjects to control a single DoF at a time using two electrode channels with a third channel used a switch. The pair of electrode channels were placed over the antagonistic muscles in the forearm on the left arm and the switch channel was placed over the forearm extensor muscle on the right arm. A ground electrode was placed over the bony part of the wrist on the left arm. The switch list was ordered as follows: Elbow Flexion/Extension, Wrist Flexion/Extension, Hand Open/Close, and Shoulder Rotation. An audible signal was added to the MTT in order to alert the subject when they had successfully switched from one DoF to another. In addition the subjets were able to see the selected DoF by looking at the GUI. After briefly demonstrating they were able to control the arm safely on the actual robotic arm, subjects completed ten timed trials. Between each trial the subject was given the option to take a break in order to help avoid fatigue. The full experimental procedure can be found in Appendix A.3.

After performing their trials the subjects were given a usability survey to fill out. The survey included a controller evaluation, a difficulty assessment of the DoF on the robotic arm, and a section for comments or suggested improvements. The three controllers that were evaluated included: the use of the subject's actual physical arm, EMG control of the robotic arm, and EMG control of the simulator. Each controller was rated on a scale from zero to five where five is the best rating and zero is the worst. The qualities rated for each controller included comfort, intuitiveness, delay, and effectiveness. For the difficulty assessment each DoF was rated on how difficult it was to perform in a timely and reliable manner with zero being very difficult and five being easy to use. A detailed break down of the rating system can be found in the usability survey in Appendix A.3.

The results from the timed trials and usability study were analyzed using Microsoft Excel ™ [29]. The times for each trial and the scores for each parameter in the usability survey were averaged across the five subjects. Student t-tests were used to test for the difference between means in the recorded parameters. These tests are well suited to small sample sizes with the underlying assumption that the population is approximately normal. For the difference between the mean of trial times a "paired two sample for means" t-test was used since there was a single set of subjects tested before and after a treatment. For the difference between the means of the parameter scores in the usability survey a "two-sample assuming unequal variances" t-test was used since the samples in this case were not paired. Both of these t-tests do not assume that the two data sets come from distributions with equal variances.

4.3 Results and Discussion

Once the MTT prototype was constructed it was evaluated to ensure it met all aforementioned design specifications and to identify additional complications. In the following sections the results of an experimental study are discussed, the design compliance is verified, and future work is suggested.

4.3.1 Experimental Results

The full experimental results with subject names removed can be found in Appendix A.3. The average trial times versus the trial number for the actual arm and the robotic arm are plotted in Figures 4.18 and 4.19 respectively. The error bars in each plot represent $\pm$ one standard deviation.

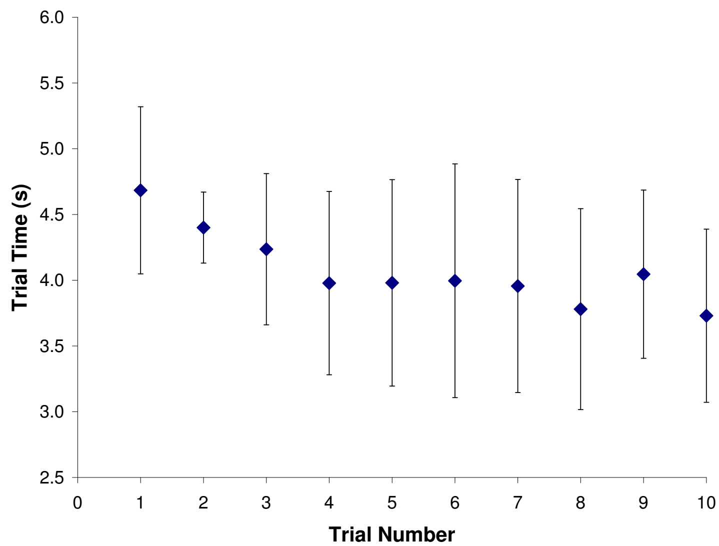

Figure 4.18: The averaged trial times for when the subjects performed the task using their actual left arm. The error bars represent $\pm$ 1 standard deviation.

As can be seen in the plots of the robotic arm trials the data points appear to be oscillatory with large standard deviations. This effect was observed to be from variations in learning patterns between subjects. Some subjects were more aggressive with their attempts while others preferred to take a more steady approach to their learning. About half the subjects had an initial increase in performance followed by a large decrease in performance as seen in trial four with the large mean and standard deviation. At this point some of the subjects had become overconfident in their skills and started taking too many risks. After this blip subjects started to gradually improve their times again, but still with some oscillations in performance.

From the trials where the subjects used the robotic arm, the mean trial time from the first trial was found to be significantly greater than the mean trial time from the tenth trial ($p < 0.005$). This result suggests that on average the subjects improved their skill in myoelectric control over the course of the trials. Comparing the subjects' trial times between the

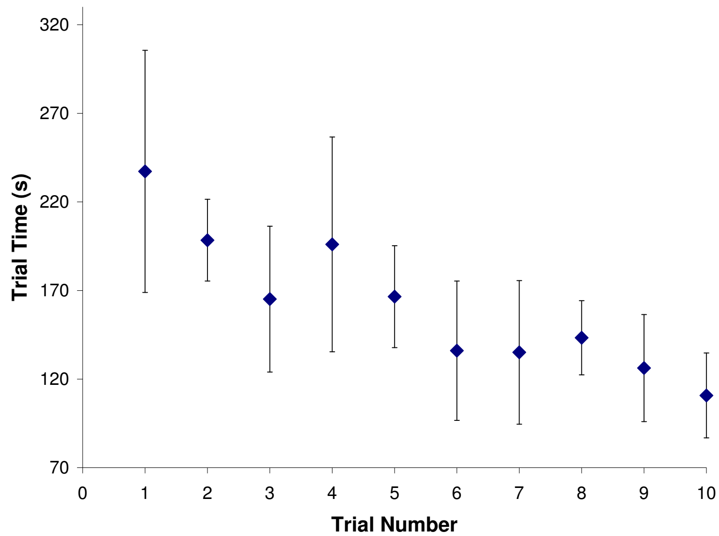

Figure 4.19: The averaged trial times for when the subjects performed the task using the EMG controlled robotic arm. The error bars represent $\pm$ 1 standard deviation.

baseline of using their actual arm versus the robotic arm indicates that the current gap in functionality between an intact and myoprosthetic limb is still very large. Clearly, there is much room for improvement over the conventional myoelectric control scheme used in this study.

Figure 4.20 plots the controller evaluation results from the usability survey. The error bars in the plot represent the standard error in the means. All subjects rated their actual arm with a score of five with no variation. The scores of the simulator came in slightly lower than scores of the robotic arm, but the differences were not significant, ($p > 0.05$).

Figure 4.21 shows the average difficulty rating for each DoF on the robotic arm. Hand open/close, wrist flexion, and elbow flexion were all rated similarly with no statistically significant differences. However, shoulder rotation was significantly more difficult to use than the other three DoF ($p < 0.005$). This result was also reflected in the subject's comments with several subjects mentioning the shoulder rotation could have been smoother.

While the subjects performed their trials their user errors and any issues with the MTT were observed. The most common type of user errors were over cycling and just passing the desired DoF on the switch list. Correspondingly, the most common comment from subjects on the usability survey was the suggestion to add in an additional myoelectric channel in order to be able to cycle up and down the switch list. Another error was for subjects to initially move in the incorrect direction before moving in the correct direction especially with the rotation DoF, which was the least intuitive. Since the robotic arm mechanism

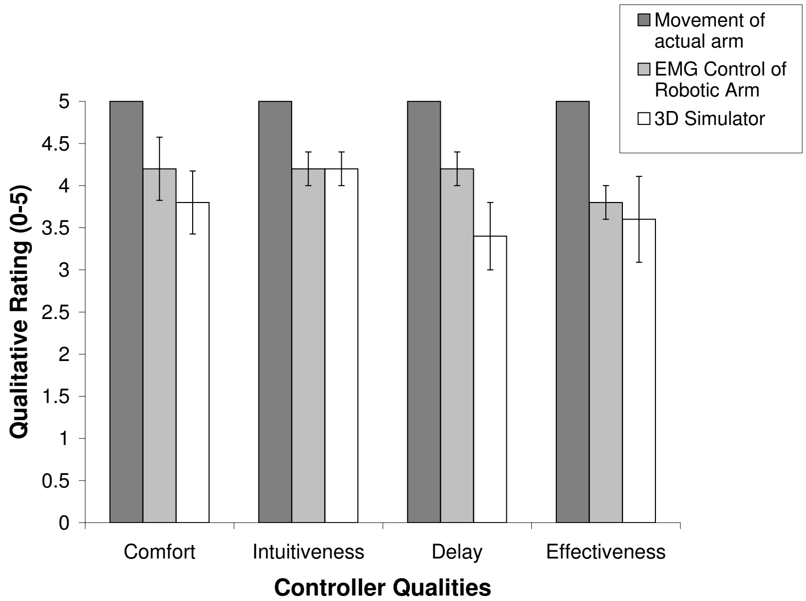

Figure 4.20: The controller evaluation results from the usability survey. The error bars represent the standard error in the mean. Note that 5 is the best rating and 0 is the worst rating.

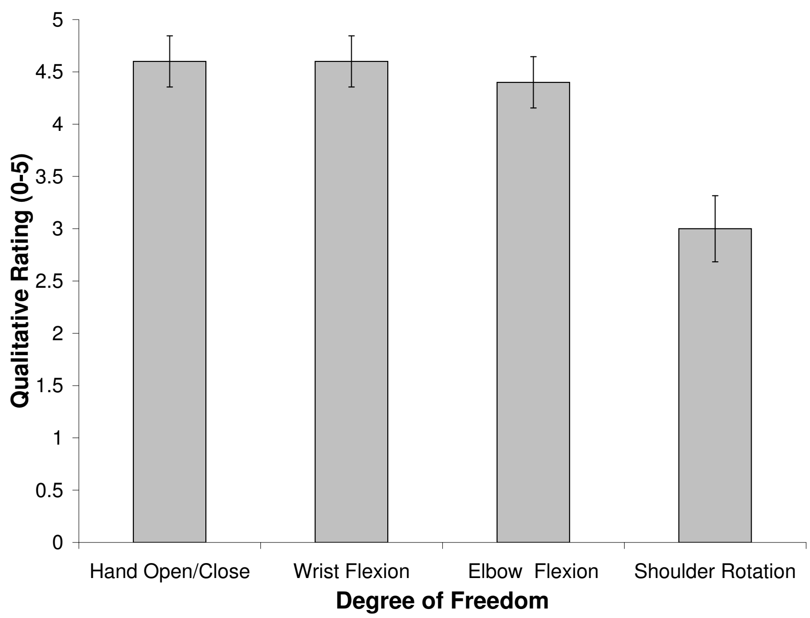

Figure 4.21: The DoF evaluation results from the usability survey. The error bars represent the standard error in the mean. Note that a rating of 5 corresponds to a DoF that is easy to control and 0 corresponds to a DoF that is very difficult to control.

moved the gripper towards or away from the balls as it closed and opened respectively a common error was for subjects to incorrectly position the gripper. Positioning the gripper too closely to the box floor would result in the gripper getting stuck on the floor or pinching the towel, while positioning the gripper too far away from the ball would result in the gripper entirely missing the ball. In some cases the subjects also dropped the balls or knocked them into the corners, which was perhaps the most time costly error. Some of the subjects also initially had difficulties early in their trials figuring out how to coordinate the positioning of the elbow and wrist flexion DoF.

Another common error was for subjects to bang into the walls or floor of the boxes and cause the servos to overload and automatically shutdown to help prevent damage. The most common servos to overload were the ones controlling the elbow DoF since they were the ones that carry the most load. The number of elbow shutdowns that occurred over the course of the trials for each subject ranged from zero to six. However, some of the shutdowns appeared to occur intermittently for no discernible reason. After the trials were completed this issue was investigated and it was found that when the elbow DoF moves very slowly the elbow servos, which run on separate controllers built into the servo housings, tend to move different angular distances and become misaligned significantly overloading one servo. A solution to this problem that was tested and confirmed to work was to send commands to the elbow servos to realign every time the elbow DoF comes to rest. Another solution is to exchange the AX-12 servos for the recently released higher and stronger torque AX-18F servos. The AX-18F servos have exactly the same form factor as the AX-12 servos and are compatible to run on the same Dynamixel bus.

4.3.2 Design Compliance and Future Work

A design compliance matrix as found in Appendix A.1.4 was created in order to verify whether the MTT prototype met the design requirements. After reviewing the requirements closely it was determined that the MTT prototype met or exceeded all of the requirements. Small issues along with suggested improvements for the future MTT prototypes are outlined below.

In the mechanical subsystems, the main deficiency with the AX-12 Smart Arm is that it is not anatomically correct. A future improvement could include redesigning the brackets in order to more closely follow anatomical proportions. The bracket redesign could include a new shoulder joint that is able to move more smoothly. A casing or sleeve could also be designed to help improve the aesthetics of the robotic arm and make it more closely resemble an actual myoelectric prostheses.

In the electrical subsystems, the servos for the elbow DoF should be replaced with the higher torque versions to prevent misalignment. A custom signal conditioning board should be developed that includes an anti-aliasing filter and additional layers of safety isolation that meet CSA 60601 standards. To increase the portability of future MTT prototypes the target computer and DAQ card will be replaced with embedded hardware that can fit inside a shoe box sized enclosure and the host computer should be replaced with a laptop. Design work on this future prototype is currently underway with the goal of ultimately being able to fit the entire system into a suitcase that can easily be shipped to remote locations.

In the software subsystems, a feature should be implemented in the EMG controller to allow the subjects to cycle up or down the switch list. A custom API should also be written to communicate with the AX-12 or AX-18F servos so that they can be controlled via a real-time xPC Target kernel. The GUI should add in functionality for recording the muscle signals over time in record files that can be analyzed remotely by therapists. The simulator should be expanded to include a dynamic model of the robotic arm that will allow it to pick up objects and interact with the environment. A valuable addition to the MTT would be to develop a custom software interface that will allow the patients to train using myoelectrically controlled video games.

A future study should be performed to test subjects ability to control two DoF freedom simultaneously. Also, the MTT can be used in studies to evaluate pattern-recognition controllers against conventional controllers. After the clinical prototype of the MTT is completed clinical trials should be performed with amputee patients as subjects and attempt to establish the effect of the MTT on clinical outcomes.

4.4 Conclusions

In conclusion, a research prototype of the MTT has been designed and built. The prototype improves upon previous commercial myoelectric training systems with support for two DoF to be controlled simultaneously by four EMG channels and a fifth channel available to be used as a switch. The system can control a five DoF robotic arm in both a physical or simulated form. This system is well suited to be used with TMR and non-TMR amputee patients alike. The system has been designed to be modular so that it can also be used to test new experimental myoelectric control schemes. Initial testing and experimental studies were performed and indicate that the completed MTT research prototype has met its core design requirements and is well on its way to meeting the overall project objectives. Future work will focus on improving the portability of the MTT and getting it ready for clinical studies to be performed on amputee patients.

Acknowledgments

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Chapter 5

Design of the MTT Clinical Prototype

5.1 Introduction

The research prototype of the MTT has been designed, built, and tested. The next step is to design, build, and test the clinical prototype of the MTT that will be used in clinical trials with actual amputee patients. Improvements in the mechanical subsystems will include switching to stronger servos and redesigning the brackets to be more anatomically correct. The main improvements in the electrical subsystems will be to switch to electrical subsystems to embedded hardware, design a portable electronics enclosure, and to add in the custom signal conditioning board. Since the original system was designed to be modular much of the mechanical and software subsystems can be directly reused in the clinical prototype. Important improvements in the software will be to increase the functionality of the simulator, create a custom robotic arm API that can be controlled directly with xPC target, and add in a training option for the patient to myoelectrically play video games. This chapter will detail the design work that has been completed thus far and focus on areas where the clinical prototype differs from the research prototype.

5.1.1 Design Specifications

A design specifications matrix was compiled and can be found in Appendix B.1.1. The overall target system cost was increased to $10000 in order to accommodate the additional features and requirements for each subsystem. The target development time of the clinical prototype is 2 years.

5.2 Methods

The design and construction work that have been completed thus far are covered in this section. The overall system flow diagram can be seen in Figure 5.1. A detailed bill of materials (BOM) for the entire MTT system can be found in Appendix B.1.2. The overall estimated cost of the prototype is $7500. The next few subsections describe the components selected that differ significantly from the components in the research MTT prototype.

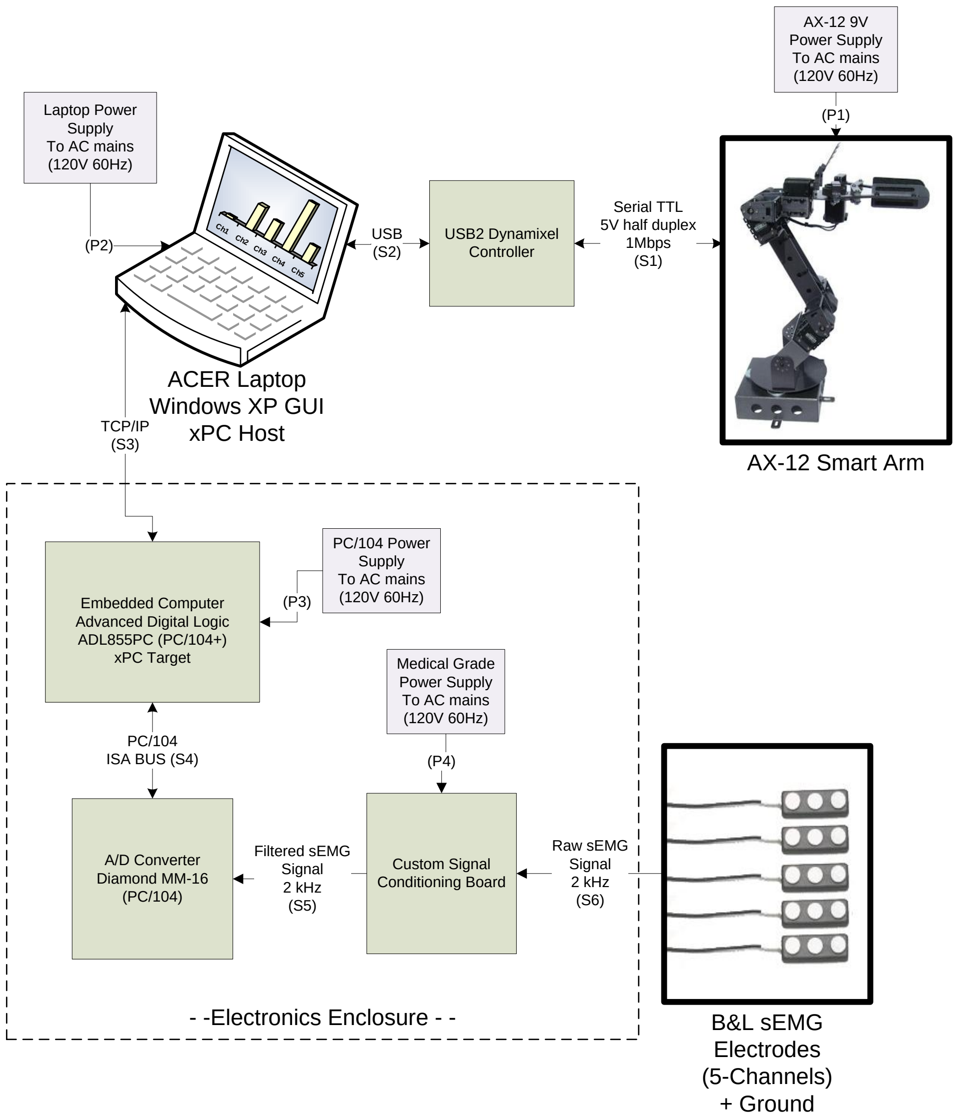

Figure 5.1: System flow diagram of the MTT clinical prototype.

Figure 5.2: Image of the polycarbonate enclosure.

5.2.1 Mechanical Subsystems

A shoe box sized polycarbonate enclosure has been purchased to house the embedded electronic components and can be seen in Figure 5.2. The enclosure lid is secured using twist latches and sealed using a polyurethane gasket. The enclosure was chosen to be polycarbonate in order to allow the MTT to have a floating ground.

5.2.2 Electrical Subsystems

In the robotic arm the AX-12 servos will be replaced by AX-18F servos, which provide 20% more torque.

A custom designed signal conditioning board was commissioned for design by a fourth year biomedical capstone design team from the Electrical Engineering Department at the UofA. The board specifications included gain adjustment knobs in order to maximize the signal resolution during data acquisition, a low-pass filter with a 500Hz cutoff to prevent anti-aliasing distortion, and overvoltage protection diodes to add an additional layer of safety for the patient. The board has been designed and built and can be seen in Figure 5.3. However, integration and testing of the board is still ongoing and so it has not yet been included in the MTT research prototype. It was determined through initial testing that the proof of concept prototype would function adequately without the board and that its inclusion could be delayed until the clinical version of the MTT.

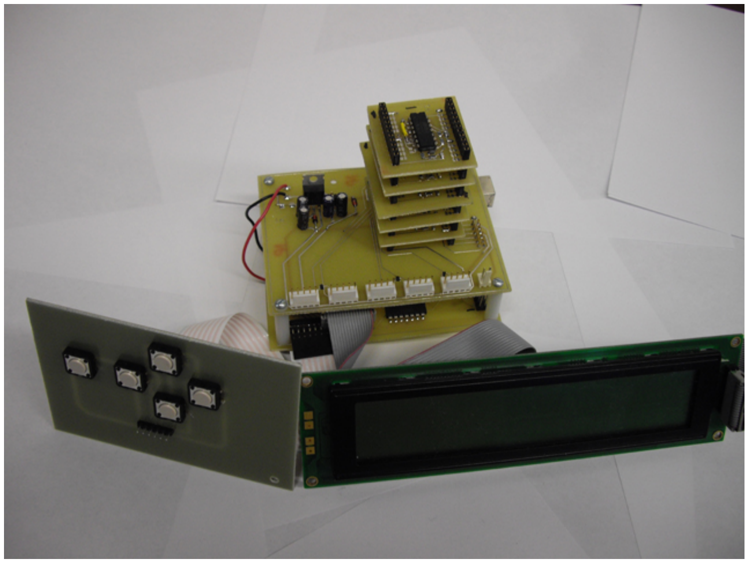

Figure 5.3: Image of the custom signal conditioning board.

The EMG signals pass through the custom signal conditioning board and are then sampled at 2kHz by an embedded Diamond MM-16 DAQ card with 16-bit resolution as seen in Figure 5.4. The EMG electrodes connect directly to the analog input pins on the top of the card. The embedded DAQ card is connected to the PC/104 target computer via an ISA slot and the target computer is connected to the host computer via a TCP/IP connection and standard ethernet cable. The target computer is an Advanced Digital Logic - ADL855PC - 745G PC/104 computer as seen in Figure 5.5 and the host computer has been specified as an ACER Notebook.

Figure 5.4: Image of the Diamond MM-16 DAQ card.

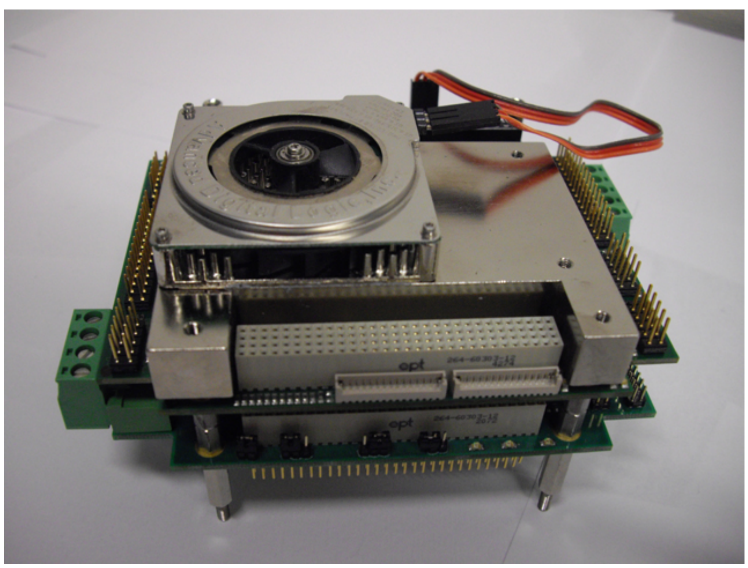

Figure 5.5: Image of the ADL885PC PC/104 computer.

5.3 Conclusions

In conclusion, a clinical prototype of the MTT has been partially designed and most of the electrical hardware has been acquired. The clinical prototype improves upon the previous research prototype in a number of areas including portability, safety, aesthetics, and applicability. Future work will focus on completing the detailed design of the clinical prototype and planning for clinical trials.

Chapter 6

Reinforcement Learning

6.1 Introduction

A brief introduction to pattern recognition based myoelectric control methods along with their advantages and disadvantages can be found in section 2.6. Since the 1970s, the myoelectric control literature has moved away from conventional control methods towards pattern recognition or machine learning methods. The majority of research thus far has focused on supervised learning techniques that are trained offline such as artificial neural networks [1], linear discriminant analysis (LDA) [2], and support vector machines (SVM) [3]. On the other end of the machine learning spectrum, relatively less work has been performed on unsupervised techniques [4]. Forming the middle ground are semi-supervised techniques that are trained online [5]. Also in this middle ground are reinforcement learning (RL) techniques, which have been relatively unexplored in the myoelectric control domain.

RL methods attempt to solve optimal control problems by having an agent learn through interaction with the environment to perform actions in order to maximize its long-term reward [6]. In terms of the myoelectric control domain, the agent's policy is the mapping between the amputee patient's EMG signals and the movements of the myoelectric prostheses. The current state of the environment could be represented to the agent via positional, velocity, or force feedback from the joints of the prosthesis. The external reward function could be defined by calibration tasks or direct human reward from the patient. The long-term reward is estimated using a value function, which represents the value of being in a given state. In order to start moving towards the objective of using the MTT as a research tool for developing new myoelectric control methods, a collaboration was initiated with the Reinforcement Learning and Artificial Intelligence (RLAI) group of the Computing Science department at the University of Alberta (UofA).

A preliminary study testing an RL method using the MTT simulator is summarized in the following section.

6.2 Preliminary Study

In 2010, we performed a study (Pilarski et al. 2010) with the main objective of showing that an RL method could be used to map from recorded EMG muscle signals to movements in a simulated robotic arm. The scope of this section is limited to an overview description of the methods used in order to summarize how the MTT was used as a research platform. In depth descriptions of the RL theory and the algorithms employed are outside of the thesis scope, but can be found in [7]. A schematic diagram of the experimental system can be seen in Figure 6.1. Four EMG signals were recorded from the antagonist muscles of the forearm and the biceps and triceps using the EMG electrodes and testing software from the MTT. These signals were filtered using a notch filter (60Hz cutoff) and a high pass filter (10Hz cutoff) to remove power line noise and motion artifacts respectively. The mean absolute value (MAV) of these previously recorded signals were fed into the RL agent, which for this study was chosen to be a type of continuous action Actor-Critic (AC) reinforcement learning method. A separate training and data set were recorded with the following pattern of contractions being performed in ten second intervals for five minute durations: reach (elbow and wrist extension), relax (all muscles relaxed), and retract (elbow and wrist flexion). For this preliminary test the AC agent was trained to output joint velocities to move the robotic arm to specific positions closely resembling the positions of the arm that the signals were recorded from. An illustration of the contraction patterns can be seen in Figure 6.2 along with the corresponding target positions of the robotic arm in the MTT simulator. A plot showing the MAV signals that are passed onto the AC agent can be seen in Figure 6.3.

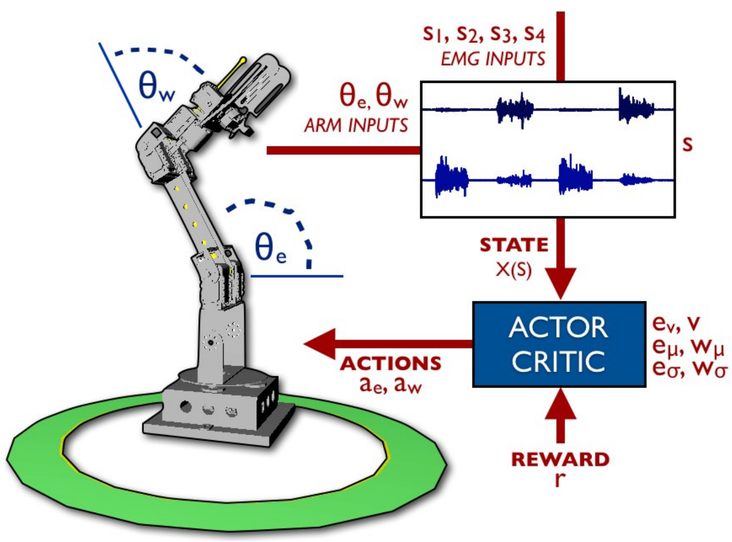

Figure 6.1: A schematic diagram of the experimental system.(reprinted from [7])

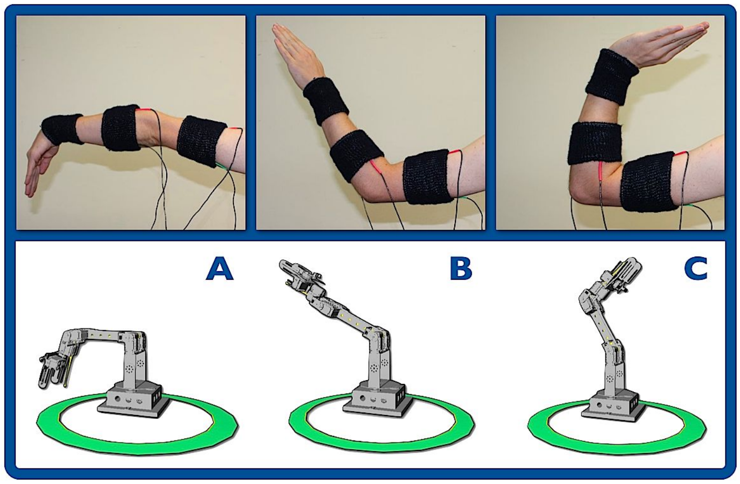

Figure 6.2: *Top:* electrode locations on an able-bodied subject's arm and limb positions for *reach* (a), *relax* (b), and *retract* (c) activity types. *Bottom:* the corresponding target joint angles. (reprinted from [7])

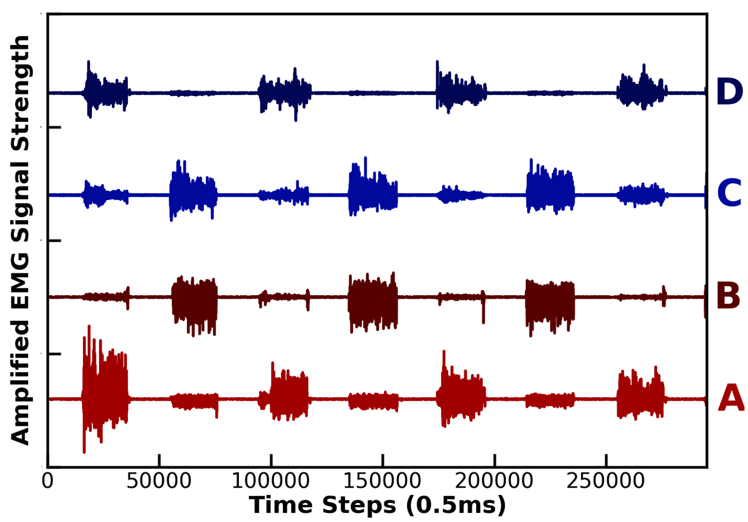

Figure 6.3: MAV for the four input EMG signals: (a) wrist extensors, (b) wrist flexors, (c) triceps, and (d) biceps. (reprinted from [7])

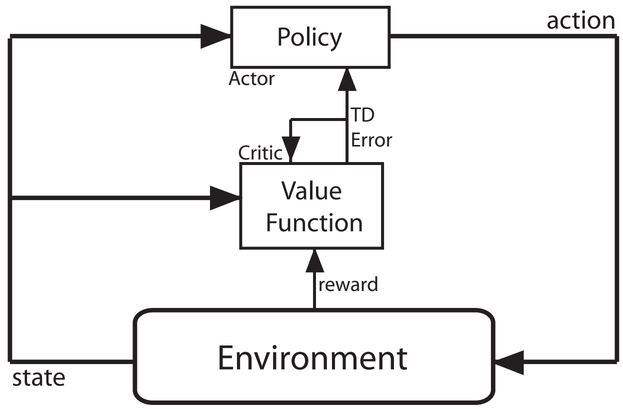

Figure 6.4: A block diagram of the AC method. (adapted from p. 151 of [6])

The architecture of the AC method can be seen in Figure 6.4. The main components of the AC method are the actor and the critic. The actor chooses an action by following its policy. The critic estimates the value function and calculates the temporal difference (TD) error, which is used to provide feedback to the actor and help shape the policy. The state of the environment is then updated and a reward is provided to the critic in order to update the estimate of the value function. The whole process then repeats indefinitely.

Two main approaches to defining the rewards were taken. In the first approach the AC agent learned with a fixed goal-based reward where the agent was rewarded when it moved within tolerance of the desired angular position. In the second approach the agent learned with a human-delivered reward with key presses to allow for positive and negative rewards of 0.5 and -0.5 respectively. When no keys were being pressed a neutral reward was given of 0.

Experiments were performed testing each reward function approach. The AC agents were trained online in both cases using the offline (batch) training datasets. The value functions were then held constant in order to halt learning and the AC agents were tested with the offline testing datasets. The results from the experiments showed that in both approaches the RL agent was able to successfully learn how to control the robotic arm and still perform well even after learning was stopped.

6.3 Conclusions

The simulator portion of the MTT has been used in a study to evaluate the performance of a continuous action AC controller of the RL class of machine learning algorithms. From this initial result it can be concluded that the MTT is a useful tool for researching novel myoelectric controllers. A MATLAB RL Framework and RL GUI need to be designed in order to extend the MTT, so that a further study can be carried out on the physical robotic arm while recording EMG signals online. Future work will focus on further modularizing the MTT software to better accommodate testing of new kinds of RL methods and to add in more types of sensors to the AX-12 Smart Arm in order to increase the amount of information available to the learning agents.

References

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Chapter 7

Conclusion

The major contributions and conclusions of this thesis are summarized in this chapter. The improvements required to realize the clinical version of the MTT prototype are discussed and the future work in the area of developing novel RL based myoelectric controllers are outlined.

7.1 Conclusions

The research prototype of the MTT was designed to meet all of the core requirements set out by the GRH and MTT design team. All of the subsystems were integrated together and a functioning research prototype was constructed. The research prototype includes a physical and simulated robotic arm, signal acquisition hardware, controller software, and a graphical user interface. The research MTT is able to accommodate TMR and non-TMR upper limb amputee patients alike by allowing them to control up to two DoF at a time on the robotic arm simultaneously using four EMG channels with a fifth channel available for switching purposes. A preliminary study was performed having five able-bodied subjects perform a motor-learning task similar to the box and blocks test. Results from the usability survey indicated that the subjects found the rotation DoF significantly more difficult to use than the other DoF. Results from the tests showed that the subjects trial times improved significantly over the course of their trials suggesting that their skill in myoelectric control also improved.

The next generation clinical prototype of the MTT was conceptually designed taking into consideration additional requirements including national standards for medical devices. The clinical prototype improves upon the previous research prototype in a number of areas including portability, safety, aesthetics, and applicability. Some of the components have already been purchased and construction is under way. The clinical prototype will be used in future studies with actual amputee patients in order to establish a link between myoelectric training and clinical outcomes.

An RL method has been tested on the research prototype of the MTT in collaboration with the Reinforcement Learning and Artificial Intelligence Group in the Computing Science department. The specific components used in this preliminary study included the MTT simulator and the signal acquisition hardware. Results from the test showed that the RL method was successfully able to control the robotic arm with EMG signals as inputs. From the results of the study it can be concluded that the MTT was a valuable research tool in testing out this novel myoelectric control method.

7.2 Future Work

The future work required for the clinical MTT prototype and further RL studies is outlined in the following sections.

7.2.1 Clinical MTT Prototype

In the mechanical subsystems, the main deficiency with the AX-12 Smart Arm is that it is not anatomically correct. A future improvement could include redesigning the brackets in order to more closely follow anatomical proportions. The bracket redesign could include a new shoulder joint that is able to move more smoothly. A casing or sleeve could also be designed to help improve the aesthetics of the robotic arm and make it more closely resemble an actual myoelectric prostheses.

In the electrical subsystems, the servos for the elbow DoF should be replaced with the higher torque, AX-18F, versions in order to help prevent the misalignment problem. It might help increase the stiffness and stability of the entire arm to eventually replace all of the servos with the stronger versions. The development of the custom signal conditioning board should also be completed and the board should be fully integrated into the prototype. Testing of the board should be carried out to make sure that it meets the critical tests in the CSA 60601 standard. To increase the portability of future MTT prototypes the target computer and DAQ card should be replaced with embedded hardware that can fit inside a shoe box sized enclosure and the host computer should be replaced with a laptop.

In the software subsystems, a feature should be implemented in the EMG controller to allow the subjects to cycle up or down the switch list. Through extended testing it was discovered that the robotic arm control currently implemented through the existing Dynamixel API is not 100 % reliable. It is believed that the root problem is in how the API and the Windows

XP operating system access the USB port. Although, the communication works properly most of the time, for medical applications it needs to operate reliably all of the time. The suggested solution in this case is to develop a custom API to communicate with the AX-12 or AX-18F servos so that they can be controlled via the real-time xPC Target kernel, which runs in real-time. The GUI should also add in functionality for recording the muscle signals over time in record files that can be analyzed remotely by therapists. The simulator should be expanded to include a dynamic model of the robotic arm that will allow it to pick up objects and interact with the environment. A valuable addition to the MTT would be to develop a custom software interface that will allow the patients to train using myoelectrically controlled video games.

A future study should be performed to test subject's ability to control two DoF freedom simultaneously. After the clinical prototype of the MTT is completed clinical trials should be performed with amputee patients as subjects and attempt to establish the effect of the MTT on clinical outcomes.

7.2.2 RL Methods

A MATLAB RL framework with an accompanying GUI needs to be designed in order to extend future studies to include control of the physical robotic arm. The MATLAB RL Framework should be combined with the existing EMG Acquisition and Control software. The GUI should be linked to the RL model using the xPC Target COM API. The MATLAB RL framework should run off of sparse matrices in order to decrease the storage space required to store the value functions. The tile coding function should also be improved to be more modular and allow for better generalization between states.

More types of sensors could be added to the AX-12 Smart Arm in order to increase the amount of information available to the learning agents. Force transducers in the grippers would allow the RL agent to learn to adjust their grip strength based on the measured normal force. An open issue with using EMG signals to control myoelectric prostheses is that the signals can change considerably depending on the position of the residual limb. Position sensors placed on the residual limb could help the learning agent better generalize the intended motion of the amputee.

Future studies should try out the AC method on the physical robotic arm. Studies could also be performed to try including more extracted EMG features besides the MAV. Additional reward approaches could be tested and evaluated against each other. Instead of training the robotic arm to move to a desired position, the robotic arm could be trained to move at a desired velocity. Finally, methods should be researched to find ways to make the entire system more adaptive and clinically applicable.

Appendix A

MTT Research Prototype Documentation

The documentation related to the design, wiring, and experimental trials of the MTT research prototype is contained in this appendix.

A.1 Design Documentation

The detailed documentation for the MTT research prototype that did not fit into the main body of the thesis can be found below.

A.1.1 Design Specification Matrix

The design specification matrix was used at the outset of the project to record all of the design requirements generated through meetings with the Glenrose Rehabilitation Hospital. The matrix is broken up into mechanical, electrical, and software subsystems. Each requirement has an associated design authority, importance, and safety factor (if applicable). A separate graphical user interface (GUI) feature list was generated in order to document which features would be available to a researcher, therapist, and patient.

DESIGN SPECIFICATION MATRIX
Robotic Training Arm

Item #	Component / System Description	Design Specification / Requirement	Safety Factor	Design Authority	Design Importance D (1-5)
1.00	**Mechanical Subsystem**				
1.10	Size	half scale with anatomically correct proportions	-	Client	3
1.20	Weight	5 -10 lb	-	Client	3
1.30	Degrees of Freedom	5 DOF to mimic conventional upper-arm prostheses	-	Client	5
1.31	Hand (open/close)	grasp up to 10cm wide objects, similar in style to Utah ETD	-	Client	4
1.32	Wrist (flexion/extension)	anatomically correct	-	Client	4
1.33	Wrist (rotation)	anatomically correct	-	Client	4
1.34	Elbow (flexion/extension)	anatomically correct	-	Client	4
1.35	Elbow (humeral internal/external rotation)	anatomically correct	-	Client	4
1.40	Maximum Payload	100g	1.5	Client	3
1.50	Repeatability	< 3mm	-	Client	4
1.60	Target Cost	$1,000	-	Client	3
1.70	Development Time	2 months or less	-	Client	5
2.00	**Electrical Subsystem**				
2.10	Actuators		-		
2.11	Feedback	provide angular position feedback to controller	-	Client	4
2.12	Holding Torque	complies with (1.40)	-	Client	3
2.13	Control Input	torque or angular velocity	-	Client	5
2.14	Low level control	controllable through serial communication and XPC target	-	Client	4
2.15	Resolution	complies with (1.50)		Client	3
2.16	No-load speed	> 60 degrees/0.3 seconds		Client	3
2.20	EMG Electrodes	5 electrodes with built in pre-amps and option for detaching electrodes	-	Client	4
2.30	Data Acquisition Card		-		
2.31	Resolution	16-bit	-	Client	3
2.32	Analog Input Channels	minimum 5 differential channels	-	Client	5
2.33	Drivers	driver blocks available for XPC target	-	Client	4
2.40	Control Computer	compatible with XPC target and can communicate with all other electrical components	-	Client	5
2.50	Power Supply		-		
	EMG electrodes	DC batteries	-	Client	5
	Other Components	DC batteries or AC Wall Power Supply	-	Client	3
	Running time	minimum of 3 hours	-	Client	3
2.60	Wiring and Connectors	wiring routed cleanly	-	Client	1
2.70	xPC Target Computer	desktop computer		Client	
2.80	xPC Host Computer	desktop computer		Client	
2.90	Target Cost	$5,000		Client	3
3.00	**Software Subsystem**				
3.10	Conventional EMG Software		-		
3.11	Extracted Feature	Mean Absolute Value	-	Client	5
3.12	Controller Type	Two state controller (1 function per muscle site)	-	Client	5
3.13	Adaptive Digital Notch Filter	60Hz notch		Client	2
3.14	High Pass Filter	10Hz cutoff		SENIAM	2
3.20	Software Environment	MATLAB XPC Target	-	Client	5
3.30	Overall Processing Time	< 0.200 seconds	-	Client	3
3.40	Graphical User Interface	See GUI_Feature_list.xls		Client	5
Notes	Design Importance	5 - Essential or required feature / 1 - Optional requirement			
	Score	10 - Meets requirement in all respects / 1 - Does not satisfy requirement			

Rev	Description	Client Approval	Date
0	Initial release		
1	Updated requirements after Client Meeting		15/7/2009
7	Updated requirements for electrical subsystems		10/8/2009
8	Updated controller type		30/11/2009

Myoelectric Training Tool Software Features/Requirements

General GUI Features	Testing	Prosthetist	Patient
Save/Open settings	x	x	x
Start/Stop xPC target	x	x	x
Start/Stop Robotic Arm	x	x	x
Display MAV of each channel graphically	x	x	x
Display two state controller points for each channel	x	x	x
Adjust 2-state controller points by sliding them or changing value	x	x	x
Assign robotic arm function to channel (also able to disable channel)	x	x	
First past the post control option	x	x	
Display 3d animation of robotic arm	x	x	x
EMG Acquisition Features (access through xPC Target COM API)			
Sampling Rate	x		
Voltage Range (I.e. +- 5v)	x		
Digital gain control for each channel	x	x	x
LP/HP Filter Cut off Frequency	x		
Size of moving average filter	x		
Robotic Arm Features (access through Dynamixel API)			
Servo Range (min/max)	x		
Velocity Range (min/max)	x	x	
Current cutoff	x		
Temperature cutoff	x		
Load cutoff	x		
Software			
Current position (feedback)	x	x (sim)	x (sim)
Current velocity (feedback)	x	x (sim)	x (sim)
Electronics Enclosure Features			
Tunable Gain knob for each channel	x	x	x
on/off button	x	x	x
snap in connectors for each electrode channel	x	x	x
on/off button for each channel?	x	x	x
LCD screen showing signal strength	x	x	x
secured box (locked or screwed shut)			x

(sim) - feature provided by simulator

A.1.2 Component Research

Component research was performed for each subsystem and each component in order to determine whether any of the parts could be purchased off-the-shelf to save on development time. For each component a table was prepared in order to compare and evaluate the relevant features. For example some of the feature parameters for the EMG electrodes included preamplifier gain, built in filters, electrode material, and cost. These parameters were cross referenced with the requirements determined from Phase I in order to choose the best option for each component.

The options for the robotic arm ranged from small hobby arms using radio controlled servos to full blown industrial arms. Small hobby arms ranged in price from $50 to $1000 and the industrial arms were too expensive at $3000 to $15000. Most of the hobby arms that used radio controlled servos did not provide position feedback and were limited to position control. A feasibility analysis was performed on the possibility of a custom designed robotic arm, but the development time for this option was deemed to be too high. Fortunately, a mid-ranged robotic arm, designed both for hobbyist and researchers was discovered that met most of the requirements including position feedback and velocity control.

To begin with, entire EMG acquisition systems were evaluated that contained all of the electrodes and signal acquisition equipment. These types of systems are typically used for gait analysis and met all of the requirements including the IEC and ISO standards. However, these systems were also too expensive, ranging in price from $10000 to $15000. The next step was to investigate the individual components to see if costs could be reduced by putting together a custom system. The cost of individual EMG electrodes ranged from $200 to $1000 and mostly varied in what type of filters were built in. Data acquisition cards compatible with xPC Target ranged from $1000 to $2000. Fortunately, an existing DAQ card that met all of the requirements was available to the author at no cost. Off-the-shelf EMG signal conditioning boards could not be found outside of the packaged systems mentioned above thus a custom board had to be designed despite the increased development time.

Robotic Arm - Subsystem Component Research

Electrical Components

Option	Source/Part No.	Channels	Includes Electrod	Filters	Programmable Gain	Safety Standards	Patient Isolation	Quantity Req	Cost/Item	Total Cost	
Delsys Bagnoli-8	http://www.delsys.com/Products/Bagnoli_Desktop.html	8	yes	20-450Hz	100, 1000, 10000	IEC 601-1, CE mark 510K	yes	1	$9,900.00	$9,900	US
Bortec AMT-8	http://www.bortec.ca/pages/amt_8.htm	8	yes (disposable)	10-1000Hz	1 to 3	?	yes	1	$10,502.10	$10,502	CAN
B+L Engineering MA-300	http://www.bleng.com/emgh.htm	6	yes	30-500Hz (selectable)	5	?	?	1	$13,800.00	$13,800	US

sEMG Electrodes (dry)

Option	Source/Part No.	Type	Interface	Material	Case Dim (mm)	IED (mm)	Electrode Shape (mm)	Noise (uV)	CMRR (60/10Hz)	Input Impedance (ohm)	Amplifier Gain	Quantity Req	Cost/Item	Total Cost	
Delsys DE-3.1	http://www.delsys.com/Products/EMGSensors.html	double differential	Dry	Ag	41x20x5	10	10x1 rectangle	1.2uV (RMS, R.T.I.)	92 dB (typica	> 10^15	10 V/V ±1%	5	NOT AVAILABLE	$0	US
LTI - BE324	http://www.liberatingtech.com/products/documents/LTI_Remote_AC_Electrode_System.pdf	?	?	?	?	?	?	?	?	> 10^15	?	5	$0.00	$0	US
B+L Engineering BL-AE-WG	http://www.bleng.com/electrod.htm	single differential	Dry	Stainless Steel	50.8x17.5x6.35	17	12.7 dia disc	?	95 dB (typical)	> 10^8	330	5	$199.00	$995	US
Motion Lab Systems Z03		double differential	Dry	Stainless Steel	38x19x8	18	12 dia disc	< 1.2uV (RMS,	> 100 dB at 65Hz	> 10^8	300	5	$325.00	$1,625	US
BIOPAC TSD 150B	http://www.biopac.com/Research.asp?Pid=3584&Main=Electrodes	?	Dry	Stainless Steel	51x17.4x6.4	20	11.4 dia disc	includes low pass filter fc = 500Hz	95 db (typical)	>10^8	350	5	$498.00	$2,490	US
Ottobock 13E200	http://www.ottobockus.com/cps/rde/xchg/ob_us_en/hs.xsl/16573.html?id=16619#t16619	double differential	?		?			Includes notch filter for 60/50 Hz line noise and	> 100 dB at 60 Hz	?	?	5	$1,000.00	$5,000	US
Motion Control - EMG Preamplifier for Myolab II	http://www.utaharm.com/myolab.php?mo=8&yr=2007	?	Dry	?	50x18.0x7	?	?	Includes 1st order bandpass	> 100 dB at 60 Hz	1012 ohms	375	5	$0.00	$0	US

Analog Filters

Option	Description	Source/Part	Active?	Order	Desired Cutoff?	Quantity Req	Cost/Item	Total Cost	
Maxim 7490	dual universal switched-capacitor filter	http://www.maxim-ic.com/quick_view2.cfm/qv_pk/23	yes	4th order	yes	10	$2.15	$21.50	US
Maxim 263	Pin-programmable universal filter	http://www.maxim-ic.com/quick_view2.cfm/qv_pk/11	yes	4th order	yes	10	$6.89	$68.90	US
Maxim 260	Microprocessor programmable universal filter	http://www.maxim-ic.com/quick_view2.cfm/qv_pk/14	yes	4th order	yes	10	$6.49	$64.90	US

PC/104 A/D DAQ cards

Option	Source/Part No.	Diff Inputs	Resolution (bits)	Max Sample Rate (kHz)	Programmable Gains?	xPc driver?	Quantity Req	Cost/Item	Total Cost	
RTD DM6430	http://www.rtd.com/pc104/DM/analog%20IO/dm6430.htm	8	16	100	1,2,4,8	yes	1	$695.00	$695	US
Sensoray Model 526	http://www.sensoray.com/products/526data.htm	8	16	10	no	yes	1	$512.00	$512	US
Measurement Computing DA516 JR/16	http://www.mccdaq.com/pc104-data-acquisition/PC104-DAS16JR-16.aspx	8	16	100	no	yes	1	$499.00	$499	US
Diamond MM-16	http://www.diamondsystems.com/products/diamondmm16at	8	16	100	1,2,4,8	yes	1	$495.00	$495	US
Advanced Digital Logic - 104-AIO16E	http://www.adl-usa.com/products/peripherals/datapage.php?pid=104-AIO16E&sc=analog	8	16	250	1,2,5,10 (by jumper)	no	1	$0.00	$0	US

PCI A/D DAQ cards

Option	Source/Part No.	Diff Inputs	Resolution (bits)	Max Sample Rate (kHz)	Programmable Gains?	xPc driver?	Quantity Req	Cost/Item	Total Cost	
NI PCI-6259 + SCB-68 Connector Block	http://sine.ni.com/nips/cds/view/p/lang/en/nid/14128	8	16	1000	?	yes	1	$1,970.00	$1,970	US

Embedded Computers

Option	Form Factor	Source/Part	CPU	RAM	Ethernet	Hard Disk?	Serial Ports?	Quantity Req	Cost/Item	Total Cost	
Advanced Digital Logic - ADL855PC	PC104+	http://www.adl-usa.com/products/cpu/datapage.php?pid=ADL855PC&sc=pc104%2B	Intel® Pentium® M / Celeron® M, 0.6GHz - 1.8GHz	128MB - 1024MB DDR-SDRAM	10/100 Base-T LAN-Ethernet	EIDE hard disk interface or compact flash adapter also available	2	1	$1,279.00	$1,279	
RTD - CML147786CX650HR	PC104+	http://www.rtd.com/PC104/CM/786/147786/CX/CML147786CX-650.htm	650 MHz, 0.95Vdc Intel® Celeron®	128MB SDRAM	10BASE-T and 100BASE-Tx	EIDE Controller with UltraDMA 33/66/100	2	1	$1,295.00	$1,295	US
RTD - CMA157886PX1400HR	PC104+	http://www.rtd.com/PC104/CM/886/157886/CMA157886-1400.htm	1.4 GHz Intel Pentium M with thermal throttling	512 Mbytes BGA DDR SDRAM	10BASE-T and 100BASE-Tx	EIDE Controller with UltraDMA 100	4	1	$2,895.00	$2,895	US
											US

Batteries and Wiring

Option	Description	Source/Part	Nominal Voltage (V)	Capacity (Ahr)	DC output (A)	Quantity Req	Cost/Item	Total Cost	
5V Pocket-Size Lithium Battery Pack	Includes AC quick charger	http://www.bixnet.com/5v7libapa.html	5	5.32	1.5	1	$79.95	$79.95	
Thunder Power RC 7.4V Prolite LIPO	offer the best combination of lightweight packs and current capacity.	http://thunderpowerrc.com/html/prolites.html (TP8000-2S4PL)	7.4V	8	80	1	$174.95	$174.95	US
Thunder Power LIPO Charger		http://www.thunderpowerrc.com/html/cba-chargers.html (TP-610C)	-	-	-	1	$129.95	$129.95	US

Option	Description	Source/Part	Quantity Req	Cost/Item	Total Cost	
LEMO - PHG.0B.305.CLLD52	female connector for cable adapter for electrodes	http://www.birde.ca/home.html	5	18.43	$92.15	CAN
LEMO - ECG.0B.305.CLL	female connector for back panel mount	http://www.birde.ca/home.html	5	15.68	$78.40	CAN
LEMO - EEG.0B.305.CLL	female connector for back panel mount	http://www.birde.ca/home.html	5	16.63	$83.15	CAN

Medical Power Supplies

	Description	Source/Part	Output Voltage	Current Output	Power (Watts)	Dimensions (mm)	Safety Standard	Quantity Req	Cost/Item	Total Cost
Elpac MSM40 - A (Triple Output)	open frame power supply	http://iccus.com/index.php?option=com_content&view=article&id=14&Itemid=28 (MSM40)	5V, +- 12V	4A	40W	127x76.2x36	CSA 601	1	did not email back	
Absopulse HOW 100	closed frame power supply	http://www.absopulse.com/acdc_1.html#Anchor-Medic-22219 (HOW 100)	5V-130V	?	100W	86x155x48	CSA 601	1	did not email back	
Absopulse MPS 420	closed frame power supply	http://www.absopulse.com/acdc_1.html#Anchor-Medic-22219 (MPS 420)	5V, +- 12V	20A	150W	140x86x151	CSA 601	1	did not email back	
Autec BPA-100-50M	closed frame power supply	http://www.autec.com/html/search.php?searchmodels=medical (BPA-100-50M)	5V	20A	100W	153.5x82x38	CSA 601	1	did not email back	
Emerson LPS42-M	open frame power supply	http://www.powerconversion.com/products/websheet/323/LPS40-M-Medical (LPS42-M)	5V	8A	40W	127x76.2x34	CSA 601	1	did not email back	
MEPOS - SHFA31-S02	open frame power supply	http://www.mepos.ca/index.php?cmd=med_50i	5V	4A	20W	102x38x27	CSA 601	1	$27.52	$27.52
MEPOS - SMFA30-S02	open frame power supply	http://www.mepos.ca/index.php?cmd=med_50i	5V	6A	30W	51x102x30	CSA 601	1	$37.26	$37.26
MEPOS - SMDA30-S02	closed frame power supply	http://www.mepos.ca/index.php?cmd=med_50e	5V	5A	25W	120x51x40	CSA 601	1	$50.36	$50.36
V-Infinity - VMS -160-5	open frame power supply	http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=102-1691-ND	5V	16A	80W	101x51x28	CSA 601	1	$140.60	$140.60
TDK Lambda - KMS40-5	closed frame power supply	http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=285-1767-ND	5V	8A	40W	89x63.5x27	CSA 601	1	$84.50	$84.50
MEPOS - SMFA60-S05	open frame power supply	http://www.mepos.ca/index.php?cmd=med_100i	12V	5A	63W	127x76x28	CSA 601	1	$61.28	$61.28
MEPOS - SMDA63-S05	closed frame power supply	http://www.mepos.ca/index.php?cmd=med_100e	12V	5.25A	63W	144x75x43	CSA 601	1	$58.09	$58.09

Actuators

Option	Description	ource/Part N	Feedback	Control Input	Operating Range (°)	Resolution (°)	Dimensions (mm)	Weight (g)	Holding Torque (Nm)	No-Load Speed (s/60deg)	Input Voltage (V)	Max Current (mA)	Command Signal	Req Items	Cost/Item	Total Cost

A - Dynamixel AX-12	servomotor with built in gear reducer, precision DC motor and control circuitry	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	Position, Temperature, Load, Input Voltage	angular position and velocity	0-300 or endless turn	0.35	50x32x38	55	1.619	0.196	7 to 10	900mA	TTL packet	7	$44.90	$314.30	US
B - Hitec HS-645MG	analog servomotor with 3 pole motor	http://www.crustcrawler.com/motors/servos/index.php?prod=6	none	angular position	?	?	40.6x19.8x37.8	55.2	0.9418 (stall torque)	0.2	4.8 to 6	450mA	PWM	7	$39.99	$279.93	US

NOTE: Torques and No-Load speeds reported at maximum voltage

Actuator Controllers

Option	Description	ource/Part N	Required Items	Cost/Item	Cost	
A - Propellor Demo Board	Serial Controller	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	1	$89	$89	US
A - MAX 212 chip	RS-232 to 3.3V TTL converter - needed to communicate between target computer and propellor board	http://www.maxim-ic.com/quick_view2.cfm/qv_pk/1051	1	$3.29	$3.29	US
B - USB2dynamixel	USB Controller	http://www.maxim-ic.com/quick_view2.cfm/qv_pk/1052	1	$59.90	$59.90	US

Actuator Accessories

Option	Description	ource/Part N	Required Items	Cost/Item	Cost	
A - AX-12 Power Supply	9V,6A,54W,P5 female barrel plug, 3 prong power cable, will power the dynamixel bus	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	1	$89	$89	US
A - AX-12 Power Harness	connects power suppply to dynamixel bus	http://www.crustcrawler.com/motors/AX12/index.php?prod=64	1	$19	$19	US

Mechanical Components

Robotic Arm Hardware

Option	Description	ource/Part N	Required Items	Cost/Item	Cost	
AX-12 smart Arm	Hardware Kit (sah)	http://www.crustcrawler.com/products/smartarm/index.php?prod=12	1	$399.00	$399.00	US

Existing Kit Modifications

Option	Description	ource/Part N	Required Items	Cost/Item	Cost	
AX-12 smart Arm Mod	Add table mount and adjustable shoulder height	machineshop	1	$100.00	$100.00	US

Option	Description	ource/Part N	Required Items	Cost/Item	Cost	
Two arm handle	Plastic Two-Arm Knob 3/8"-16 Threaded Insert, 2-1/2" Dia, Nylon	McMaster 6	1	$1.74	$1.74	
Stud	ASTM A193 B7 Alloy Steel Full Thread Stud 3/8"-16 Thread, 6" Length	McMaster 9	1	$2.17	$2.17	
Swivel Leveling Mount	Swivel Leveling Mount Nickel-Plated Steel, 3/8"-16 Thrd, 3750 lb Load	McMaster 6	1	$5.88	$5.88	
Bar Clamps	Light-Force Cast Iron Bar Clamp 8" Maximum Opening, 300# Holding	McMaster 6	2	$6.07	$12.14	
Socket Cap Screws	Alloy Steel Button Head Socket Cap Screw 5-40 Thread, 3/8" Length	McMaster 9	3		$12.70	US

Electronics Enclosure

Option	Description	ource/Part N	Required Items	Cost/Item	Cost	
Polycarbonate Enclosure	Polycarbonate Enclosure (NEMA 4X) Opaque Gray Lift-Off Cover, 10.9" H X 7.4" W X 7.1" D	mcmaster 69945K173	1	$77.11	$77.11	US

Software Components

EMG Acquisition

Option
Matlab xPC Target
Windows Application
Matlab Data Acquisition Tool Box

Motor Control

Option
Matlab xPC Target
Windows Application
Matlab Data Acquisition Tool Box

Laptop

Option	Description	Source/Part	Quantity Req	Cost/Item	Total Cost (CA)	Total Cost	
ACER Notebook from BCOM	ACER ASPIRE ONE D150-1676 N270 1.6GHZ 160GB 1GB 10.1" WSVGA 6CELL BLACK XPH LU.S570B.149	http://www.b-com.ca/product.php?productid=224404&page=1	1	$426.00	$426.00	$388.49	US

ACER Netbook from Bestbuy	Acer Aspire 8.9" Netbook featuring Intel Atom Processor N270 (AOA150-1283) - Blue	http://www.bestbuy.ca/catalog/proddetail.asp?sku_id=0926INGFS10112480&logon=&langid=EN	1	$329.99	$329.99	$300.98	US

A.1.3 Bill of Materials

A detailed bill of materials for the MTT Research prototype is provided below.

MTT Research Prototype - Bill of Materials

Part Name	Option	Source/Part No.	Required Items	Cost/Item	Cost (US)
Electrical Components					
sEMG Electrodes	B+L Engineering BL-AE-N	http://www.bleng.com/electrod.htm	5	$199	$995.00
Analog Input DAQ card	NI PCI-6259 + SCB-68 Connector Block	http://sine.ni.com/nips/cds/view/p/lang/en/nid/14128	1	$1,970	$1,970.00
Actuators	Dynamixel AX-12	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	7	$44.90	$314.30
Actuator Controller	USB2 Dynamixel	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	1	$49.90	$49.90
Actuator PSU	AX-12 Power Supply	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	1	$89	$89.00
Actuator Power Cable	AX-12 Power Harness	http://www.crustcrawler.com/motors/AX12/index.php?prod=64	1	$19	$19.00
xPC Host Computer	New desktop computer		1	$1,000	$1,000.00
xPC Target Computer	Used desktop computer		1	$500	$500.00
Mechanical Components					
Robotic Arm Hardware	AX-12 smart Arm	http://www.crustcrawler.com/products/smartarm/index.php?prod=12	1	$399.00	$399.00
Existing Kit Modifications	AX-12 smart Arm Mod	machineshop	1	$100	$100.00
Software Components					
EMG Acquisition	Matlab xPC Target				
Motor Control	Matlab xPC Target				
				TOTAL COST:	$5,436.20

NOTE: Cost (US) do not include taxes, shipping charges, or miscellaneous wiring and connectors

A.1.4 Design Compliance Matrix

The design compliance matrix was used at the end of the project to verify whether the prototype met all of the design requirements. The matrix is broken up into mechanical, electrical, and software subsystems. Each requirement has an associated design authority, importance, and safety factor (if applicable). The design compliance indicates whether or not a requirement has been met. If a requirement has not been met a recommendation for future work is supplied.

DESIGN COMPLIANCE MATRIX
Design Project: Digital X-Ray Equipment

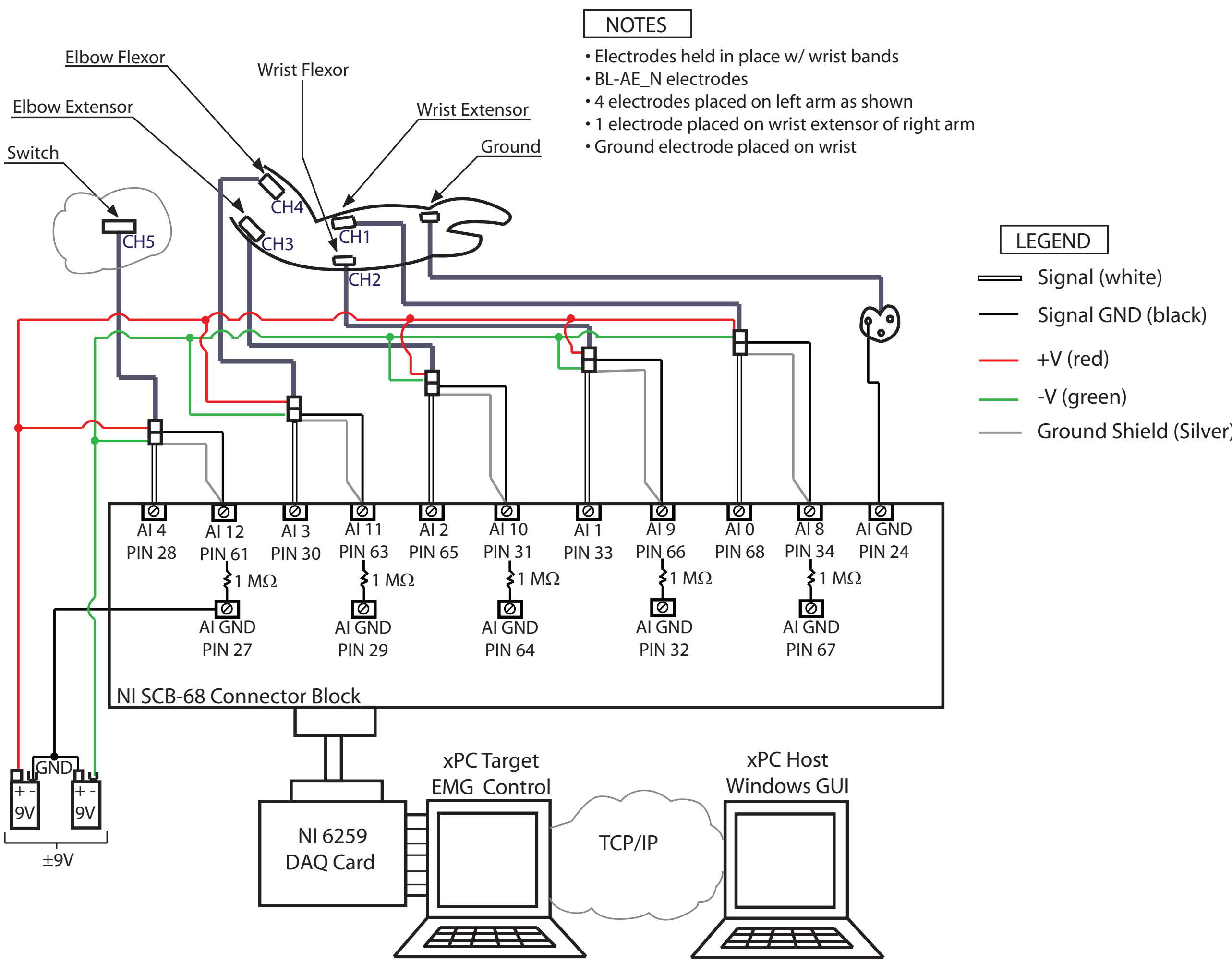
Item #	Component / System Description	Design Specification / Requirement	Safety Factor	Design Authority	Design Importance D (1-5)	Design Compliance
1.00	**Mechanical Subsystem**					
1.10	Size	half scale with anatomically correct proportions	-	Client	3	Roughly half scale in size. Recommend custom brackets to achieve anatomical proportions
1.20	Weight	5 -10 lb	-	Client	3	Complies
1.30	Degrees of Freedom	5 DOF to mimic conventional upper-arm prostheses	-	Client	5	Complies
1.31	Hand (open/close)	grasp up to 10cm wide objects, similar in style to Utah ETD	-	Client	4	Does not comply. Recommend modification to gripper in order to grasp larger objects with an ETD style gripper
1.32	Wrist (flexion/extension)	anatomically correct	-	Client	4	Complies
1.33	Wrist (rotation)	anatomically correct	-	Client	4	Complies
1.34	Elbow (flexion/extension)	anatomically correct	-	Client	4	Complies
1.35	Elbow (humeral internal/external rotatio	anatomically correct	-	Client	4	Complies
1.40	Maximum Payload	100g	1.5	Client	3	Recommend switch to AX-18F servos in elbow joint
1.50	Repeatability	< 3mm	-	Client	4	Achieved 2.5 mm
1.60	Target Cost	$1,000	-	Client	3	Complies (cost of hardware and modifications ~ $500)
1.70	Development Time	2 months or less	-	Client	5	Complies
2.00	**Electrical Subsystem**					
2.10	Actuators		-			
2.11	Feedback	provide angular position feedback to controller	-	Client	4	Complies
2.12	Holding Torque	complies with (1.40)	-	Client	3	Does not comply. Recommend switch to AX-18F servos in elbow joint
2.13	Control Input	torque or angular velocity	-	Client	5	Complies
2.14	Low level control	controllable through serial communication and XPC target	-	Client	4	Complies
2.15	Resolution	complies with (1.50)		Client	3	Complies
2.16	No-load speed	> 60 degrees/0.3 seconds		Client	3	Complies
2.20	EMG Electrodes	5 electrodes with built in pre-amps and option for detaching electrodes	-	Client	4	Complies
2.30	Data Acquisition Card		-			
2.31	Resolution	16-bit	-	Client	3	Complies
2.32	Analog Input Channels	minimum 5 differential channels	-	Client	5	Complies
2.33	Drivers	driver blocks available for XPC target	-	Client	4	Complies
2.40	Power Supply		-		2.4	
	EMG electrodes	DC batteries	-	Client	5	Complies
	Other Components	DC batteries or AC Wall Power Supply	-	Client	3	Complies
	Running time	minimum of 3 hours	-	Client	3	Complies
2.50	Wiring and Connectors	wiring routed cleanly	-	Client	1	Complies
2.60	xPC Target Computer	desktop computer compatible with XPC target and can communicate with all other electrical components		Client		Complies
2.70	xPC Host Computer	desktop computer		Client		Complies
2.80	Target Cost	$5,000		Client	3	Complies. Actual cost ~ $5400
3.00	**Software Subsystem**					
3.10	Conventional EMG Software		-			
3.11	Extracted Feature	Mean Absolute Value	-	Client	5	Complies.
3.12	Controller Type	Two state controller (1 function per muscle site) + switch	-	Client	5	Complies.
3.13	Notch Filter	60Hz notch		Client	2	Complies.
3.14	High Pass Filter	10Hz cutoff		SENIAM	2	Complies.
3.20	Software Environment	MATLAB XPC Target	-	Client	5	Complies.
3.30	Overall Processing Time	< 0.200 seconds	-	Client	3	Complies.
3.40	Graphical User Interface	See GUI_Feature_list.xls		Client	5	Complies.
Notes	Design Importance	5 - Essential or required feature / 1 - Optional requirement				
	Score	10 - Meets requirement in all respects / 1 - Does not satisfy requirement				

Rev	Description	Client Approval	Date
0	Initial release		2010/12/03

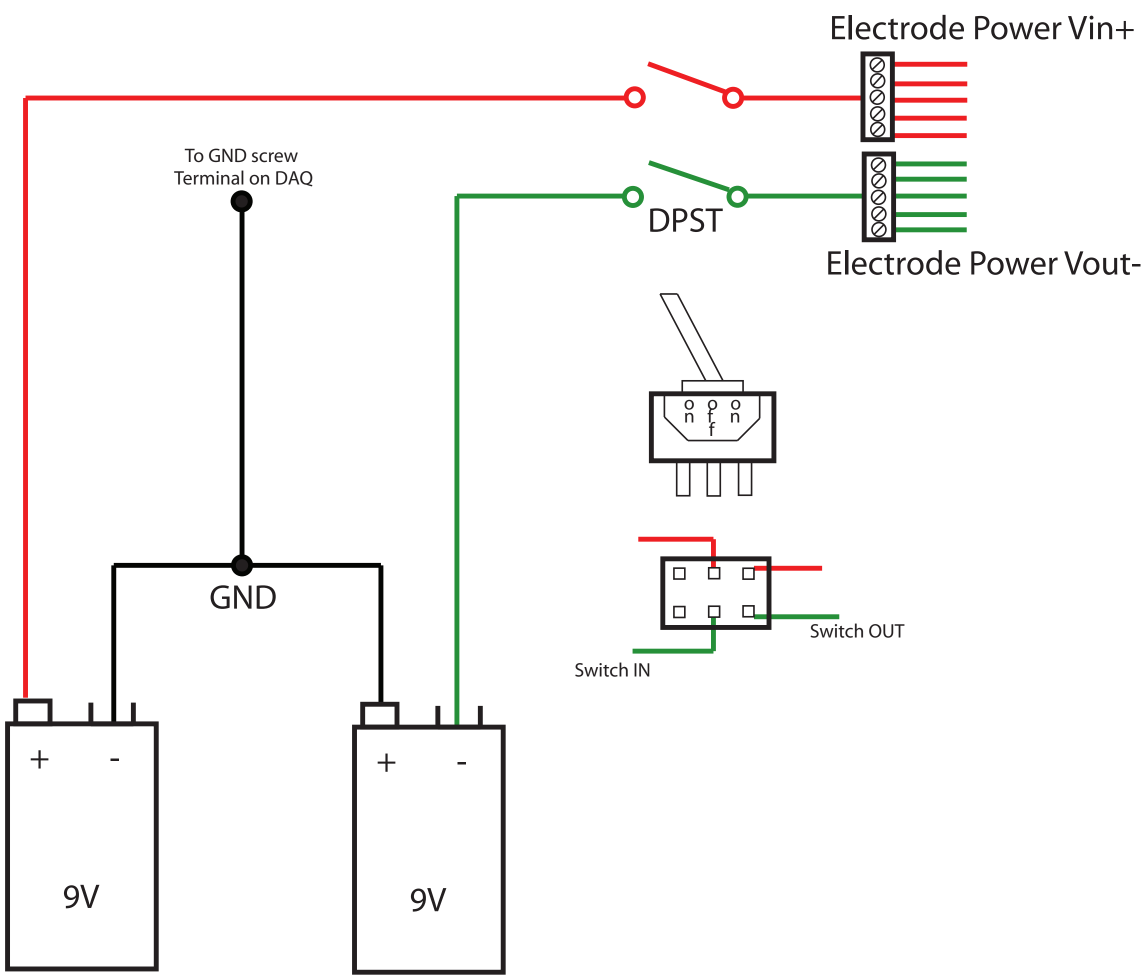
A.2 Wiring Diagrams

The following wiring diagrams can be used to connect the EMG electrodes to the DAQ system and to connect the EMG electrodes to their power supply respectively.

A.2.1 BL-AE-N Electrode to SCB-68 Connector Block Interface Diagram



A.2.2 Custom Powering Harness for BL-AE-N Electrodes



A.3 Experimental Trials

The documentation relating to the experimental trials can be found in the following subsections including the subject consent form, a detailed experimental procedure, and the usability survey from the study. The full experimental data and analysis sheets from excel are also included. The specific student t-tests including the null and alternate hypotheses are located within the analysis sheet.

A.3.1 Subject Consent Form

UNIVERSITY OF ALBERTA

Mechanical Engineering
Faculty of Engineering

4-9 mechanical Engineering Building
Edmonton, Alberta, Canada T6G2G8

/www.engineering.ualberta.ca/mece/

PARTICIPANT INFORMATION SHEET

Title of Project: Development of a Myoelectric Training Tool for Above Elbow Amputees

Principal Investigator(s): Dr. J.P.R. Carey, Department of Mechanical Engineering, U of Alberta

Co-Investigator(s): Michael Dawson, MSc Student, Department of Mech. Eng., U of Alberta
Dr. Patrick Pilarski, Department of Computing Science, U of Alberta
Dr. Richard Sutton, Department of Computing Science, U of Alberta
Dr. Farbod Fahimi, Mechanical and Aerospace Engineering, U of Alabama

This paragraph describes the purpose of the research:
You are being asked to participate in a research study to validate an inexpensive myoelectric training tool to help above-elbow amputees learn how to use myoelectric prostheses. The myoelectric training tool maps the muscle contractions on an above-elbow amputee patients' residual limb to the degrees of freedom of a robotic arm using surface electromyography (EMG) electrodes (a non-invasive means of measuring the physiological signal corresponding to muscle force). The purpose of the tool is to train amputees in using myoelectric technology in advance of receiving their actual myoelectric prostheses. This research will serve as an evaluation of the training tool and will be performed initially healthy volunteers. Being in this study is completely voluntary – you do not have to participate and even if you agree to participate you can decide to stop at any time without any reason. Please read this information sheet carefully to learn more about this study.

Procedure:
If you agree to be in this study, surface EMG electrodes and a ground electrode will be placed over your forearm and upper arm muscles to record the muscle signals. These electrodes will be placed on your skin and will be held in place with wristbands. The first 4 electrodes will be placed over the antagonistic muscles in the forearm and upper arm on the selected arm of the subjects. The ground electrode will be placed over the bony part of the wrist. The 5th electrode is used as a switch and will be placed on the opposite forearm. A calibration procedure will be performed in order to tailor the tuning parameters of the EMG controller to each subject. Total setup time including calibration is about 15 minutes. After calibration, subjects will perform 10 timed trials where they will use the robotic arm to move 5 plastic balls from one box to another as fast as possible. A 3-minute break will be allowed to the subject between trials in order to avoid muscle fatigue. Before using the EMG controlled robotic arm, the subject will perform 10 trials of the same task with their actual arm in order to establish a baseline. Subjects will be videotaped during trials. After completing all of their trials the subject will be asked to fill out a short usability survey which will take about 5 minutes.

Time requirement:
- Actual arm ball movement trials – 5 minutes
- Setup time including calibration – 15 minutes
- Robotic arm ball movement trials – 60 minutes
- Usability survey – 5 minutes

Benefits and Risks:
There will be no benefit to you for being in this study. We hope that the information we learn from doing this study will help us to develop our training tool and will help people with arm amputations in the future.

There may be risks associated with being in this study. It is possible that a very rare system failure could harm the subject. We have tried to avoid this possibility by using skin electrodes that are battery powered. This prevents major power surges to reach the participant. Another risk is for the robotic arm and subject to collide unintentionally. In case of contact the motors automatically shut down. Another risk is from muscle fatigue. This risk will be mitigated by offering a suitable amount of rest time between each trial. The subject will also always have the option to stop or take longer rest times if they feel too fatigued.

Protection of personal information
We will keep the information that we get from this study confidential. Only the researchers will have access to the data. The videotapes that we will be taking will show your face and as such you will be identifiable to people who may view them. However any publication that we do as a result of this study will not reveal your name or your identity (i.e. by showing the video tapes). We will keep the information that we get from this study for five years after which time it will be destroyed.

By signing this form, you agree to participate in the above study:

Name of Participant **Signature of Participant**

Name of person explaining and requesting consent **Signature**

____
Dated

A.3.2 Experimental Procedure

Experimental Procedure for Initial Myoelectric Training Tool (MTT) Validation Study (3ch)

Introduction

Objective: To show that people can learn using the myoelectric training tool
Participants: Able-bodied members of our research group
Task: Modified box and blocks
Analysis: Statistical significance between first and last trial of experiment averaged between participants. Fit learning curve to averaged trial times. Discuss effect of fatigue

Preparation

Perform the following steps before the participant arrives:

1. Load the control software "TWO_STATE_CONTROLLER_5CH_REV6.mdl" onto the target computer
    a. Turn on target computer with xPC target boot floppy inserted into the floppy drive
    b. Reboot host computer and do not open additional programs not mentioned in this procedure. This will help make sure that the maximum amount of system resources are available for the MTT software.
    c. Open MATLAB R2009b on host computer
    d. Type "xpcexplr" into matlab command prompt. The xPC Target Explorer will open up.
    e. Make sure that the xPC target kernel has fully loaded on the target computer. Right click on "TargetPC1" and select "Connect".
    f. Right click on "TWO_STATE_CONTROLLER_5CH_REV6.mdl" and select "Download to TargetPC1"
    g. Right click on "TargetPC1" and select "Disconnect"
    h. Close the xPC Target Explorer
    i. In the matlab command prompt type "close(xpc)"
    j. Close MATLAB R2009b
2. Load the MTT graphical user interface (GUI) onto the host computer. The MTT GUI communicates between the myoelectric control software on the target computer, the GUI on the host computer, and the dynamixel bus, which controls the movements of the robotic arm.
    a. Open "Microsoft Visual Studio 2008" on the host computer
    b. Open "Demo.sln" located in the following folder: "C:\Program Files\MATLAB\R2009b\toolbox\rtw\targets\xpc\api\VBNET\GUI_DOF2_5ch"
    c. Load the MTT GUI software by pressing the "Start debugging" button, which looks like a play button. In the right sidebar the Form1 version should be "Form1_rev7.vb". The MTT GUI will open up.
3. Check the voltage of the batteries that power the EMG electrodes. If the voltage reads less than 8V replace with new 9V batteries of same brand.

4. Check that all the fasteners on the AX-12 robotic arm are tight.
5. Make sure the host computer speakers are plugged in and the volume is at an appropriate level.
6. Print off “MTT info sheet_draft3.doc”, “MTT_Usability Survey.doc” located in the folder “H:\Grad Studies\Experimental Trials”
7. Print off sheet1 from “MTT Subject Data.xls” located in the folder “H:\Grad Studies\Experimental Trials”
8. Move the host computer keyboard and mouse outside of the robotic arm workspace
9. Attach the robotic arm to the desk with clamps
10. Attach the box testing apparatus to the desk with duct tape
    a. Center box and place approx 2cm in front of robotic arm
11. Take out five test balls and four wrist-bands and leave them out on the table

Running the Experiment

Perform the following steps once the participant has arrived:

1) Review “MTT info sheet_draft3.doc” and “MTT_Usability Survey.doc” with participant
    a. Let them know they can opt out of the study at anytime if they feel uncomfortable
2) Have participant sign the consent form.
3) Explain the rules of the modified box and blocks task
    a. The robotic arm will start in the default position (pointed upwards and centered over the partition with all joints in their default positions (position = 512)
    b. Balls will be initially preplaced into the left box in the predefined locations
    c. The timer will start and the participant will try and move all five blocks from the left box to the right box as fast as they can.
    d. The timer will stop when the fifth ball touches the floor of the right box
    e. Throwing the balls is not allowed. Participants must move their fingers into the plane of the right partition before dropping the balls
    f. Participants must pick up only one ball at a time.
    g. If a ball bounces out of the right partition then it will still be counted as a success
    h. Under any other condition i.e. ball falls out of the left box, servo overload, ect the trial will be marked incomplete and the participant will redo that trial
4) Actual arm ball movement trials
    a. Have the participant run through the task outlined in step 3) by using their actual left hand with their left elbow fixed to the table
    b. The participant will perform successful 10 trials
    c. Record data on “MTT Subject Data” sheet
5) Place electrodes onto the patient using wrist-bands
    a. Place “Channel 1” onto wrist flexor of left arm (top of forearm)
    b. Place “Channel 2” onto wrist extensor of left arm(bottom of forearm)

c. Place “Ground” onto bony area of wrist on left arm
d. Place “Channel 5” onto wrist flexor of right arm (top of forearm)

6) Flip electrode battery power switch into the “on” position
7) Connect to the target computer and start the control software
   a. In the MTT GUI in the “EMG Acquisition – Communications Settings” section click “Connect” and then “Start”
8) Load the default profile: “exp_trials_sequential.dat”
9) Explain to the patient how to generate the appropriate signals for conventional myoelectric control
   a. As you contract your muscles more intensely the signal strength increases. Once your signal strength exceeds a threshold value we map it proportionally to the angular velocity of the servo motors on the robotic arm.
   b. Each antagonistic muscle pair can control one degree of freedom
   c. Channels 1 and 2 control Elbow Extension/Flexion, Wrist Extension/Flexion, Hand Open/Close, and Shoulder Rotation CCW/CW
   d. Channel 5 switches sequentially between the above mentioned degrees of freedom on Channels 1 and 2.
10) Basic signal training and calibration (5 minutes)
   a. Have the patient control each signal independently
   b. Calibrate the control parameters by adjusting the signal gain and thresholds in the “EMG Acquisition – Parameters” section of the MTT GUI in order to allow the patient to control each degree of freedom without cocontraction
   c. Save their profile in the MTT GUI by selecting “file -> Save Profile As” and saving the file as “Last name_date.dat”. Do not change any of the control parameter values after this point.
11) Simulator training (5 minutes)
   a. In the MTT GUI in the “Simulator – Communications Settings” click “Launch” wait 20 seconds and then click “Connect”
   b. Allow the patient to demonstrate their understanding of how the controller works by performing the movements described in a) and b) in the simulator
   c. Have the patient try using the “Channel 5” switching functionality
12) Explain to the participant how the robotic arm works
   a. Show motion of robotic arm
   b. Explain that the arm can reach its mechanical limits in which case the servos might overload and need to be reset. If this happens they will need to redo that particular trial
   c. Explain that the hand cannot overgrip the balls and cause the servos to overload.
   d. Explain how the gripper actually moves vertically as it narrows
   e. Explain that the power to the robotic arm can be cut by hitting the red button on the power bar
13) Turn on power to robotic arm and initialize the robotic arm controller
   a. Flip the red switch on the power bar to the “on” position

b. In the MTT GUI in the "Robotic Arm – Communication Settings" click "Connect" and then "Start"

14) Robotic arm ball movement trials
    a. The participant will perform successful 10 trials
    b. 2 minute break between each trial (optional)
    c. Suggest to the patient to put their elbow on the table in order to reduce fatigue
    d. Replace balls that move from carpet snag
    e. When the subject is first starting (Trials 1-3) help them know if they have grabbed the balls properly
    f. Record data on "MTT Subject Data" sheet
    g. Observe the participant closely and answer the analysis questions. Develop new analysis questions if required.
15) Have the participant fill out the usability survey
16) Thank the participant for participating in the study and send them on their way.

Cleanup

Perform the following steps once the participant has left:

1) Disconnect from the robotic arm and target computer in the MTT GUI
2) Turn off the power to the robotic arm and EMG electrodes
3) Turn off the target computer
4) Finish answering the analysis questions while the trials are still fresh in your head
5) Record the data into a new sheet in "MTT Subject Data.xls" located in the folder "H:\Grad Studies\Experimental Trials"

A.3.3 Usability Survey

UNIVERSITY OF ALBERTA

Mechanical Engineering
Faculty of Engineering

4-9 mechanical Engineering Building
Edmonton, Alberta, Canada T6G2G8

/www.engineering.ualberta.ca/mece/

Name:

Date:

Usability Survey:

Comfort is classified as how comfortable the controller was to you. A 0 corresponds to a controller that was uncomfortable, or caused muscle fatigue. A 5 corresponds to a controller that was comfortable while causing minimal or no fatigue.

Intuitiveness is classified as how easy it was to learn how to use the controller. A 0 corresponds to a controller that was difficult or took a long time to learn. A 5 corresponds to a controller that was easy to learn or was learned quickly.

Delay is classified as how long it took for a controller to respond to an input command. A 0 corresponds to a controller that was sluggish or unresponsive. A 5 corresponds to a controller that responded quickly.

Effectiveness is classified as how well the controller was able to perform the task. A 0 corresponds to controllers that were frustrating or cumbersome to use and performed the task poorly. A 5 corresponds to controllers that were easy to use and performed the task effectively.

	Comfort	Intuitiveness	Delay	Effectiveness
EMG control of robotic arm				
Movement of actual arm				
EMG control of 3D Simulator				

For the EMG controller please rate each movement from 0 to 5 on how difficult it was to perform in a timely and reliable manner with 0 being very difficult and 5 being easy to use:

Degree of Freedom	Rating
Hand Open/Close	
Wrist Flexion/Extension	
Wrist Rotation	
Elbow Flexion/Extension	
Shoulder Rotation	

Please add any additional comments that you might have here:

A.3.4 Experimental Data and Analysis

MTT Data Analysis

Averaged Times for each Trial Across 5 Subjects

Actual Arm Trials		
Trial #	Time (s)	StdDev
1	4.68	0.636
2	4.40	0.270
3	4.24	0.575
4	3.98	0.697
5	3.98	0.785
6	4.00	0.889
7	3.96	0.810
8	3.78	0.764
9	4.05	0.640
10	3.73	0.658

Robotic Arm Trials		
Trial #	Time (s)	StdDev
1	237.23	68.36
2	198.40	23.05
3	165.15	41.16
4	196.03	60.63
5	166.54	28.76
6	136.04	39.31
7	135.08	40.53
8	143.32	20.95
9	126.25	30.21
10	110.76	23.94

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments

MTT Usability Survey (Averaged Ratings)

	Comfort	Intuitiveness	Delay	Effectiveness
EMG Control of Robotic Arm	4.2	4.2	4.2	3.8
Movement of actual arm	5	5	5	5
3D Simulator	3.8	4.2	3.4	3.6

Degree of Freedom	Rating
Hand Open/Close	4.6
Wrist Flexion	4.6
Wrist Rotation	N/A

Elbow Flexion	4.4
Shoulder Rotation	3

MTT Usability Survey (Standard Error in Mean)

	Comfort	Intuitiveness	Delay	Effectiveness
EMG Control of Robotic Arm	0.374165739	0.2	0.2	0.2
Movement of actual arm	0	0	0	0
EMG Control of 3D Simulator	0.374165739	0.2	0.4	0.509901951

Degree of Freedom	Std Error
Hand Open/Close	0.244948974
Wrist Flexion/Extension	0.244948974
Wrist Rotation	N/A
Elbow Flexion/Extension	0.244948974
Shoulder Rotation	0.316227766

Summary Statistics

Actual Arm Trials	Robotic Arm
Trial 1 - Time (s)	Trial 10 - Time (s)
5.22	198.09
5.62	227.82
3.94	179.28
4.82	189.76
4.28	177.34
4.76	217.81
Std Dev	Std Dev
0.60934938	0.364933784
Average	Average
4.77	198.35

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	198.35	4.773333333
Variance	425.22264	0.371306667
Observations	6	6
Pearson Correlati	0.802705904	
Hypothesized Me	0	
df	5	
t Stat	23.54915374	
P(T<=t) one-tail	1.28541E-06	
t Critical one-tail	2.015048372	
P(T<=t) two-tail	2.57083E-06	
t Critical two-tail	2.570581835	

	Column1
Mean	4.773333333
Standard Error	0.248765843
Median	4.79
Mode	#N/A
Standard Deviation	0.60934938
Sample Variance	0.371306667
Kurtosis	-0.689541384
Skewness	-0.003483967
Range	1.68

Minimum	3.94
Maximum	5.62
Sum	28.64
Count	6

Robotic Arm Trials

Trial 1 - Time (s)	Trial 8 - Time (s)	Trial 10 - Time (s)
331.47	135.66	
199.83	167.08	89.13
139.64	123.41	110.32
249.48	131.01	100.12
305.06	164.96	151.37
292.15	130.12	102.88

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*	
Mean	237.232	110.764	NOTE: Had to discard subject 1 data since subject 1 only completed 8 trials
Variance	4672.43647	573.13163	
Observations	5	5	
Pearson Correlation	0.464938623		Null and Alternate Hypotheses:
Hypothesized Mean I	0		Ho: mu_trial1 - mu_trial10 <= 0
df	4		vs
t Stat	4.634123274		H1: mu_trial1 - mu_trial10 > 0
P(T<=t) one-tail	0.004888474		(1 tail test)
t Critical one-tail	2.131846782		
P(T<=t) two-tail	0.009776948		Conclusion:
t Critical two-tail	2.776445105		Since p < 0.05 we can conclude that the subjects on
			average completed the 10th trial faster than the 1st trial

	Elbow Flexion	Shoulder Rotation
Subject 1	4	4
Subject 2	4	2
Subject 3	5	3
Subject 4	4	3
Subject 5	5	4
Subject 6	4	3

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*	For Subject 2-6
Mean	4.4	3	
Variance	0.3	0.5	
Observations	5	5	Null and Alternate Hypotheses:
Hypothesized Mean I	0		Ho: mu_elbowflex - mu_shoulderrot <= 0
df	8		vs
t Stat	3.5		H1: mu_elbowflex - mu_shoulderrot > 0
P(T<=t) one-tail	0.004039541		(1 tail test)
t Critical one-tail	1.859548033		
P(T<=t) two-tail	0.008079082		Conclusion:
t Critical two-tail	2.306004133		Since p < 0.05 we can conclude that the subjects on average thought
			the shoulder rotation degree of freedom was more difficult to
			control than the elbow flexion degree of freedom

	Delay Robot	Delay Simulator
Subject 1	4	2
Subject 2	4	2
Subject 3	4	3
Subject 4	4	4
Subject 5	5	4
Subject 6	4	4

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*	For Subject 2-6
Mean	4.2	3.4	
Variance	0.2	0.8	

Observations	5	5	Null and Alternate Hypotheses:
Hypothesized Mean I	0		Ho: mu_elbowflex - mu_shoulderrot <= 0
df	6		vs
t Stat	1.788854382		H1: mu_elbowflex - mu_shoulderrot > 0
P(T<=t) one-tail	0.061924585		(1 tail test)
t Critical one-tail	1.943180274		
P(T<=t) two-tail	0.12384917		Conclusion:
t Critical two-tail	2.446911846		Since p > 0.05 we cannot make any statistically significant conclusions

Info on each T-test:
http://office.microsoft.com/en-us/excel-help/about-statistical-analysis-tools-HP005203873.aspx

MTT Subject Data Sheet

Subject Name:
Date:
Time:
Averaged Tiı andedness:

Actual Arm Trials	
Trial #	Time (s)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

Robotic Arm Trials	
Trial #	Time (s)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments

MTT Subject Data Sheet

Subject Name:
Date:
Time:
Averaged Tir andedness: Right

Actual Arm Trials	
Trial #	Time (s)
1	5.12
2	4.93
3	4.14
4	3.67
5	3.42
6	4.55
7	3.41
8	3.07
9	2.94
10	3.14

Robotic Arm Trials	
Trial #	Time (s)
1	114.88
2	112.94
3	100.05
4	93.87
5	87.79
6	101.55
7	85.52
8	87.8
9	80.59
10	71.32

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments
Did not need to take breaks in order to avoid fatigue
Need to explain proper orientation of the arm to achieve certain movementse
Difficult to keep track of which switched function is currently active
sometimes knock the ball away and this adds a lot of time to trial
After waeraing the electrodes/wristband for an hour or more skin feels a bit irritated
DoF2 mapping does not save or reload in profile file
Switch does not work if you load profile before connecting to target.
2 elbow shutdowns and 1 wrist shut down

MTT Usability Survey

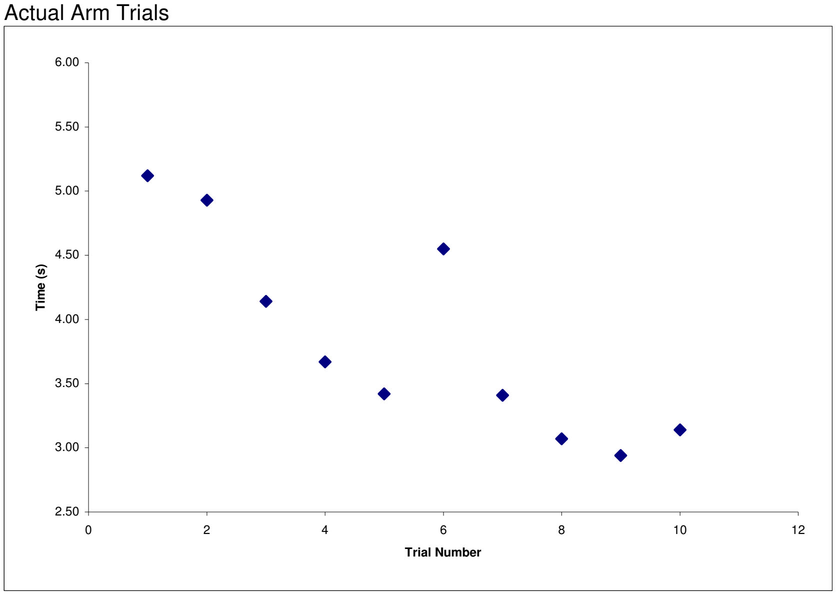
	Comfort	Intuitiveness	Delay	Effectiveness
EMG Control of Robotic Arm	3	3	3	3

Movement of actual arm	5	5	5	5
3D Simulator	2	2	1	2

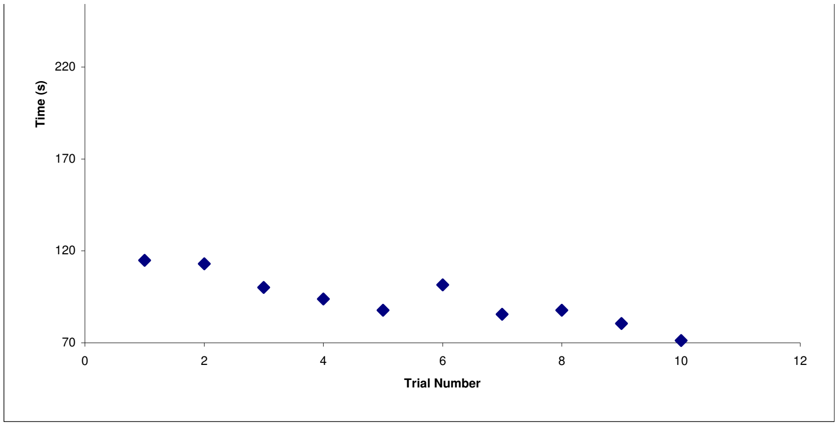
Degree of Freedom	Rating
Hand Open/Close	5
Wrist Flexion/Extension	5
Wrist Rotation	N/A
Elbow Flexion/Extension	4
Shoulder Rotation	3

Comments

Actual Arm Trials



Robotic Arm Trials



220
170
120
70
Time (s)
0
2
4
6
8
10
12
Trial Number

MTT Subject Data Sheet

Subject Name:
Date:
Time:
Averaged Tir andedness: Right

Actual Arm Trials	
Trial #	Time (s)
1	5.22
2	5.07
3	4.57
4	4.14
5	4.42
6	4.01
7	4.61
8	4.34
9	4.49
10	3.87

Robotic Arm Trials	
Trial #	Time (s)
1	331.47
2	198.09
3	180.68
4	263.98
5	174.24
6	169.07
7	190.66
8	135.66
9	
10	

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments
Actual arm trials are awkward because elbow is fixed
Sometimes moves the wrong way before moving the right way (wrong way on shoulder)
Trial 1: has not figured out optimal sequence of commands for pick and place
Explain pincers go forwards in future trials
Comments that ball on bottom left is difficult to reach
Suggestion: cycle both ways on switch
Trial 4: 2 unintentional drops
Right elbow buggin him a bit -> left elbow ok
Trial 6: dropped ball
Switching speed has slowed considerably by 7th trial
Whiffing the ball -> common error
6 elbow shutdowns

MTT Usability Survey

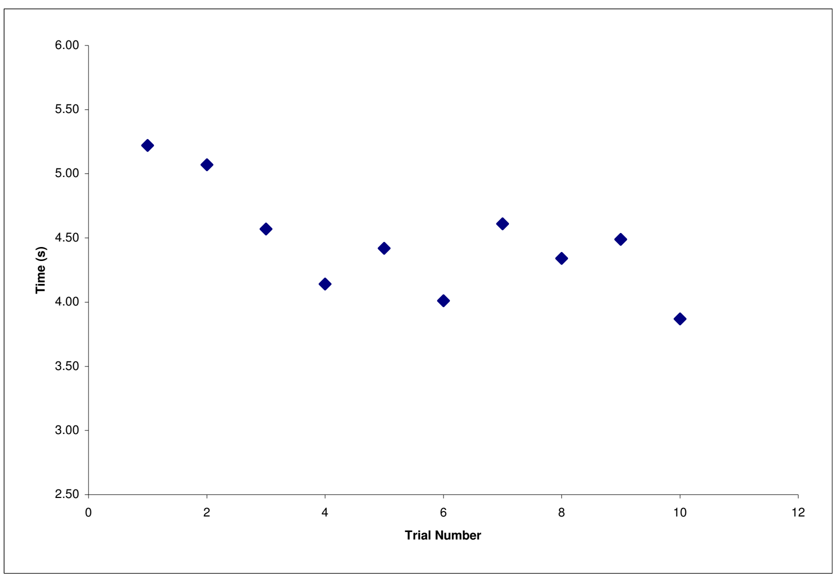
	Comfort	Intuitiveness	Delay	Effectiveness
EMG Control of Robotic Arm	3	4	4	3

Movement of actual arm	5	5	5	5
3D Simulator	3	4	2	2

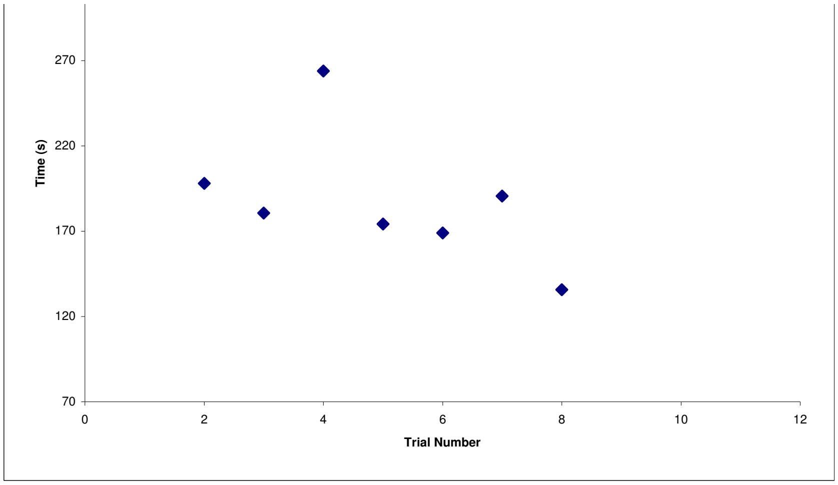
Degree of Freedom	Rating
Hand Open/Close	4
Wrist Flexion/Extension	4
Wrist Rotation	N/A
Elbow Flexion/Extension	4
Shoulder Rotation	2

<u>Comments</u>
Possibly add control to cycle forwards and backwards beteen DoF
Shoulder rotatoin was the most difficult to control and be accurate with.

Actual Arm Trials



Robotic Arm Trials


270
220
170
120
70
Time (s)
0
2
4
6
8
10
12
Trial Number

MTT Subject Data Sheet

Subject Name:
Date:
Time:
Averaged Tir andedness: Right

Actual Arm Trials	
Trial #	Time (s)
1	5.62
2	4.75
3	4.75
4	4.54
5	5.22
6	5.23
7	5.02
8	4.87
9	4.95
10	4.62

Robotic Arm Trials	
Trial #	Time (s)
1	199.83
2	227.82
3	152.57
4	177.6
5	144.08
6	96.92
7	126.97
8	167.08
9	90.94
10	89.13

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments
Took more of a consistent approach to his learning. He did not try to rush
Used a pattern to choose which balls to go for
Gains had to be set really high
Sometimes moves in the wrong direction before moving in the right direction
-> especially on the shoulder rotation
On Trial 2: he fumbled the last ball a couple times
Sometimes he overcycles the switch
By trial 3 making less rotation errors
-> showing greater fine motor control
Common error -> being too far away from the ball and "whiffing"
Trial 5 -> knocked the ball away
Says that switching is the hardest part
Trial 8 -> double whiff
1 elbow shutdown

MTT Usability Survey

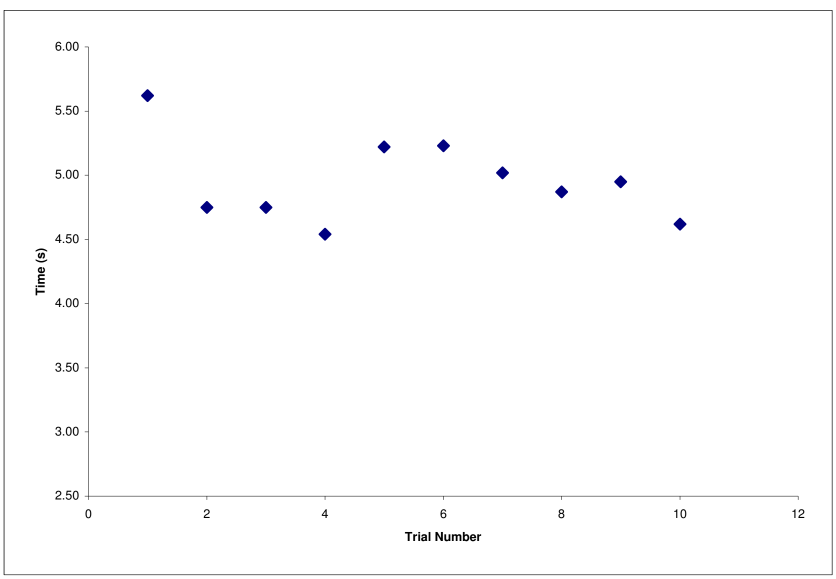
	Comfort	Intuitiveness	Delay	Effectiveness

EMG Control of Robotic Arm	3	4	4	3
Movement of actual arm	5	5	5	5
3D Simulator	3	4	2	2

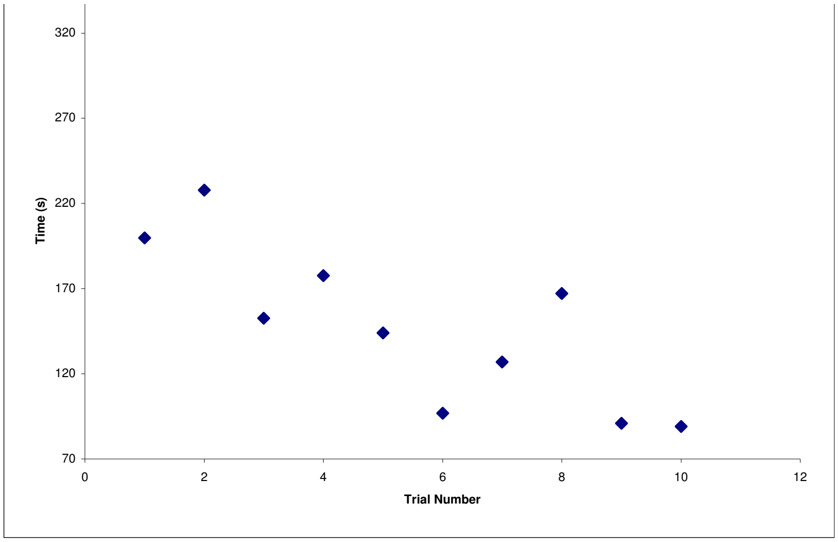
Degree of Freedom	Rating
Hand Open/Close	4
Wrist Flexion/Extension	4
Wrist Rotation	N/A
Elbow Flexion/Extension	4
Shoulder Rotation	2

<u>Comments</u>
Possibly add control to cycle forwards and backwards beteen DoF
Shoulder rotatoin was the most difficult to control and be accurate with.

Actual Arm Trials



Robotic Arm Trials


320
270
220
170
120
70
Time (s)
0
2
4
6
8
10
12
Trial Number

MTT Subject Data Sheet

Subject Name:
Date:
Time:
Averaged Ti andedness: Right (somewhat ambidexterous)

Actual Arm Trials	
Trial #	Time (s)
1	3.94
2	4.00
3	3.27
4	2.79
5	3.07
6	2.87
7	2.86
8	3.06
9	3.68
10	2.87

Robotic Arm Trials	
Trial #	Time (s)
1	139.64
2	179.28
3	233.39
4	142.04
5	149.11
6	109.47
7	109.47
8	123.41
9	129.26
10	110.32

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments
Over cycling and missing the desired functions is a common error
Sometimes has jerky movements w/ the elbow which cause them to SD
->after 2 consecutive shutdowns became very careful w/ the elbow joint
In early trials would sometimes inadvertantly flex ch2 while switching through functions
Trial 3: knocked ball away (SD)
The elbow problem might have been from ch2 gain being too high
-> lowered gain from 200 to 80 -> fixed problem
Suggests that the ball order be fixed in the experiment in order to deconvolute the learning of the task with the learning of how to use the myoelectric control
4 elbow shutdowns

MTT Usability Survey

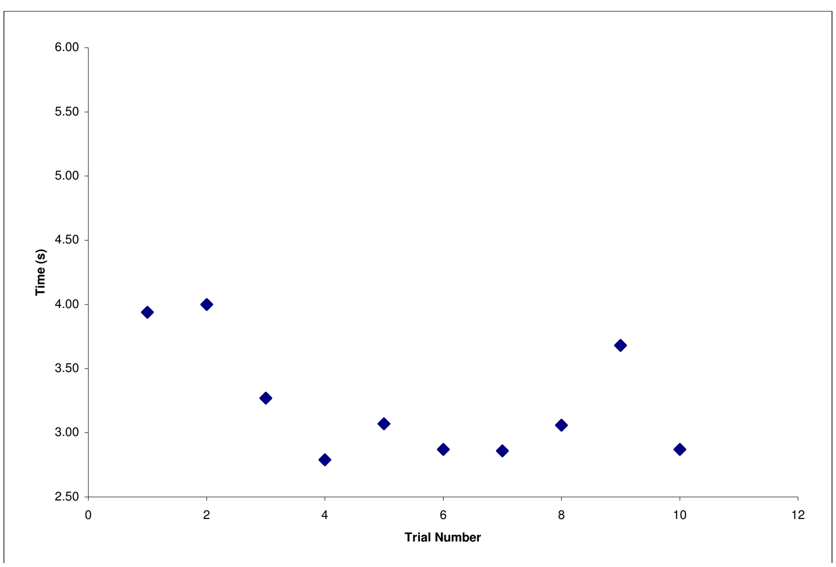
	Comfort	Intuitiveness	Delay	Effectiveness
EMG Control of Robotic Arm	5	5	4	4

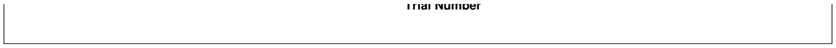
Movement of actual arm	5	5	5	5
3D Simulator	3	5	3	5

Degree of Freedom	Rating
Hand Open/Close	5
Wrist Flexion/Extension	5
Wrist Rotation	N/A
Elbow Flexion/Extension	5
Shoulder Rotation	3

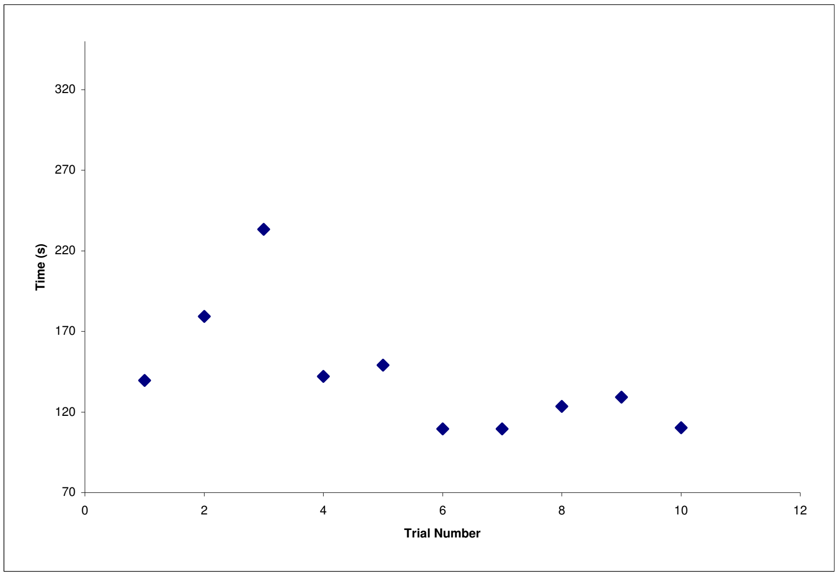
<u>Comments</u>
Calibration with the electrodes took some adjustment between trials
(why effectivness for EMG control of robotic arm is 4).
Shoulder rotation is not as smooth as it oculd have been.
Co-contraction or simultaneous muscle contraction control would be more
intuitive than single muscle contraction.
It would be better to have a set pattern of balls that you had to move
so that the movement is consistent and the problem solving task
is not convoluted with th elearning of how to move the arm. This would show specifically how the
use of the tool improved over the trials rather than how the user figured
out how to do the task more efficientlly.
It would be nice to have a forwarsd/backwards switch for changing between
which servo is controlled.

Actual Arm Trials





Robotic Arm Trials



MTT Subject Data Sheet

Subject Name:
Date:
Time:
Averaged Tir andedness: Right

Actual Arm Trials	
Trial #	Time (s)
1	4.82
2	4.48
3	4.54
4	4.41
5	4.01
6	4.44
7	4.08
8	4.28
9	4.48
10	4.08

Robotic Arm Trials	
Trial #	Time (s)
1	249.48
2	189.76
3	121.92
4	139.78
5	144.04
6	118.11
7	87.16
8	131.01
9	100.13
10	100.12

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments
Trial 1: has some difficulty coordinating elbow and wrist movement
Sometimes whiffs
cycling errors => sometimes over cycles and performs the incorrec function
Sometimes closes instead of opens
Different order in trial 5 increased time
First action is to rotate
 - sometimes misaligns with intended ball before extending elbow down towards it
0 elbow shutdowns

MTT Usability Survey

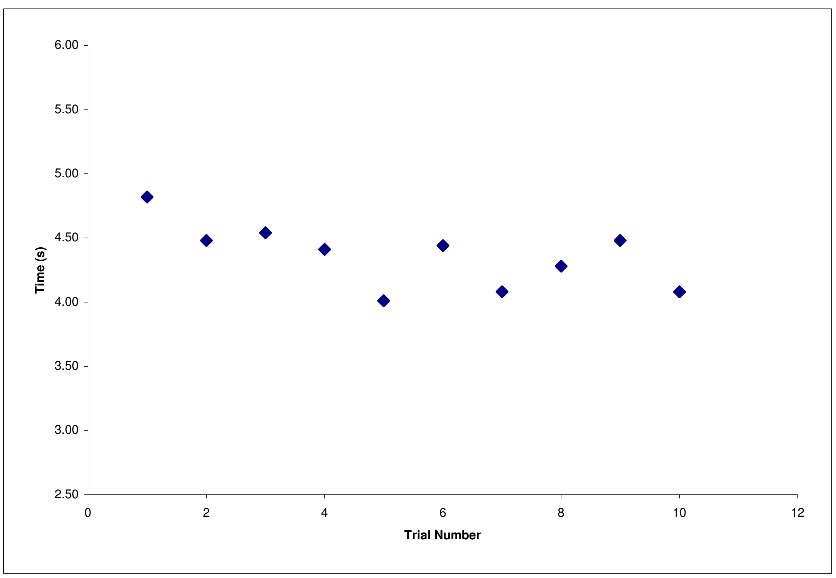
	Comfort	Intuitiveness	Delay	Effectiveness
EMG Control of Robotic Arm	4	4	4	4

Movement of actual arm	5	5	5	5
3D Simulator	4	4	4	4

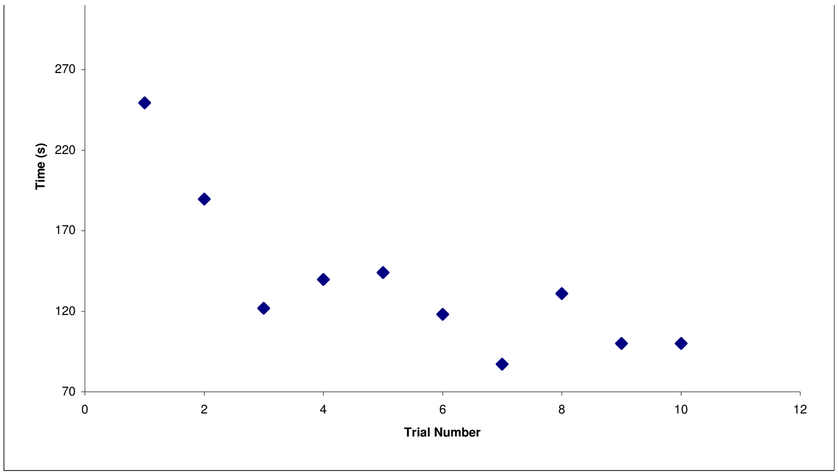
Degree of Freedom	Rating
Hand Open/Close	5
Wrist Flexion/Extension	4
Wrist Rotation	N/A
Elbow Flexion/Extension	4
Shoulder Rotation	3

Comments
Include a 2nd channel on the switch so that the movements can be cycled through.
Most difficult to gauge the required mixture of wrist flexion and
elbow flexion requred to perform the task.

Actual Arm Trials



Robotic Arm Trials


Time (s)
270
220
170
120
70
0
2
4
6
8
10
12
Trial Number

MTT Subject Data Sheet

Subject Name:
Date:
Time:
Averaged TiıHandedness: Right

Actual Arm Trials	
Trial #	Time (s)
1	4.28
2	4.42
3	4.21
4	4.00
5	3.93
6	3.62
7	3.54
8	3.34
9	3.45
10	3.48

Robotic Arm Trials	
Trial #	Time (s)
1	305.06
2	177.34
3	161.83
4	262.45
5	192.91
6	185.86
7	186.39
8	164.96
9	157.42
10	151.37

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments
Trial 1 : started w/ shoulder rotate ->21:21 whiff on third ball
Trial 1: over cycle errors
Trial 1: elbow sd hit table
Starts w/ shoulder rotate usually on lower left ball and works his way up to upper balls
Sometimes goes wrong way with shoulder rotation.
Trial 4: multiple whiffs -> knocked last ball across the box
Tends to grab the ball shallow and then whiff
Lots of whiffs in trials 4-6
It seems like the elbow SD's randomly or when its moving slowly or when its vibrating
Once the elbow SD'd when the only function active was rotation
Could the gears on the elbow joint be wearing out and causing increased SD's?
4 elbow shutdowns

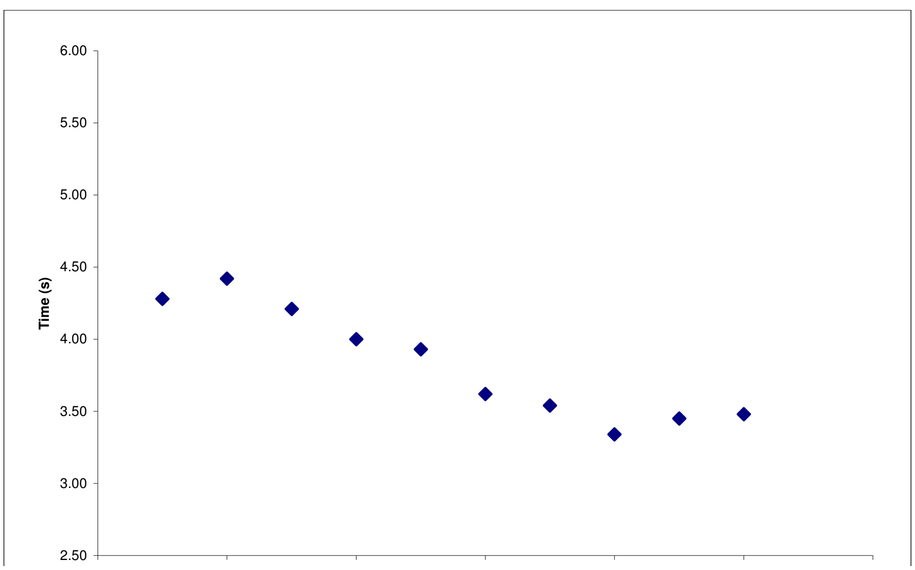
MTT Usability Survey

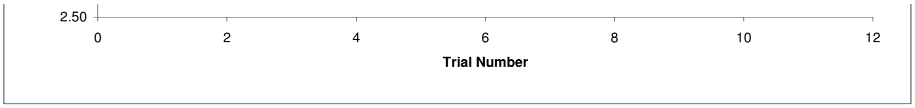
	Comfort	Intuitiveness	Delay	Effectiveness
EMG Control of Robotic Arm	4	4	5	4
Movement of actual arm	5	5	5	5
3D Simulator	4	4	4	3

Degree of Freedom	Rating
Hand Open/Close	4
Wrist Flexion/Extension	5
Wrist Rotation	N/A
Elbow Flexion/Extension	5
Shoulder Rotation	4

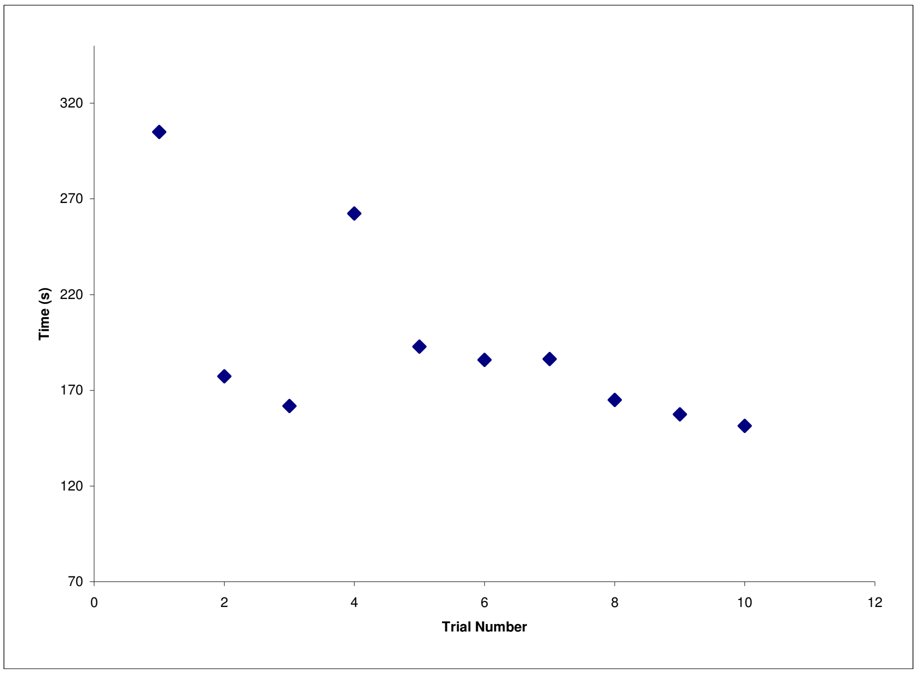
Comments
One suggestoin for the future would be making it possible to cycle forwards and backwards through operations.

Actual Arm Trials





Robotic Arm Trials



MTT Subject Data Sheet

Subject Name:
Date:
Time:
Averaged Tiı andedness: Left

Actual Arm Trials	
Trial #	Time (s)
1	4.76
2	4.35
3	4.41
4	4.15
5	3.67
6	3.82
7	4.28
8	3.35
9	3.67
10	3.60

Robotic Arm Trials	
Trial #	Time (s)
1	292.15
2	217.81
3	156.06
4	258.27
5	202.58
6	169.82
7	165.43
8	130.12
9	153.49
10	102.88

Analysis Questions
1) What type of user errors did the subject commit?
2) Did the subject exhibit fatigue at any point in their trials? Did they require longer breaks?
3) Was the subject able to control the degrees of freedom equally?
4) What starting DOF does the subject choose?

Comments
Always started with elbow flex/ext
Trial 1: cycing errors -> difficulty switching
->whiffs and difficulty coordinating elbow/wrist flex
-> difficulty switching ->over cycles ->after 2nd trial I explained he needed to relax in between switches
Starts w/ elbow flex in trial 3 -> stars w/ ball in top left
Tends to come in deep and pinch towel
Trial 9: has gotten used to the cycling

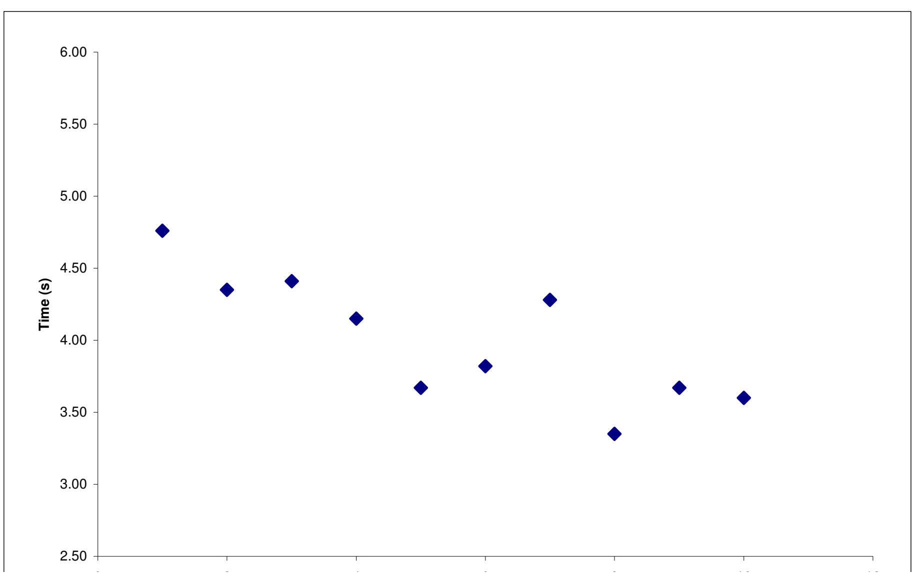
MTT Usability Survey

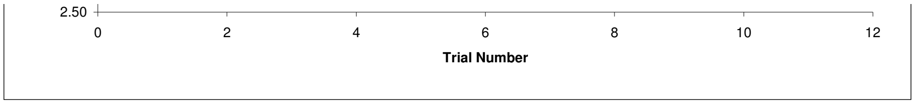
	Comfort	Intuitiveness	Delay	Effectiveness
EMG Control of Robotic Arm	5	4	4	4
Movement of actual arm	5	5	5	5
3D Simulator	5	4	4	4

Degree of Freedom	Rating
Hand Open/Close	5
Wrist Flexion/Extension	5
Wrist Rotation	N/A
Elbow Flexion/Extension	4
Shoulder Rotation	3

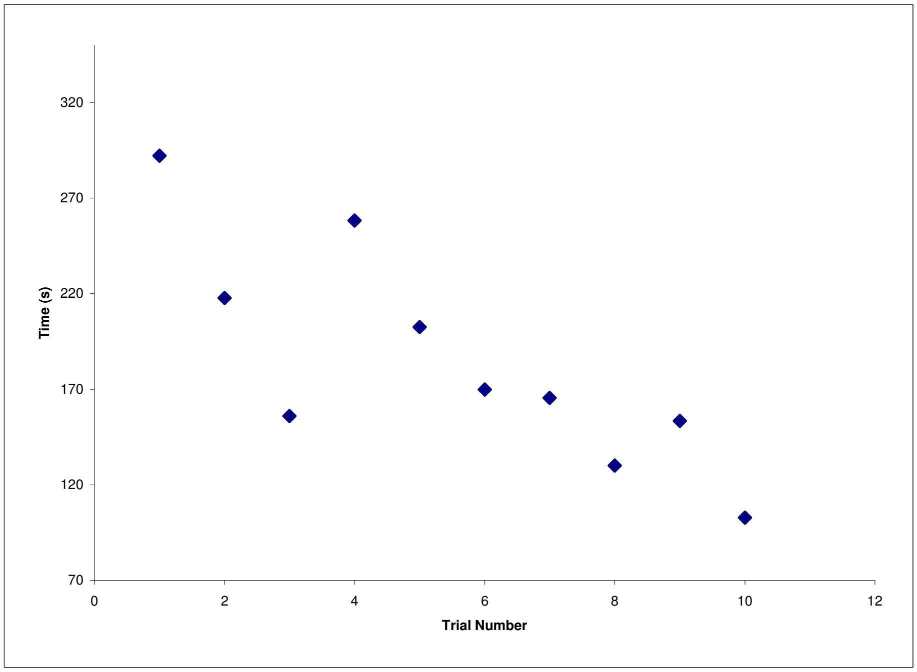
<u>Comments</u>
Awesome system.
Really easy to use.

Actual Arm Trials





Robotic Arm Trials



Appendix B

MTT Clinical Prototype Documentation

The documentation related to the design of the MTT clinical prototype is contained in this appendix.

B.1 Design Documentation

B.1.1 Design Specification Matrix

The design specification matrix was used at the outset of the project to record all of the design requirements generated through meetings with the Glenrose Rehabilitation Hospital. The matrix is broken up into mechanical, electrical, and software subsystems. Each requirement has an associated design authority, importance, and safety factor (if applicable). A separate graphical user interface (GUI) feature list was generated in order to document which features would be available to a researcher, therapist, and patient.

DESIGN SPECIFICATION MATRIX
Robotic Training Arm

Item #	Component / System Description	Design Specification / Requirement	Safety Factor	Design Authority	Design Importance D (1-5)
1.00	**Mechanical Subsystem**				
1.10	Size	half scale with anatomically correct proportions	-	Client	3
1.20	Weight	5 -10 lb	-	Client	3
1.30	Degrees of Freedom	5 DOF to mimic conventional upper-arm prostheses	-	Client	5
1.31	Hand (open/close)	grasp up to 10cm wide objects, similar in style to Utah ETD	-	Client	4
1.32	Wrist (flexion/extension)	anatomically correct	-	Client	4
1.33	Wrist (rotation)	anatomically correct	-	Client	4
1.34	Elbow (flexion/extension)	anatomically correct	-	Client	4
1.35	Elbow (humeral internal/external rotation)	anatomically correct	-	Client	4
1.40	Maximum Payload	100g	1.5	Client	3
1.50	Repeatability	< 3mm	2	Client	4
1.60	Target Cost	$2,000	-	Client	3
1.70	Development Time	6 months or less	-	Client	5
1.00b	Electronics Enclosure	Must contain all electrical components	-	Client	5
2.00	**Electrical Subsystem**				
2.10	Actuators		-		
2.11	Feedback	provide angular position feedback to controller	-	Client	4
2.12	Holding Torque	complies with (1.40)	-	Client	3
2.13	Control Input	torque or angular velocity	-	Client	5
2.14	Low level control	controllable through serial communication and XPC target	-	Client	4
2.15	Resolution	complies with (1.50)		Client	3
2.16	No-load speed	> 60 degrees/0.3 seconds		Client	3
2.20	EMG Electrodes	5 electrodes with built in pre-amps and option for detaching electrodes	-	Client	4
2.30	Data Acquisition Card		-		
2.31	Resolution	16-bit	-	Client	3
2.32	Analog Input Channels	minimum 5 differential channels	-	Client	5
2.33	Drivers	driver blocks available for XPC target	-	Client	4
2.40	Custom Signal Conditioning Board		-		
2.41	Low pass filter	500Hz cutoff		SENIAM guidelines	2
2.42	High pass filter	10Hz cutoff		SENIAM guidelines	2
2.43	Target filter rolloff	40 dB/decade		Client	3
2.44	Preferred filter type	Butterworth		Client	4
2.45	Adjustable Gain	wide range of available gains for each channel that can be set through tuning knobs located on the exterior of the electronics enclosure		Client	5
2.46	Safety	complies with (2.80)			
2.50	Power Supply		-		
	EMG electrodes	DC batteries or Medical Grade Power Supply	-	Client	5
	Other Components	DC batteries or Medical Grade Power Supply	-	Client	3
	Running time	minimum of 3 hours	-	Client	3
2.60	Wiring and Connectors	wiring routed cleanly with snap in polar connectors on the exterior of the electronics enclosure	-	Client	1
2.70	xPC Target Computer	embedded computer compatible with XPC target and can communicate with all other electrical components		Client	
2.80	xPC Host Computer	laptop computer		Client	
2.90	Safety	meet all relevant electrical safety standards including requirements for leakage currents, ground integrity, and high potential application testing for both the EMG-human/electrode interface and the medical grade power supply	-	CAN/CSA-C22.2 No. 60601-1:08 and IEC 60601-1 Edition 3.0 2005-12	5
2.95	Target Cost	$8,000		Client	3
3.00	**Software Subsystem**				
3.10	Conventional EMG Software		-		
3.11	Extracted Feature	Mean Absolute Value	-	Client	5
3.12	Controller Type	Two state controller (1 function per muscle site) + switch	-	Client	5
3.13	Adaptive Digital Notch Filter	60Hz notch		Client	2
3.14	High Pass Filter	10Hz cutoff		SENIAM	2
3.20	Software Environment	MATLAB XPC Target	-	Client	5
3.30	Overall Processing Time	< 0.200 seconds	-	Client	3
3.40	Graphical User Interface	See GUI_Feature_list.xls		Client	5
Notes	Design Importance	5 - Essential or required feature / 1 - Optional requirement			
	Score	10 - Meets requirement in all respects / 1 - Does not satisfy requirement			

Rev	Description	Client Approval	Date
0	Initial release		
1	Updated requirements after Client Meeting		15/7/2009
7	Updated requirements for electrical subsystems		10/8/2009
8	Updated controller type		30/11/2009
thes	updated requirements		30/11/2010

Myoelectric Training Tool Clinical Prototype Software Features/Requirements

General GUI Features	Testing	Prosthetist	Patient
Save/Open settings	x	x	x
Start/Stop xPC target	x	x	x
Start/Stop Robotic Arm	x	x	x
Display MAV of each channel graphically	x	x	x
Display two state controller points for each channel	x	x	x
Adjust 2-state controller points by sliding them or changing value	x	x	x
Assign robotic arm function to channel (also able to disable channel)	x	x	
First past the post control option	x	x	
3D Simulator of robotic arm with dynamic model	x	x	x
Saveable record files that store the EMG signals over a session	x	x	x
Myoelectrically controlled video games	x	x	x
EMG Acquisition Features (access through xPC Target COM API)			
Sampling Rate	x		
Voltage Range (I.e. +- 5v)	x		
Digital gain control for each channel	x	x	x
LP/HP Filter Cut off Frequency	x		
Size of moving average filter	x		
Robotic Arm Features (access through Dynamixel API)			
Servo Range (min/max)	x		
Velocity Range (min/max)	x	x	
Current cutoff	x		
Temperature cutoff	x		
Load cutoff	x		
Current position (feedback)	x	x (sim)	x (sim)
Current velocity (feedback)	x	x (sim)	x (sim)
Electronics Enclosure Features			
Tunable Gain knob for each channel	x	x	x
on/off button	x	x	x
snap in connectors for each electrode channel	x	x	x
on/off button for each channel?	x	x	x
LCD screen showing signal strength	x	x	x
secured box (locked or screwed shut)			x

(sim) - feature provided by simulator

B.1.2 Bill of Materials

A detailed bill of materials for the MTT Research prototype is provided below.

MTT Clinical Prototype - Bill of Materials

Part Name	Option	Source/Part No.	Required Items	Cost/Item	Cost (US)
Electrical Components					
sEMG Electrodes	B+L Engineering BL-AE-N	http://www.bleng.com/electrod.htm	5	$199	$995.00
Custom Signal Conditioning Board	Option A	electronic shop (EE capstone)	1	$2,000.00	$2,000.00
Analog Input DAQ card	Diamond MM-16	http://www.diamondsystems.com/products/diamondmm16at	1	$499	$499.00
Embedded Computer	Advanced Digital Logic - ADL855PC - 745G	http://www.adl-usa.com/products/cpu/datapage.php?pid=ADL855PC&sc=pc104%2B	1	$1,279.00	$1,279.00
Medical Grade Power Supply	MEPOS - SMDA63_S05	http://www.mepos.ca/index.php?cmd=med_100e	1	$58.09	$58.09
Actuators	Dynamixel AX-18F	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	7	$94.90	$664.30
Actuator Controller	USB2 Dynamixel	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	1	$49.90	$49.90
Actuator PSU	AX-12 Power Supply	http://www.crustcrawler.com/motors/AX12/index.php?prod=63	1	$89	$89.00
Actuator Power Cable	AX-12 Power Harness	http://www.crustcrawler.com/motors/AX12/index.php?prod=64	1	$19	$19.00
Mechanical Components					
Robotic Arm Hardware	AX-12 smart Arm	http://www.crustcrawler.com/products/smartarm/index.php?prod=12	1	$399.00	$399.00
Existing Kit Modifications	AX-12 smart Arm Mod	machineshop	1	$100	$100.00
Electronics Enclosure	Polycarbonate Enclosure	mcmaster 69945K173	1	$77.11	$77.11
Enclosure Modification	mounting surface for electronics, mill holes for connectors	machineshop	1	$1,000.00	$1,000.00
Software Components					
EMG Acquisition	Matlab xPC Target				
Motor Control	Matlab xPC Target				
Laptop for GUI	ACER Notebook from BCOM	http://www.b-com.ca/product.php?productid=225236&page=1	1	$405.00	$405.00
				TOTAL COST:	$7,634.40

NOTE: Cost (US) do not include taxes, shipping charges, or miscellaneous wiring and connectors