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Evaluation of a novel myoelectric training device

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EVALUATION OF A NOVEL MYOELECTRIC TRAINING DEVICE
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EVALUATION OF A NOVEL MYOELECTRIC TRAINING DEVICE

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biomedical Engineering at Virginia Commonwealth University.

by

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Abstract

EVALUATION OF A NOVEL MYOELECTRIC TRAINING DEVICE

By Ryan Clingman, B.S. Biomedical Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biomedical Engineering at Virginia Commonwealth University.

Virginia Commonwealth University, 2012

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While research shows that a patient's success in using a myoelectric prosthetic arm is dependent on receiving effective training, current methods of training are not designed to effectively hold attention long enough for optimal training. This study focused on evaluating a novel myoelectric training device, consisting of a toy car controlled by EMG signals from the arm. Subjects' performance with the trainer was evaluated to determine its ability to provide experience with EMG controls. Eight healthy adult subjects were taken through typical initial stages of myoelectric training, then asked to drive the car through a slalom course while the time, number of errors, and reversals required to complete the course were recorded, as well as the degree of difficulty subjects reported. The learning induced by using the trainer was found to be statistically significant ($p < 0.002$), with subjects demonstrating dramatic improvements (> 49%) in performance.

Chapter 1

Introduction

Loss of a limb is a disability that affects thousands in the United States and can drastically decrease the independence and ability to perform activities of daily living in individuals who are affected by it. One in 4,200 children is born with congenital limb deficiencies each year, leaving the child missing part or all of a limb (13). There are approximately 500,000 individuals with upper limb loss due to injury in the United States alone, and an estimated 185,000 people undergo an upper or lower extremity amputation each year (26). All of these conditions can result in individuals with decreased functionality and independence if no corrective measures are taken. The focus of this research is to create a novel training device that can be effectively used with all patients to assist in the development of motor plans conducive to the use of myoelectric prosthetics. This paper will begin with a review of muscle physiology as it pertains to measurement and control of theses replacement devices.

1.1 – Muscle Physiology

Skeletal muscle is composed of groups of many muscle fibers grouped together into larger functional groups typically called muscles. These functional elements have the ability to contract or shorten when exposed to a mechanical, chemical, or electrical stimulus. Their proximal and distal attachments transmit the resulting force to skeletal bones, resulting in volitional movement. Each of these muscle fibers (or cells) are capable of firing and contracting by themselves, as well as firing in synchrony with the surrounding fibers when there is a signal to coordinate them.

Muscle cells are organized into groups called motor units. A single motor unit contains a motor neuron and all the cells it innervates. As a result, all of the muscle cells in a motor unit contract together when the motor neuron fires. The number of muscle cells in a motor unit is generally inversely proportional to the amount of control needed in the muscle. The large muscles of the thigh can have around 1000 or more muscle cells per motor unit, the muscles controlling the hand can have around 100 muscle cells per motor unit, and the muscles controlling eye movement can have around 10 muscle cells per motor unit. (2, 9, 16) Motor units that contain a larger number of muscle cells generate greater force when the motor neuron is activated. When a muscle is activated, its motor units are activated in order of ascending size to allow for control of the resulting muscle force. Having a muscle with smaller motor units allows for greater control of the force that the muscle generates, as the activation of individual motor units causes a smaller gradation of the force generated by the entire muscle than would be possible with larger motor units alone. (16)

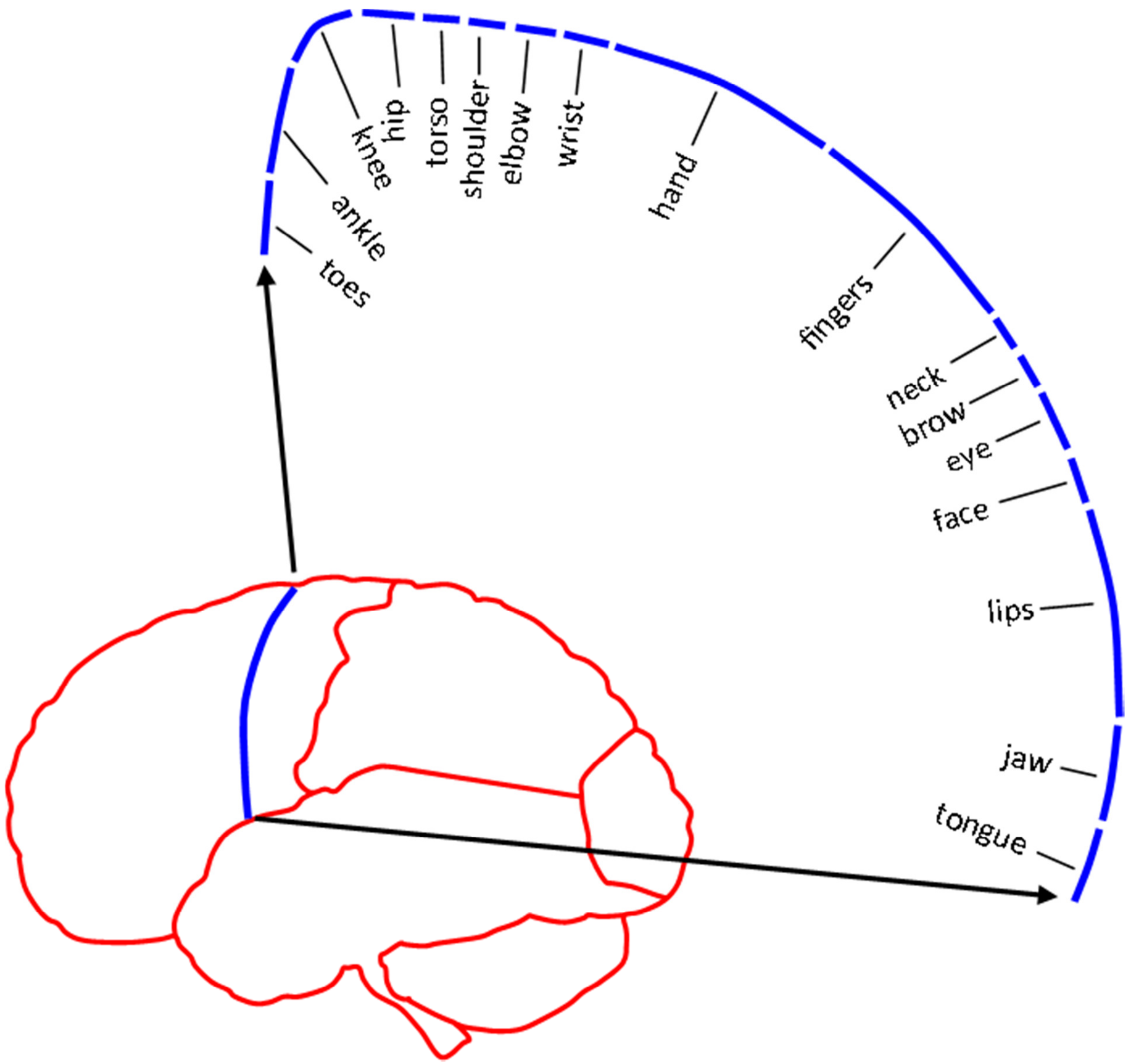

Figure 1: The spatial layout of the motor cortex, comparing the relative sizes of the areas of the brain devoted to controlling the different parts of the extremities.

Muscles of the limbs tend to have greater innervation on the distal segments than in the proximal segments. The area of the brain that controls these muscles is in the frontal lobe and is called the motor cortex. It is organized into geographical regions that map to the different parts of the extremities, as illustrated in Figure 1. As the figure shows, the size of the motor cortex area that is devoted to controlling each part of the body is not an equal distribution. Larger more proximal muscles that deal with greater forces are controlled by areas of the brain that are smaller than muscles that require fine control such as the muscles of the hand and face. The result in the limbs is that the larger proximal muscles are used for the large movements of the limb and body while many small and highly innervated muscles at the distal end of the limb are used to achieve more complex and nuanced interaction and manipulation.

Activation of muscle cells is initiated by electrochemical processes in the cell membrane. Muscle cells are normally held with a small negative electrical potential between the inside and outside of the cell due to the differing concentrations of certain ions on each side of the membrane. Na-K pumps in the membrane maintain high concentration gradients by actively pumping sodium out of the cell and potassium into the cell, creating the small negative resting potential across the membrane and polarizing the cell. When the motor neuron activates a muscle cell, it causes ion gates at the neuromuscular junction to open and allow sodium to flood into the cell. This inrush of sodium increases the membrane voltage, depolarizing that portion of the membrane, and the sudden increase in voltage triggers nearby voltage-gated ion channels to open, letting in more sodium and causing a cascading reaction down the length of the muscle cell. This depolarization also opens up channels that allow potassium to flow out of the cell, countering the voltage change from the sodium and helping to repolarize the membrane shortly after it is depolarized.

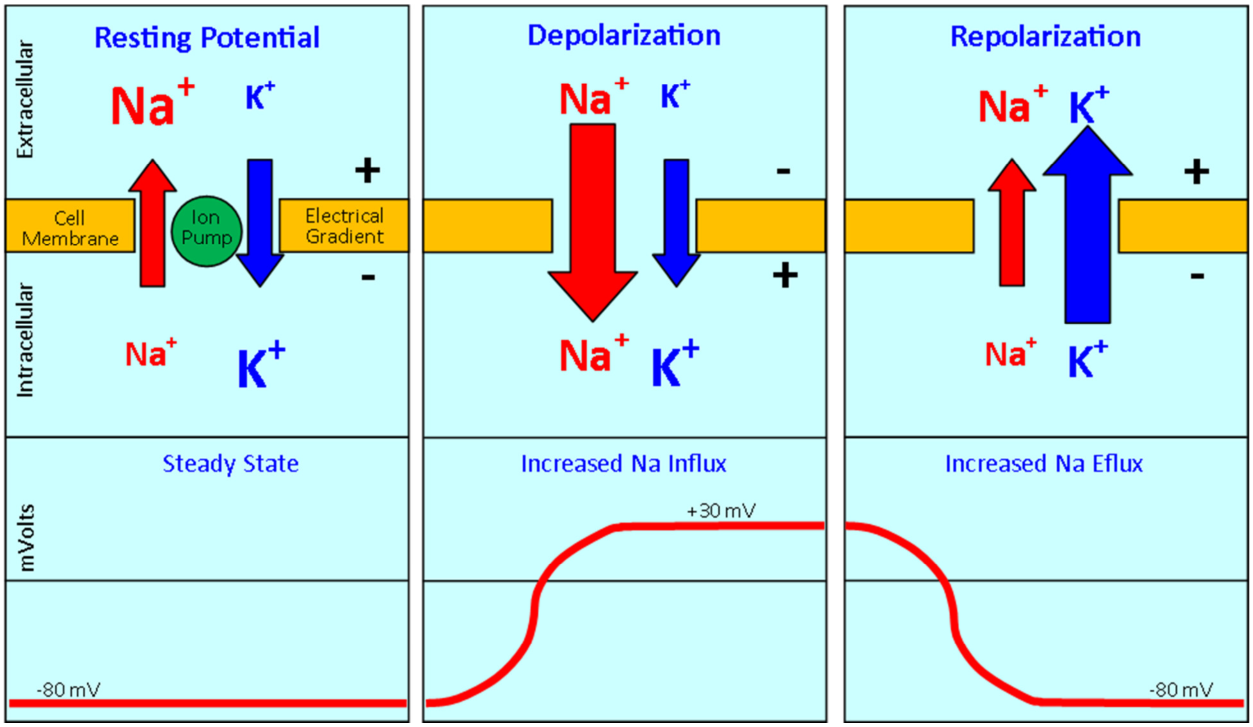

Figure 2: Schematic illustration of depolarization/repolarization cycle within excitable membranes.

The net effect of this action potential is an electrochemical pulse that flows down the length of the muscle where the current goes positive, negative, and back to normal, as can be seen in Figure 2. This signal can be monitored or recorded using electromyography (EMG) and used for medical diagnosis or as a control signal for certain types of devices. EMG signals can be measured by applying electrodes over the muscle to record the strength of the electrical signal that results in contraction. This is dependent on the position, type, and orientation of the electrodes that are being used and its magnitude is loosely proportional to muscle force generation. (9, 16)

Segment movement is typically controlled with pairs of muscles set up in an agonist-antagonist fashion. As an example, for motions like elbow flexion, there are agonist muscles that help facilitate this motion (like the biceps brachii), as well as antagonist muscles that can oppose that motion or facilitate the opposite motion (like the triceps brachii). This antagonistic pairing of muscle groups helps to move the joint in both directions while providing a higher degree of control by modulating the joint viscosity via co-contraction. Muscles that cross multiple joints make the system more complicated to control, since muscle contraction that causes torque production at one joint can also result in torque at an adjacent joint. The result of this is that motion at one joint at can result in complicated muscle activation patterns in an effort to maintain the desired limb position. This interplay often makes it difficult to isolate the contraction of a muscle without influencing the activity of other muscles as well.

In addition to containing muscle fibers to contract and produce movement, muscles also contain sensor cells to produce feedback and give information to the brain on muscle length and joint position. Muscle spindle cells react to changes in the length of a muscle and the velocity of those changes, and combining this information from several muscles can allow the brain to determine the position of the limb in space without needing to use other senses. (2) This system provides feedback and allows the brain to make adjustments during movement to help move the limb into the desired position. Amputation can remove much of this type of feedback as touch receptors in the removed limb are lost and remaining muscles to control the amputated segments are typically set in a fixed position and length.

1.2 – Electromyography

The history of electromyography can be traced all the way back to 1666, when Francesco Redi discovered that a muscle was the source of electrical energy from an electric eel. It was not until 1792 that Luigi Galvani more firmly established the link between muscles and electricity, when he demonstrated that static electricity could be used to evoke muscle contractions. In 1849, Emil du Bois-Reymond showed that electrical signals were generated during voluntary muscle contractions in humans, marking first documented case of electromyography being used, although the term was not coined until 1890 by Étienne-Jules Marey. The technology behind EMG improved steadily over the decades, until surface EMG entered clinical usage in 1966 with Hardyk. From that point on, technology and techniques for electrodes, amplifiers, and measurement have only improved. (4, 9)

After a signal is transmitted from a motor neuron to the muscle fibers of the motor unit, it causes a motor unit action potential (MUAP) that races toward both ends of the muscle fibers from where the motor neuron comes in contact. The electrical activity from multiple motor units are additive, with the signal detected at the electrodes increasing in magnitude as more motor units are recruited, as shown in Figure 3, and can be detected from electrodes inserted in the muscle or placed on the surface of the limb.

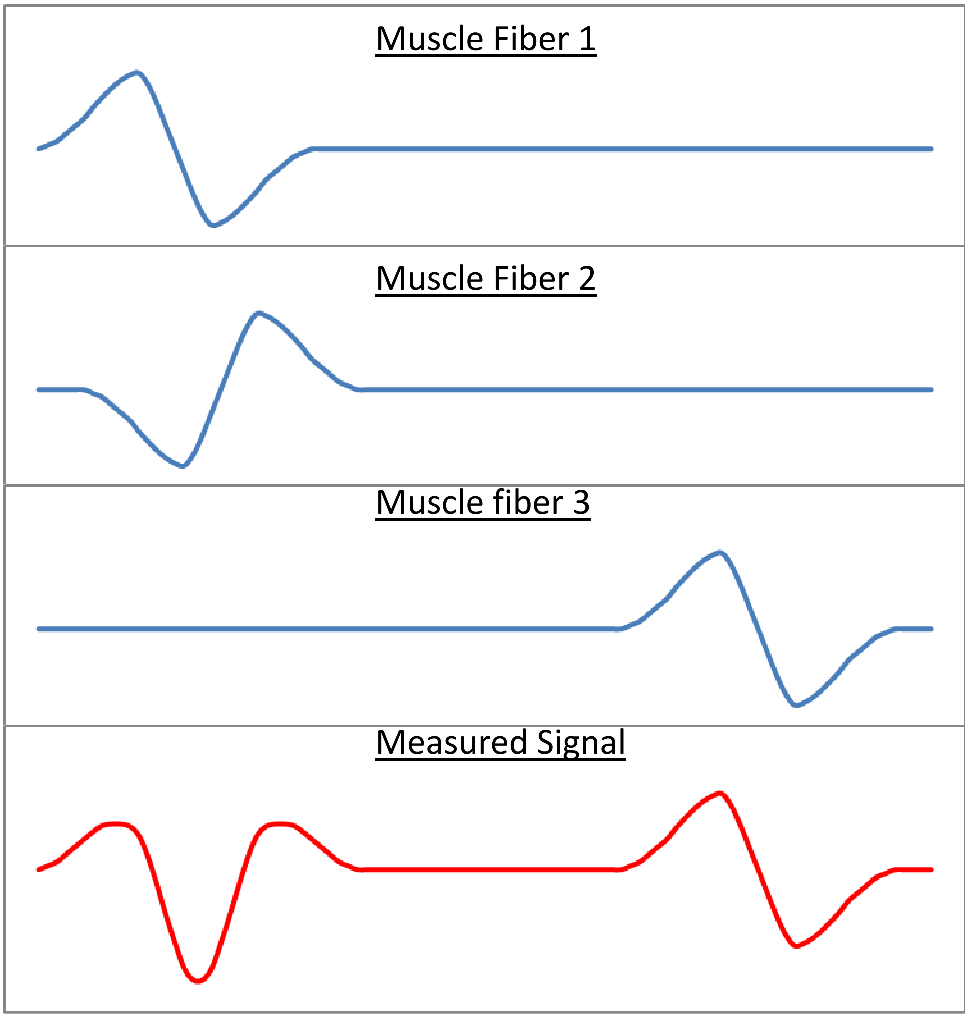

Figure 3: Illustration of the temporal summation of EMG signals observed from the electrodes from multiple muscle fibers, showing both constructive and destructive interference.

The rapid depolarization-repolarization charges traveling down the muscle fibers gives EMG its bipolar nature, with the electrode picking up first a positive and then a negative signal as the MUAP races by, as shown in Figure 4, making the signal require rectification to make all of the values positive before it can undergo a more thorough analysis. Most of the signal power from skeletal muscle surface EMG (sEMG) falls between 20 and 200 Hz, so frequencies above and below this range can be discarded to improve signal quality. It is also important to have a sampling frequency at least twice that of the maximum EMG frequency or higher in order to avoid aliasing and maintain signal quality. (11)

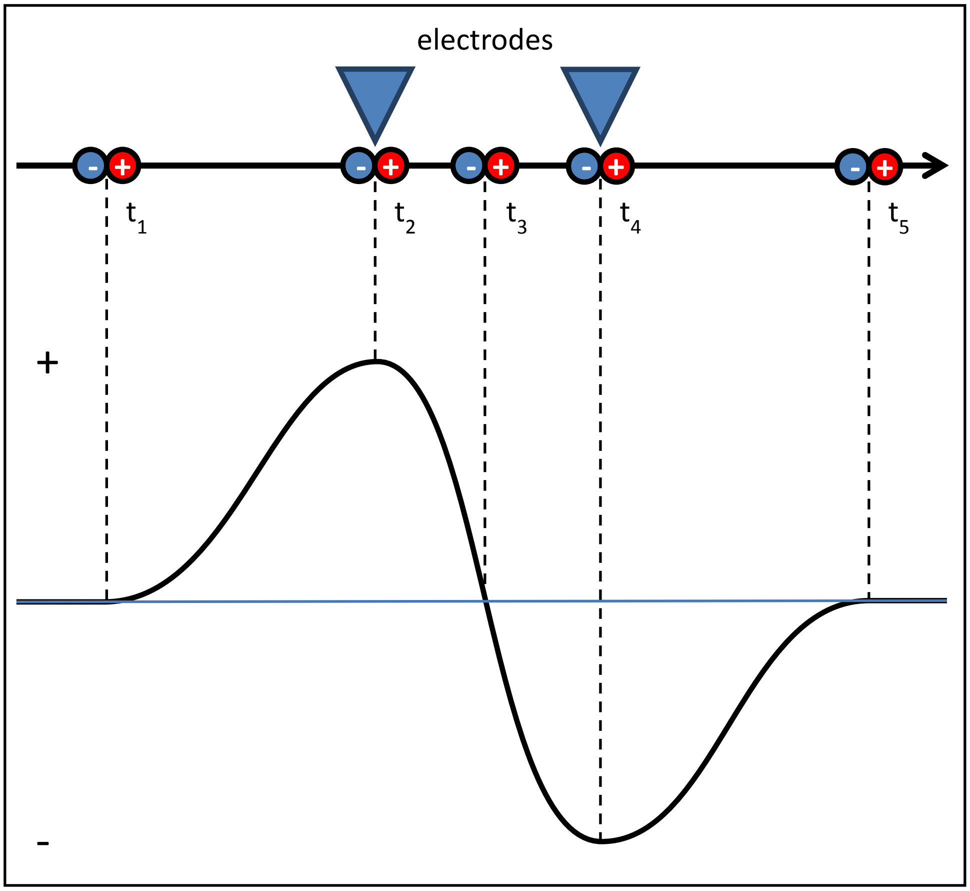

Figure 4: Model of electrical dipole movement along a muscle fiber and the resulting EMG signal.

The signals collected by EMG are extremely dependent on both the type and location of the electrodes used. Intramuscular electrodes come in the form of needles or very fine wires that are inserted into the muscle tissue to pick up the electrochemical signals directly from within the muscle. This type of electrode provides the best signal quality and the greatest specificity, being able to collect EMG data from specific muscle fibers. The downside to these electrodes is that they are somewhat invasive, require a trained physician to place it safely and effectively, and may not give an accurate representation of the activity of the muscle as a whole. Surface electrodes typically consist of an electrode in contact with the skin over a muscle through a conductive gel, secured in place by some form of adhesive. These electrodes are much simpler to place than intramuscular electrodes, not requiring any advanced training to use them safely, and they can provide a better measure of the activity of the entire muscle. The drawbacks of surface electrodes are that they are limited to detecting surface muscles, they provide lower amplitude in the resulting signal, and the impedance of the connection of the electrode to the skin can cause interference, introduce higher levels of noise into the signal, and act to filter out high frequency portions of the signal. (11, 16) With their differing capabilities, needle electrodes are used primarily for diagnosing pathology and investigating deep muscles, while surface electrodes have seen increasing clinical use for recording from superficial muscles. (9)

While relationship between muscle activity and EMG amplitude is well established, there is no such simple relationship that exists between EMG amplitude and the resulting muscle force. A general correlation does exist that increased muscle force generation is accompanied by increased EMG activity, but the relationship is not strong enough to predict the muscle force from the resulting EMG data due to several confounding factors. Surface EMG electrodes can pick up the electrical signals from many motor units, but the motor units that are closer to and more aligned with the electrodes will register higher amplitudes, biasing the signal toward the activity of the closer motor units and giving electrode placement a large effect on the resulting signal. The movement of the muscle itself can also affect the amplitude of the signal, as the length of the muscle affects the force it can generate and the contraction of the muscle could move the muscle belly out from under the electrodes, decreasing the signal strength. It is for these reasons that isometric bracing and maximum voluntary contraction (MVC) normalization are sometimes used in studies to provide a more consistent EMG signal that can be compared between subjects. Isometrically bracing the limb ensures that the muscle stays in the same position and length while the study is being conducted, allowing a more consistent signal to be collected. Because the signal strength can vary so greatly between subjects or with electrode placement, normalizing the resulting signal as a percentage of the MVC signal, the signal amplitude from the strongest voluntary contraction that the individual can make, allows the data that is collected to be compared between different trials or between different patients. (11)

1.3 – Prosthetics

The goal of prosthetic limbs has always been to increase the functionality of the limb closer to normal levels of activity (5), and the gradual development of prosthetics technology has brought these devices progressively closer to this goal. The history of prosthetic limbs dates back to the ancient Egyptians using aesthetic prosthetics about 4000 years ago and Greek historians telling the story of a Persian man 2000 years ago who escaped imprisonment by amputating his own leg and replacing it with a wooden one. In the middle ages, it became common for nobility who were wounded in battle to have prosthetic arms made to hold their shield and allow them to fight again. For centuries, prosthetics were only available to the rich, and the materials used to make them remained crude, with wood, heavy metals, and leather being the predominate construction materials. It was not until the 16th century that Ambroise Paré began to revolutionize the field, first by advancing the medical practices surrounding amputation, then later by inventing more advanced mechanical prosthetics to replace the hand and leg. Other improvements in amputation and prosthetics were made over time but it was the techniques developed with the funding of the US government after the Second World War that brought the next big advancement in prosthetics and began to make them resemble what is available today. (24)

The most common type of upper extremity prosthesis used has been prosthetic arms with a mechanical hook on the end of the prosthesis operated by steel cables leading to a harness across the user's shoulders, and this type of device is still quite common today. The first prosthesis not powered by the user was a pneumatic hand patented in Germany in 1915, which was soon followed by a design for a rudimentary electric powered hand in 1919, both presumably controlled by an external switch. It was not until 1943 that Reinhold Reiter created the first myoelectrically operated prosthetic hand, although the system was large, heavy and not portable, making it of limited use. A turning point in the field came in 1945, as a conference involving the US military, engineers, surgeons, and prosthetists helped to bring about the creation of the national Committee on Prosthetics Research and Development, which created a large push for research in this area. Though this surge in research brought about a large number of small innovations and new prosthetics, it was not until 1965 that the first prosthetic hand to make use of proportional control was created by Bottomley, allowing the speed of the hand to be controlled by the user. Powered prosthetics left the laboratory setting for the first time in 1967and became commercially available in the United States, with the number of patients using them steadily increasing over the next decade. While these early prostheses were powered from a bulky battery pack that had to be worn on the belt, 1968 saw the first usage of a below elbow prosthesis that was completely self-contained and self-suspended. One of the final technological developments bringing myoelectric prosthetics to their current level of capability came in 1978 with the creation of the first prosthetic to allow control of multiple joints through the use of EMG pattern recognition. Since this time, there has been a steady rise in the usage of myoelectric prosthetics as improvements in the technology allowed the prosthetics to become more sophisticated, lighter, and easier to use. (3)

Several different types of myoelectric prosthetic control schemes have been developed over the years. The simplest type of control schemes are digital control schemes, where each action of the prosthesis is either on or off at any time, but control of the speed or strength of the movement is not possible. With this type of control scheme, the patient can activate a specific action when the EMG signal from the associated muscle rises above a certain threshold and deactivate it by allowing the EMG signal to fall below the threshold again. Proportional control is a more advanced form of control scheme that allows the user to control the speed or strength of the prosthesis as well. As with digital control, the action of the prosthesis starts and stops when the EMG signal rises above or falls below the threshold, but as the signal rises above the threshold the speed or strength of the prosthesis increases as well. As more complex prosthetic limbs that contain multiple active joints have been developed, new control schemes have been needed to provide the users with adequate control. Pattern based control schemes look for a temporal pattern in the EMG signals rather that instantaneous amplitude alone, and the multiple patterns that can be produced by a muscle allow a larger number of functions to be controlled by just a couple of muscles. Which control scheme a patient needs to use is a function of both their ability to control the EMG signals of their muscles as well as the prosthetics that are available to them.

Modern myoelectric prosthetics have been shown to have some advantages over conventional cable-powered hooks for their users, and a majority of the users studied expressed a preference for the myoelectric hands. (21, 26) Myoelectric arms were shown to be able to produce about seven times more grasping force than conventional hook grippers, and their users felt that the myoelectric hands provided them with a more secure grip on objects. Users of myoelectric arms also reported that they wore their arms longer and used them more frequently each day than the users of body-powered prostheses. (25) The users also tend to have a positive response and experiences with the improved cosmetics of the myoelectric hands compared to the metal hook of conventional prosthetics. (21, 25) Myoelectric prosthetic arms are not better in every way though; the inclusion of the batteries, processors, and motors in the prosthetics make them heavier than other designs, causing some users to initially complain about the comfort of the device. (25) Additionally, testing showed that body-powered prosthetics allowed users to complete some activities twice as fast as myoelectric hands, though the myoelectric hands allowed them to maintain a more natural and comfortable posture while they were working. (21) Overall, most users who have tried both types of prosthetic devices have found that the myoelectric prosthetics' strengths outweigh their weaknesses and are preferable to body-powered devices, and these myoelectric prosthetics are now well accepted by upper limb amputees. (6)

The ability to produce the appropriate myoelectric signals to control the devices is necessary to use them, making appropriate training of the user before they receive the device important in its success. (1) Training for myoelectric prosthetics is typically broken down into three phases: signal training, control training, and functional training. (A) Signal training involves displaying the live signals from the patient's measurement sites, allowing them to learn how to activate and isolate individual muscles, as can be seen in Figure 5.

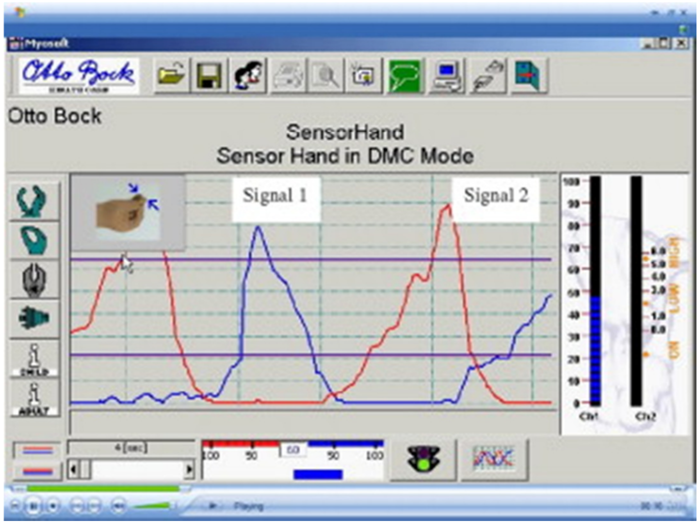

Figure 5: Signal training display for a commercial myoelectric training system. Image courtesy of Otto Block ©. (20)

This stage is important because it helps the patient to begin to associate the muscle contractions with the desired movements as well as learning to avoid co-contractions, which would cause undesired movements of the prosthesis. (B) Control training involves learning to use the muscles appropriately through the use of a more active system of feedback such as computer simulations, games, or toys controlled by their EMG outputs, as seen in Figure 6.

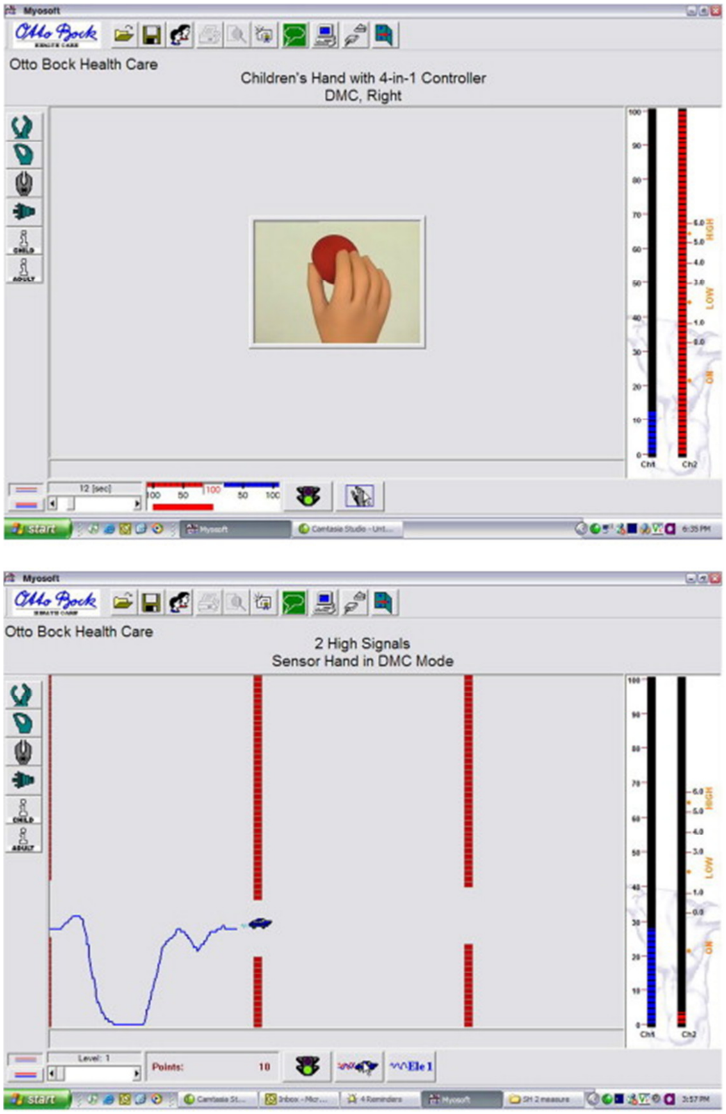

Figure 6: Control training displays for a commercial myoelectric training system, involving opening and closing a hand and a simple game involving moving a car up and down. Image courtesy of Otto Block ©. (20)

This stage allows for further training of the muscles to be used and isolating muscles to accomplish more concrete tasks. (C) Functional training involves being trained in using the actual prosthesis for activities of daily living, starting with basic motor skills and working up to more advanced tasks. All of this training together helps the patient to become more accustomed to wearing the prosthesis and more skilled in using it on a regular basis. (5, 6)

An important factor in a patient's acceptance of a prosthetic limb is the training that the patient receives on how to use it. (6) A lack of proper training has been cited as one of the primary reasons that patients choose not to wear their prostheses, and proper training has been shown to double the acceptance rate of myoelectric prosthetics. (6) To this end, training systems using features such as interactive video games to help maintain the patient's motivation have been used. (22) The device described in this study is of this design, but the experiment is designed to better understand the development of control strategies resulting from these training systems.

1.4 – Focus of study

This study is focused on the development and evaluation of a training device for myoelectric prosthetics. The training device is a prototyping microprocessor and associated circuits designed to accept raw EMG signals from a commercial EMG system and use these signals as control signals for driving a remote control car. Figure 7 depicts the completed EMG training system built for this study. This setup is intended to provide a more engaging and free-form type of feedback for training with EMG controls prior to being fitted with a final prosthetic device. The system is programmed to use a dual-site three state control scheme similar to many commercial prosthetics, but this control scheme could be easily modified to conform to other control schemes with simple modifications to the programming.

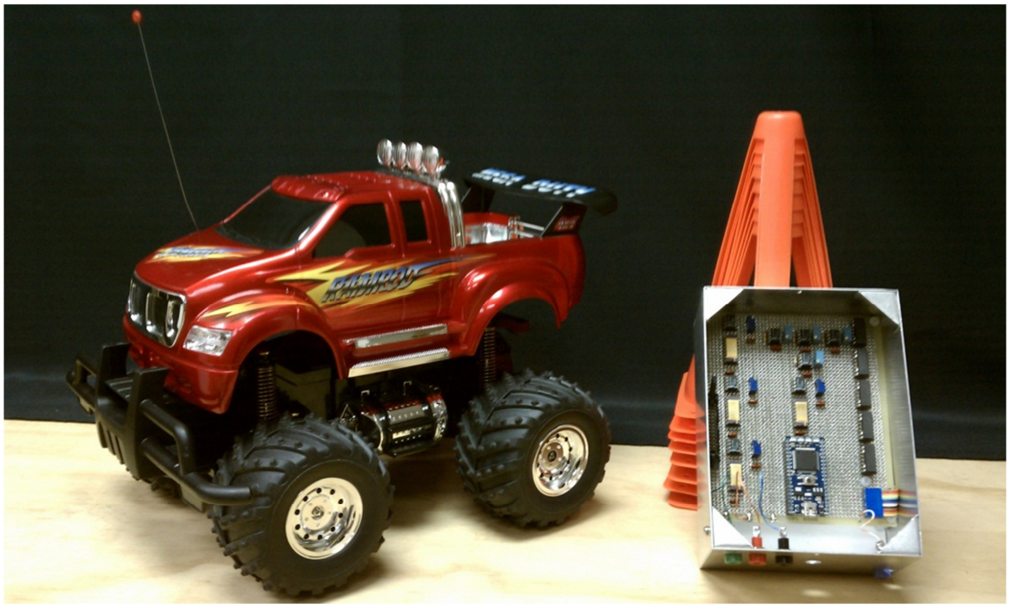
Figure 7: The EMG training system designed for this study.

While there have been a number of academic studies involving the creation of myoelectric training systems designed to provide a more entertaining form of training to help hold the attention of younger patients, there is as yet no commercially available training system that truly provides this type of engagement in its training. (5) Coupling an EMG training system with a remote controlled car would allow the patient to gain experience with isolating the contractions of single muscles necessary for operating a myoelectric prosthetic limb while providing a more enjoyable experience to the patient, making it easier to hold their attention for a longer duration of time. In addition, as Figure 6 shows, the training activities that have been developed have been fairly rigid in design, taking all patients through a prescribed set of actions. A myoelectric training system involving a remote controlled car could provide the patient with effective training while still being more flexible or free form than currently existing devices, allowing the patient to drive it however they choose to and making it easier to hold the patient's attention for longer durations.

Cost is also an advantage for this type of training system. Since the EMG interface device was built using inexpensive off the shelf components, it could be produced for a minimal cost and be reused with many patients over time. The same type of functionality could also be integrated into existing products with relatively little difficulty.

1.5 – Specific aims

Proper training prior to receiving a myoelectric prosthetic is a crucial factor in the patient accepting the prosthesis and being able to make good use of it in their daily lives. A lack of sufficient training has been identified as one of the top reasons that patients fail to accept and properly use their prosthesis. Because of this, it is important to provide adequate training for the patients to enable them to accept and make good use of the prosthesis in their daily lives. (6) While a number of systems have been developed to provide signal training and control training before an actual prosthetic is used, they have all been fairly rigid in their training methods and could encounter some difficulty in maintaining the attention and motivation of the patients in order to provide them with the appropriate training. Therefore, the primary aim of this thesis project was to design a novel training device to assist in the control training phase of myoelectric prosthetic training. The secondary aim of this thesis project is to evaluate the performance of this training device compared to other methods of myoelectric training. This will provide validation for the efficacy of the device and demonstrate that it is a valid proof of concept for a new method of training the use of myoelectric prosthetic devices.

Because limb loss can happen at various levels, it is important that the device functions adequately using a variety of muscle groups commonly used in myoelectric prosthetic devices for different levels of amputation. Because the device will be tested with both proximal and distal muscle groups, this provides the opportunity to investigate the difference in myoelectric control between proximal and distal muscle groups. Therefore, an additional aim of this thesis study will be to investigate the difference in the user's ability to control a myoelectric device between distal and proximal muscle groups in a normal population. The order of the muscle group training will be randomized between subjects in order to remove this as a source of error in the results.

Chapter 2

Materials and Methods

The experiment utilized a randomized cross over design. Eight health adult subjects (4 male and 4 female) participated in five sessions lasting less than one hour each, with consecutive sessions for a subject being spaced approximately one week apart as scheduling allowed. Subjects had an average age of 27.1 years (SD = 4.83) and did not have any known orthopedic or neurological issues. Subjects were asked to navigate a remote controlled car through a slalom course as quickly and cleanly as possible. Data on the time and accuracy of driving was collected.

2.1 – Experimental Design

The myoelectric control system utilized one of the most common digital control schemes, known as dual-site three state control, where EMG signals from one muscle controls one action while EMG signals from another muscle controls the opposite action and rest is considered a third state. (17) Electrodes were placed over opposing muscles for movements of the wrists, elbow, and shoulder and subjects were progressed through calibration, signal training, control training, and functional training steps (additional details are provided in the following sections). Subjects were randomly assigned to one of two groups. Half of subjects were assigned to progress through the muscle groups in a distal-to-proximal order, while the other half were assigned to progress through the muscle groups in a proximal-to-distal order. For each muscle group, subjects were allowed to train by maneuvering the vehicle through 360° of rotation in a small square 2.5 times the length of the car. Training was completed when subjects successfully completed the task and typically took no more than one minute. This allowed subjects to become accustomed to the necessary muscle movements for the control scheme. Subjects were then allowed to complete three timed runs with the car on the course before moving on to the next muscle group.

2.2 – Experimental Details

Control of the car required both upper extremities. The subject's dominant arm was used to control the steering direction while the non-dominant arm was used to control forward and reverse propulsion. Subjects self-identified their dominant arm as the arm they wrote with prior to the beginning of the study. Steering control was varied by using proximal, medial, and distal muscle groups in separate sets of trials. Forward and reverse propulsion was always controlled by the distal muscle group of the non-dominant arm. Subjects were asked to wear clothing that would allow easy access for placing adhesive electromyography electrodes on the arms and shoulders. In order to control the steering of the car, pairs of 34 mm clinical surface electrodes were placed directly next to each other, providing similar spacing of the electrodes to those used in myoelectric prosthetics. The electrodes were placed over three opposing pairs of muscles in the dominant arms of subjects according to standard clinical placement guidelines (11, 15). Steering control electrodes were placed in a distal group over the flexor carpi radialis muscle and extensor carpi radialis muscle of the wrist, a medial group over the biceps brachii muscle and lateral head of the triceps brachii muscle of the elbow, and a proximal group over the pectoralis major muscle and posterior deltoid muscle of the shoulder. These electrode sites were chosen because they are routinely used for the control of myoelectric prosthetic arms due to their relative ease of volitional control of the EMG signal. (8, 10, 17, 18) A rough illustration of the placement locations and associated functions of the electrodes can be seen in Figure 8. Due to the isometric bracing of the arm for the medial and proximal muscle groups causing discomfort with the electrodes for the distal muscle groups, the distal electrodes were removed after the distal trials for the distal-to proximal subjects and the placement of the distal electrodes was delayed until needed for the proximal-to-distal subjects. To control the propulsion of the car, additional electrodes were placed over the same wrist flexors and extensors in the contralateral arm of subjects.

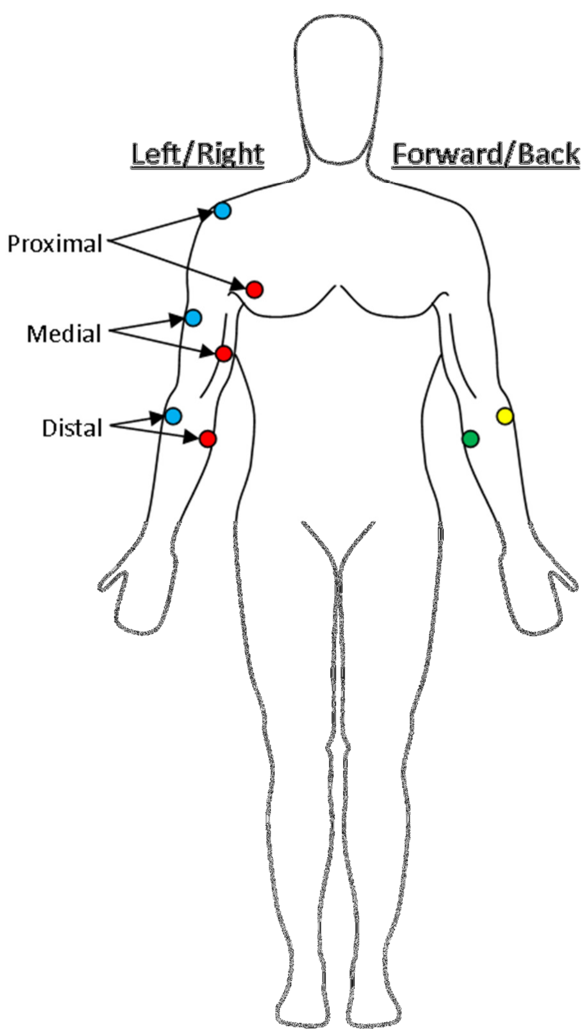

Figure 8: Electrode placement locations used in the study and the corresponding actions they controlled.

Subjects were isometrically braced for each muscle group while it was in use. A wrist brace was employed to hold the wrist in neutral position for the wrist flexors and extensors. Bracing of the elbow muscles was achieved by placing the shoulder in neutral position and strapping the arm to the top of a horizontal bar in the anterior direction in 90° of elbow flexion, preventing elbow flexion or extension at the humeroulnar joint. Bracing of the shoulder muscles was achieved by placing the shoulder in neutral position and strapping the arm to the side of a horizontal bar in the anterior direction in 90° of elbow flexion, preventing internal or external rotation at the glenohumoral joint. Each muscle group underwent a calibration step when connecting the electrodes to the EMG instrument by asking the subject to produce a maximum voluntary contraction (MVC) for normalization of the EMG signals. The signals were converted to a percentage of this measured MVC rather than using their absolute amplitude. This allowed for comparison between subjects, muscle groups, and electrode placements. (11)

Once the electrodes and braces were in place and the system had been calibrated, subjects were given an EMG signal training exercise. Subjects were shown two plots similar to the one seen in Figure 9, providing a live display of the amplitude of the EMG signals from the current muscle groups.

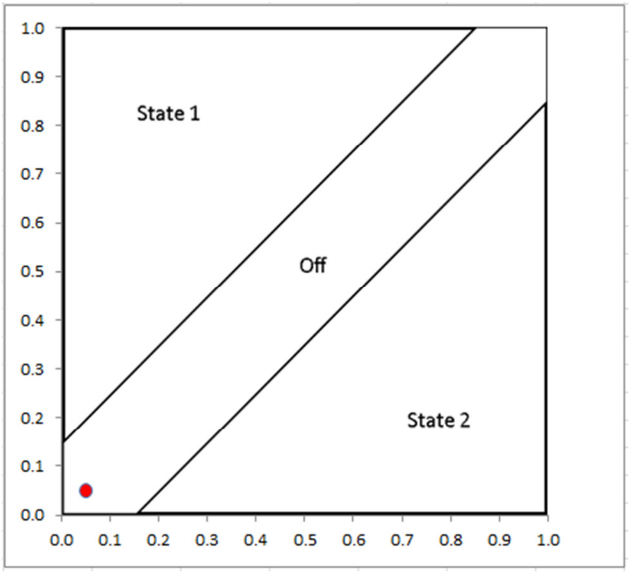

Figure 9: Relative signal display used in the signal training portion of the study. Each axis represents the EMG amplitude of one muscle normalized to MVC.

The X-axis of the plot is the EMG amplitude from the extensor or external rotator muscles in use as a percentage of MVC, and the Y-axis is the amplitude of the flexor or internal rotator muscles in use as a percentage of MVC, with the red dot moving in these two dimensions as subjects contracted their muscles. The result is that contraction of the flexor causes the red dot to move upward, contraction of the extensor causes the dot to move to the right, and co-contraction causes the dot to move diagonally. The diagonal lines on the display represent the cut-off thresholds for the group of muscles, or the minimum level of muscle activity needed to maintain the particular action. A higher cut-on threshold was used to initiate the actions, making it easier for subjects to use the neutral non-contraction actions without making it more difficult to maintain the active contraction actions, but this threshold was not shown on the display in order to avoid confusion. The EMG signal display was first used to help make adjustments to the individual EMG thresholds to account for baseline muscle activity and electrode placement, then to provide subjects with signal training by observing the movement of the red dot on the screen in response to the movement of their muscles. The signal training was complete when subjects were able to contract their muscles to hold the red dot in each area for 5 seconds, validating their control of the EMG signals.

After the calibration and signal training phase was completed, subjects moved on to a control training phase. The car was placed in a 3' by 3' box in front of the subject as seen in Figure 10, and they were asked to drive the car to take it through a full 360° of rotation.

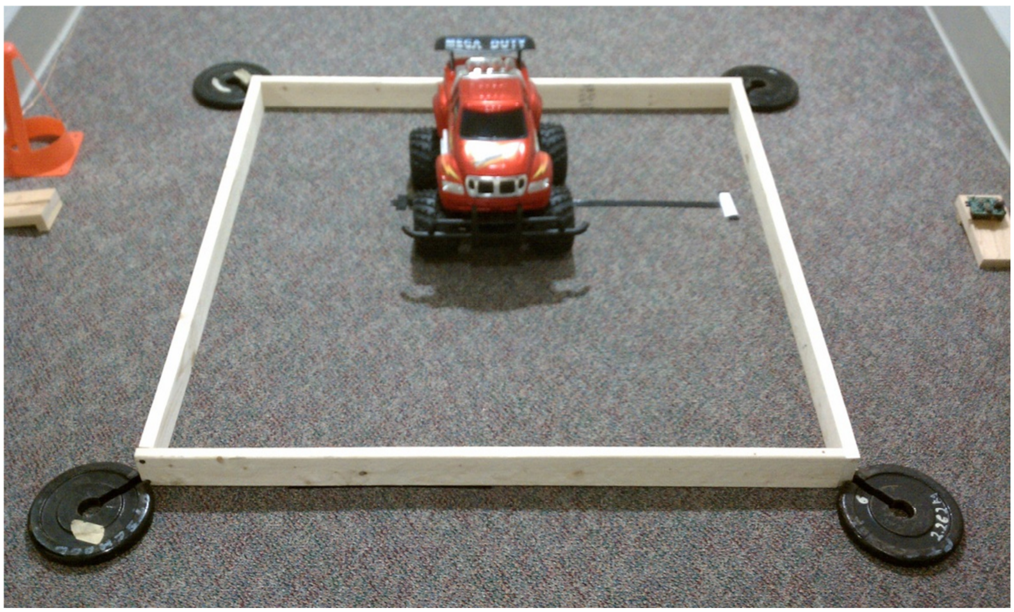

Figure 10: Control training area used in the experiments.

This area was large enough to allow the car to turn, but small enough that the car could only make as much as a 45° rotation at a time, forcing subjects to practice making multiple turns both forward and backward in order to take the car through a full rotation. This training technique allowed subjects to adjust to the current control scheme for the car and have the opportunity to train to a baseline level of expertise before measurements begin. The control training was complete when subjects successfully rotated the car 360° on the vertical axis, which typically required no more than one minute.

Once this control training activity had been completed, subjects moved on to the functional training and data acquisition phase by performing a driving task. Subjects were instructed to drive the car down a slalom course marked by cones on the inside of each turn and a marker on the outside of the turn, enclosing a distance two times the width of the car. The course was 5 feet wide and 40 feet long, with the cones for each turn spaced at 5 foot intervals down the length of the course. The course was designed with 8 turns of differing lateral spacing designed to provide variation in the turns required to complete the course while still retaining the ability of the car to complete the course without needing to reverse or commit an error if it is driven appropriately. The last half of the course is identical to the first half of the course except rotated 180°, providing an equal number and difficulty of turns both to the left and to the right. The designed layout of the course can be seen in Figure 11. Subjects were instructed to attempt to finish as quickly as possible and avoid hitting anything.

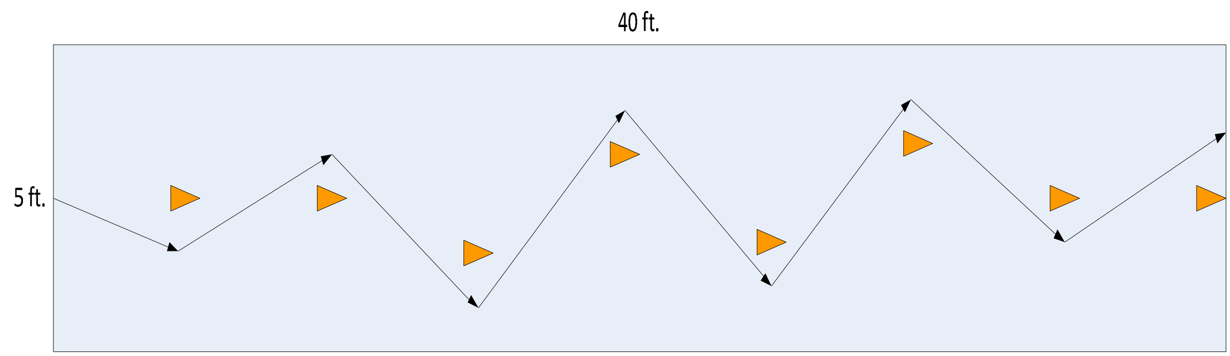

Figure 11: Layout of the driving course for the toy car used in the study.

The remote controlled car used in this study was only equipped for digital control of its functions. As such, the car was limited to turning full left, full right, or straight, and it was limited to driving full speed forward, full speed reverse, or stopping depending on the signals it received from the controller. The car was fitted with a stepping voltage regulator to maintain a constant speed throughout the study regardless of the voltage of its battery, and was calibrated to travel at approximately 0.67 meters per second. As a baseline to compare the performance of subjects driving the car, the car was measured to be able to drive the length of the course in a straight line in 18.5 seconds.

The time each subject required to complete a trial was measured by a pair of light gates at the first and last cones of the course that were linked to a stopwatch, and the time was recorded after each trial. While subjects were completing the trials, the experimenter observed the car and recorded the number of instances that subjects made errors in driving. Errors included hitting a cone, hitting a wall, or driving outside of the marked zone extending from the cone to two times the width of the car. After three trials had been completed for a muscle group, subjects were then presented with a visual analog scale 100 mm long ranging from “very easy” to “very hard” and asked to mark on the line how difficult they felt it was to complete the course using the current group of muscles for control. A linear measurement of this scale was used to quantify their subjective learning from the training. Additionally, the EMG signals from all four muscle groups during the trial were recorded and saved for later analysis. After all of these procedures had been completed for a muscle group, subjects moved on to the next muscle group in the sequence and began again at the calibration and signal training step. An illustration of the experimental setup used in this study can be seen in Figure 12.

Figure 12: Illustration of experimental setup used in the experiments.

2.3 – Data Processing

The recorded trial time data was ensemble averaged for each muscle group in each session. For each session the difficulty data from the visual analog scale was measured to the nearest half millimeter for each muscle group and recorded. The recorded errors data was ensemble averaged for each muscle group in each session. The recorded EMG signals were examined and the number of reversals in a trial was counted and ensemble averaged for each muscle group in each session. SPSS data analysis software was used with the resulting data sets to implement a repeated measures ANOVA analysis.

2.4 – Instrumentation

The design of the circuit driving the myoelectric trainer was all based around an mBed embedded controller. Four EMG signals were pre-conditioned and then sampled, filtered, analyzed by the mBed to result in the motion of a remote controlled car. The circuit was designed to accept four independent signals from a Noraxon MyoSystem 1200 EMG system through a twisted pair ribbon cable connector. The cable configuration was selected to minimize cross talk between the EMG channels. The signal for each input channel was then run through gain adjustment and offset adjustment circuits before being sent to the microcontroller. These adjustments were under the experimenter's control and were used during the calibration phase of the experiment to condition the EMG signals from the subject to fit the detection range of the microcontroller. The microcontroller continuously runs its program to sample, filter, rectify, smooth, and normalize the incoming EMG signals, then analyze and compare the resulting signals to thresholds in order to determine what actions should be taken by the car based on the current amplitudes of the signals, as described in the following section. The resulting outputs were then sent to the car by closing relays connected to the joystick inputs on the original control board for the car. To extend the range of the controller, a wire antenna running the length of the course was added to provide uniform signal strength for the entire course. The circuit diagram for the circuit can be seen in Figure 13 below. The completed circuit with an outline of its major components can be seen in Figure 14 below.

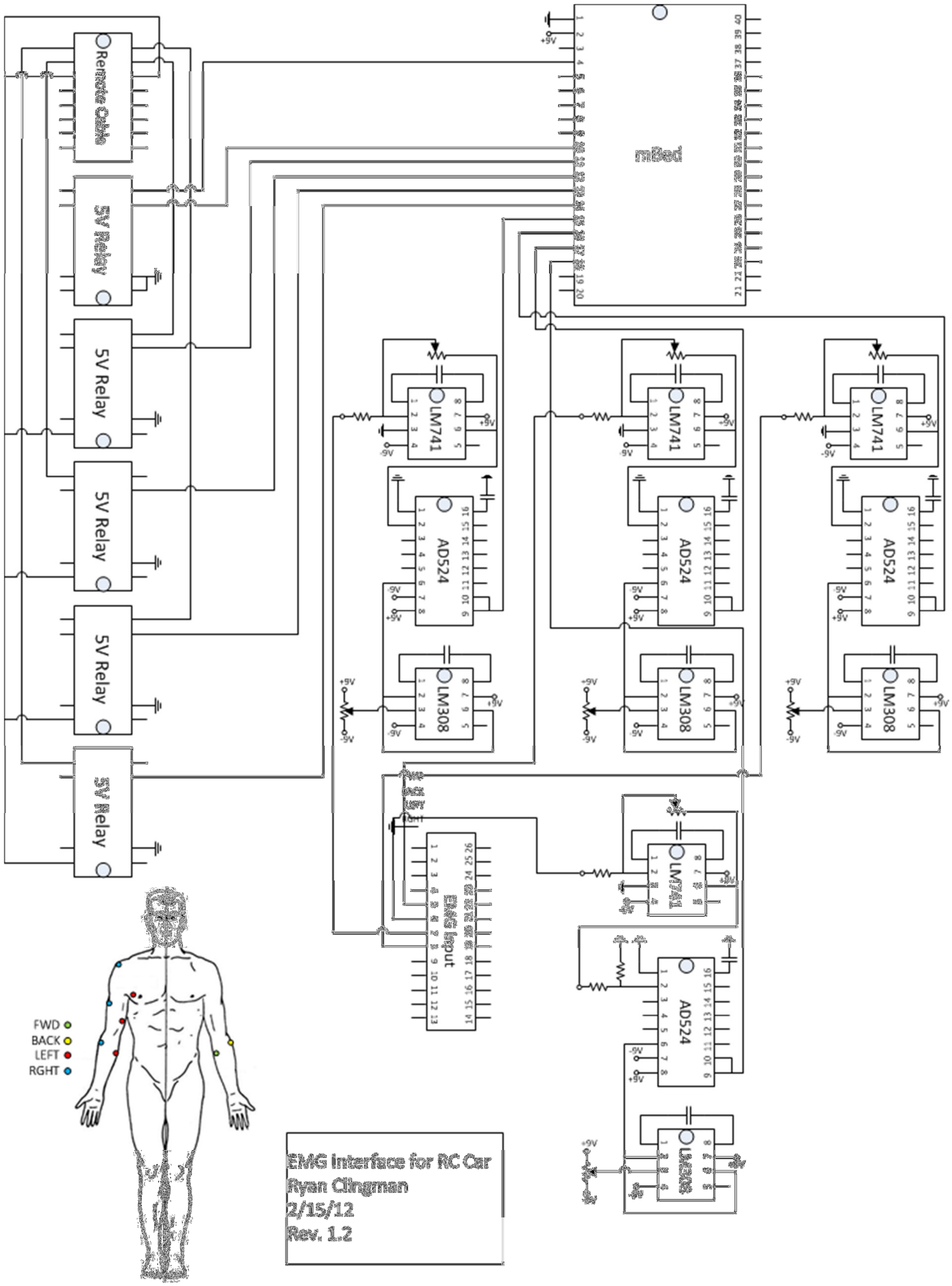

Figure 13: Circuit diagram of EMG processing and control circuit

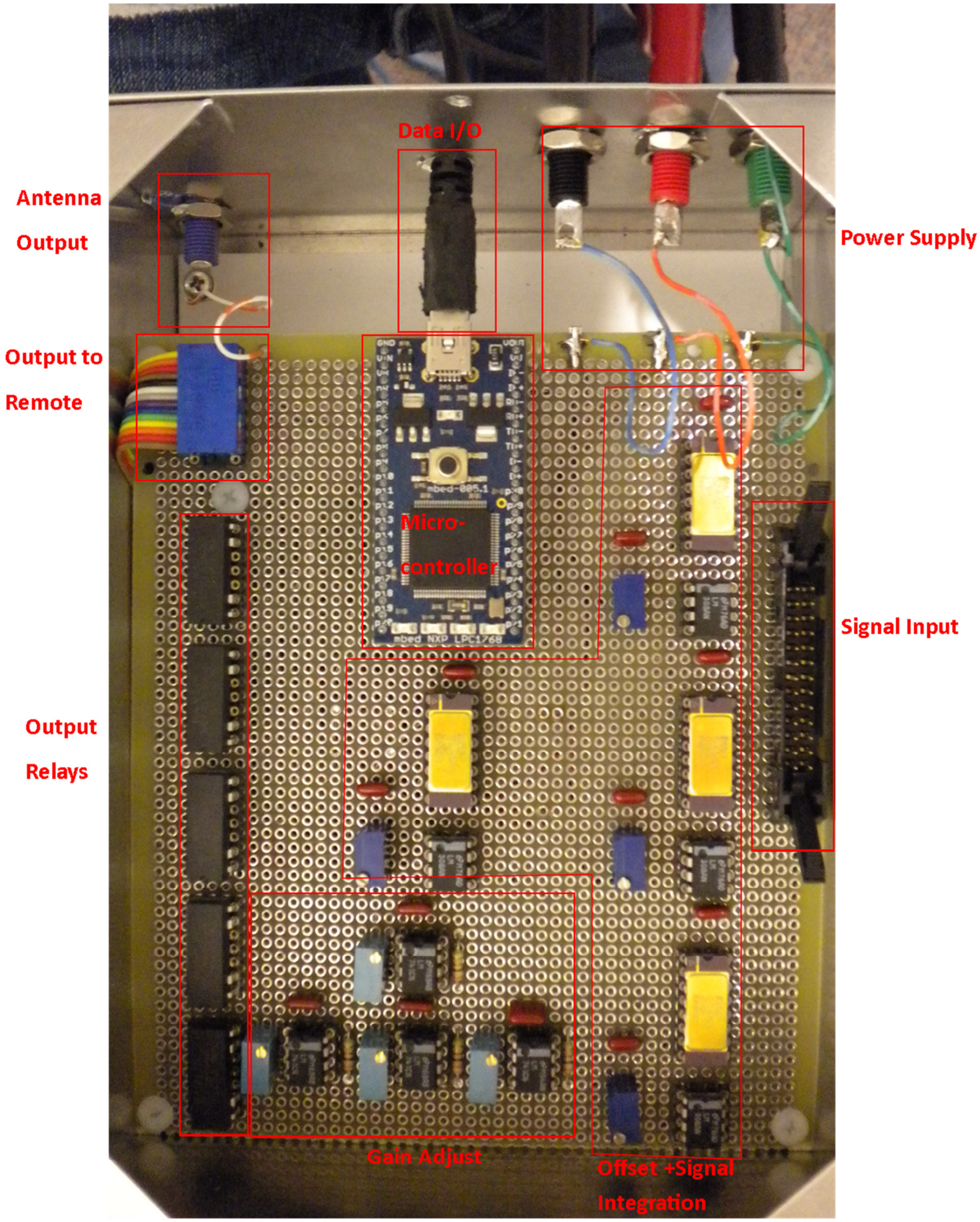

Figure 14: The completed EMG control circuit used in the study.

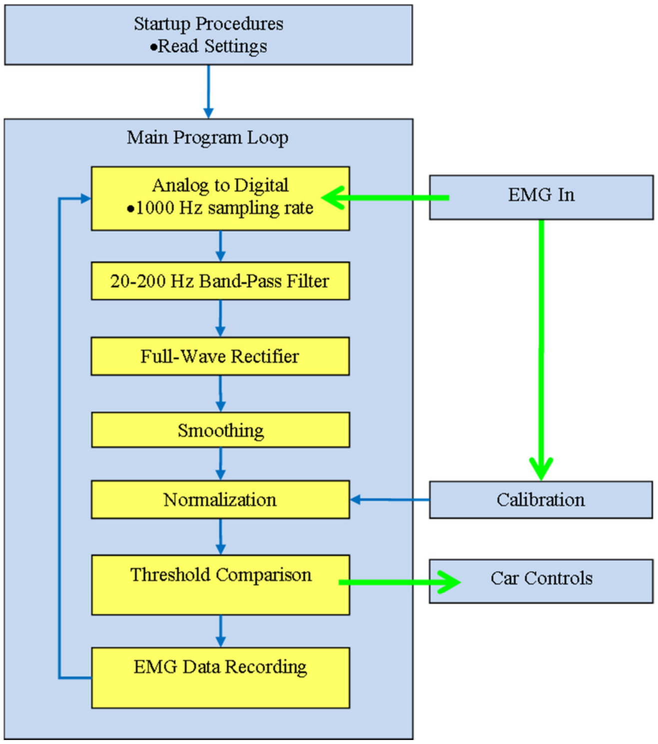

Figure 15: Outline of EMG processing program

The program that the microcontroller runs to process the raw EMG signals and drive the car follows a simple loop of collection, processing, and analysis, as can be seen in the outline of the program in Figure 15. The program runs in a continual loop at a rate of 1000 Hz, beginning with analog to digital sampling via polling of the incoming signals for later processing. The digital signals are then band-pass filtered between 20 and 200 Hz using a Butterworth filter in the software to remove any high or low frequency noise outside the frequency range of surface EMG. Following this, the signal was full-wave rectified to provide a signal with only positive values that could be used for control. The rectified signal was then run through a 100 millisecond rectangular smoothing window to change the sporadic impulses of the signal into a more continuous and smooth signal. This technique is commonly used in EMG analysis and is similar in function to a 6 Hz low-pass filter. (11) The final form of processing applied to the signals was normalization, where the current amplitude of the signal was converted to a percentage of the MVC amplitude found from calibration, allowing the system to compensate for both differences between users and variances in electrode placement. An example of the processed EMG data collected with the training device during the study can be seen in Figure 16 and Figure 17, which show EMG signals from controlling the turning and propulsion of the car respectively.

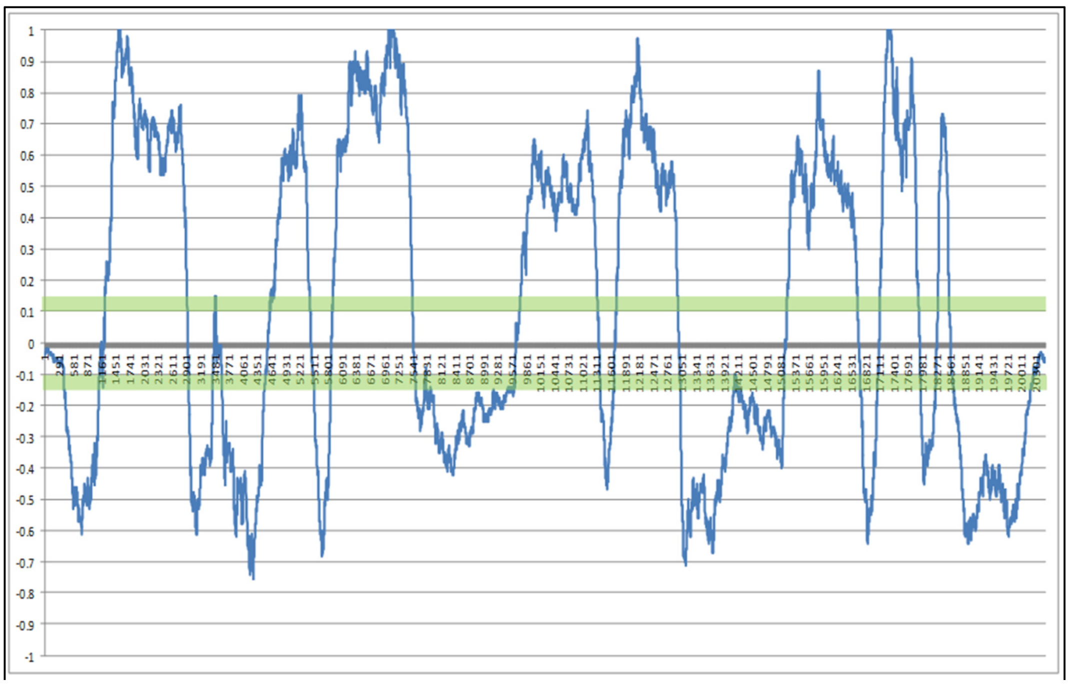

Figure 16: EMG data controlling car turning collected from a subject during a trial on the course. The X-axis is time and the Y-axis is the difference between two channels of EMG amplitude. Signals above the green lines result in a left turn, below the green lines result in a right turn, and between the green lines results in driving straight.

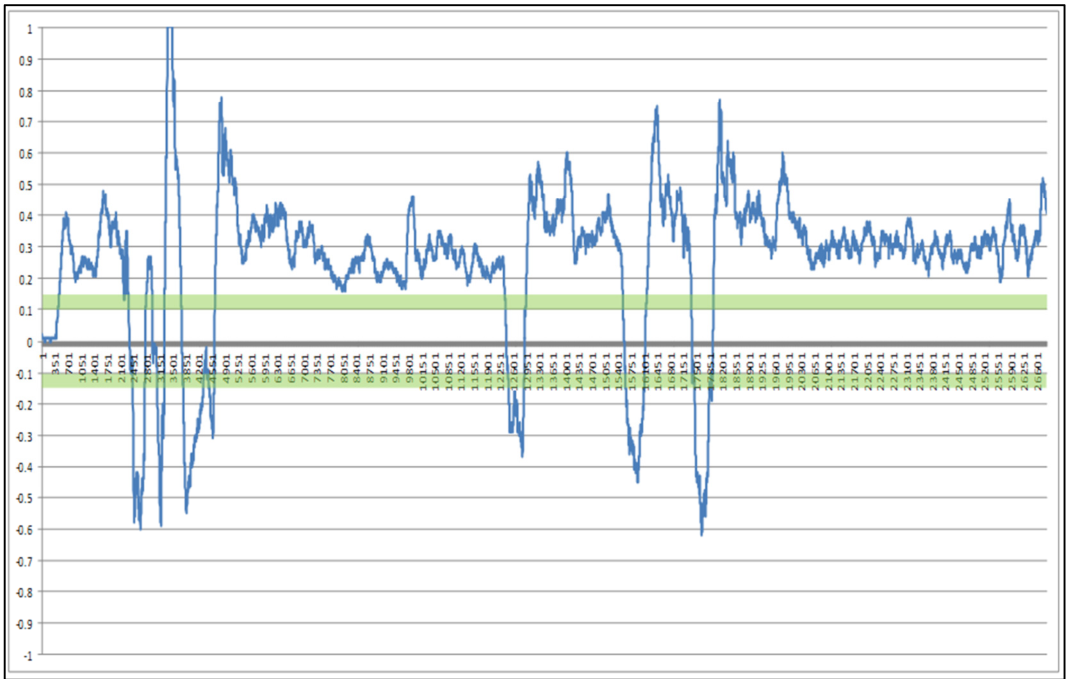

Figure 17: EMG data controlling car propulsion collected from a subject during a trial on the course. The X-axis is time and the Y-axis is the difference between two channels of EMG amplitude. Signals above the green lines result in driving forward, below the green lines result in driving backward, and between the green lines results in a stop.

After the signals were processed, they were compared to thresholds set during the calibration phase to determine which actions should be sent to the car. The difference between the amplitudes of the opposing muscle EMGs was taken, and if the result was above one of the set thresholds then the corresponding action was sent to the car, as seen in Figure 9. A dual threshold system was employed to reduce fatigue in users while maintaining ease in selecting all three control states, with the desired action being triggered when the signal rises above the upper threshold and remaining active until the signal drops below the lower threshold for a set duration of time. When necessary, these thresholds were adjusted up or down to accommodate for high baseline EMG in a muscle, high variability in the EMG signal, or other issues. The lower threshold was set approximately 10% of MVC above the highest EMG amplitude observed while the muscle was at rest and the upper threshold was set an additional 5% of MVC higher, typically at 10% and 15% of MVC respectively. Finally, the data points from the processed EMG signals were written to a file for post-hoc analysis. At this point, the program pauses until one millisecond has passed since the last measurement. This maintained the constant 1000 Hz sampling rate, and the entire loop was repeated again. Both console outputs and analysis of the resulting data files was used to verify the sampling rate prior to the beginning of the study.

Chapter 3

Results

A repeated measures ANOVA test was performed on the data collected for time per trial, reported difficulty while using each muscle group, errors per trial, and reversals per trial. The use of a Greenhouse-Geisser correction was necessary because the data violated the assumption of sphericity that is inherent in using a repeated measures ANOVA test. Additionally, post hoc tests using the Bonferroni correction were used to compare the data points of the first and last sessions. The results of these analyses are summarized in the sections below. A summary of the data can be seen in Table 1. The full set of data collected can be seen in Appendix A.

	First Session		Last Session		
	Mean	SD	Mean	SD	% Change
Time	58.13	35.70	26.63	5.84	- 54
Difficulty	46.96	22.25	18.00	14.79	- 62
Errors	3.78	1.53	1.92	0.88	- 49
Reversals	10.93	9.06	1.44	1.52	- 87

Table 1: Comparison of first and last session measurements of collected data, negative change indicates improvement in performance.

3.1 – Time Data

Figure 18 shows the results for the average time per trial for each session. A repeated measures ANOVA test with a Greenhouse-Geisser correction showed that the mean time differed statistically significantly between sessions ($F(1.189, 14.271) = 23.981$, $P < 0.0005$). Post hoc tests with the Bonferroni correction showed that the myoelectric training elicited a statistically significant ($p = .002$) decrease in the time per trial between the first and last session (58.13 ± 35.70 sec *vs.* 26.63 ± 5.84 sec). This represents a 54% decrease in the average time per trial over the course of the training.

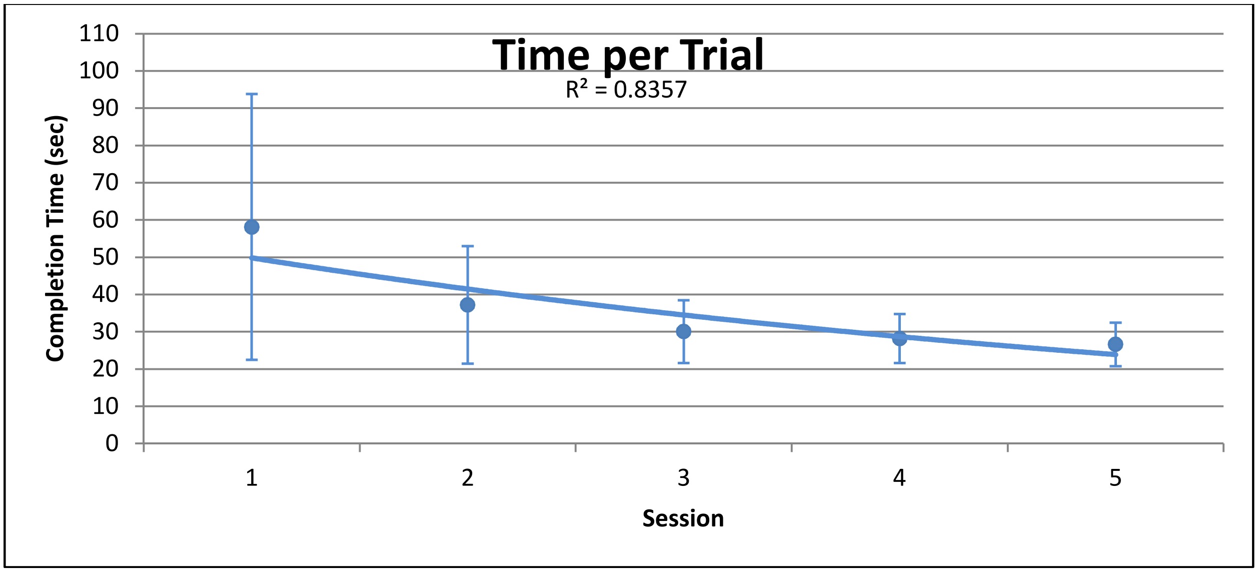

Figure 18: Average time across all subjects to complete a trial on the course with respect to how many sessions had been completed. The solid line represents an exponential best-fit function of the data.

Both the distal-first and the proximal-first groups of subjects demonstrated a steady decrease in the time required to complete a trial on average as they progressed through each session. As Figure 19 shows, the distal-first subjects produced their best completion times while using the proximal group of muscles in each session, they produced their worst completion times while using the distal group of muscles in each session, and their performance with the medial group of muscles fell somewhere between the other two muscle groups. The proximal-first subjects tended to produce their best completion times while using the distal muscle group in each session, they produced their worst completion times while using the proximal group of muscles in each session, and their performance with the medial group of muscles fell somewhere between the other two muscle groups. This demonstrates that in respect to trial completion time both groups performed the worse with the first muscle group they used each session and better with the last muscle group they used each session. There was found to be no statistically significant difference in performance between the distal-first and proximal-first groups of subjects with respect to the average trial completion time, but the difference in performance with the distal and proximal muscle groups between the groups of subjects was found to be statistically significant (P = 0.04).

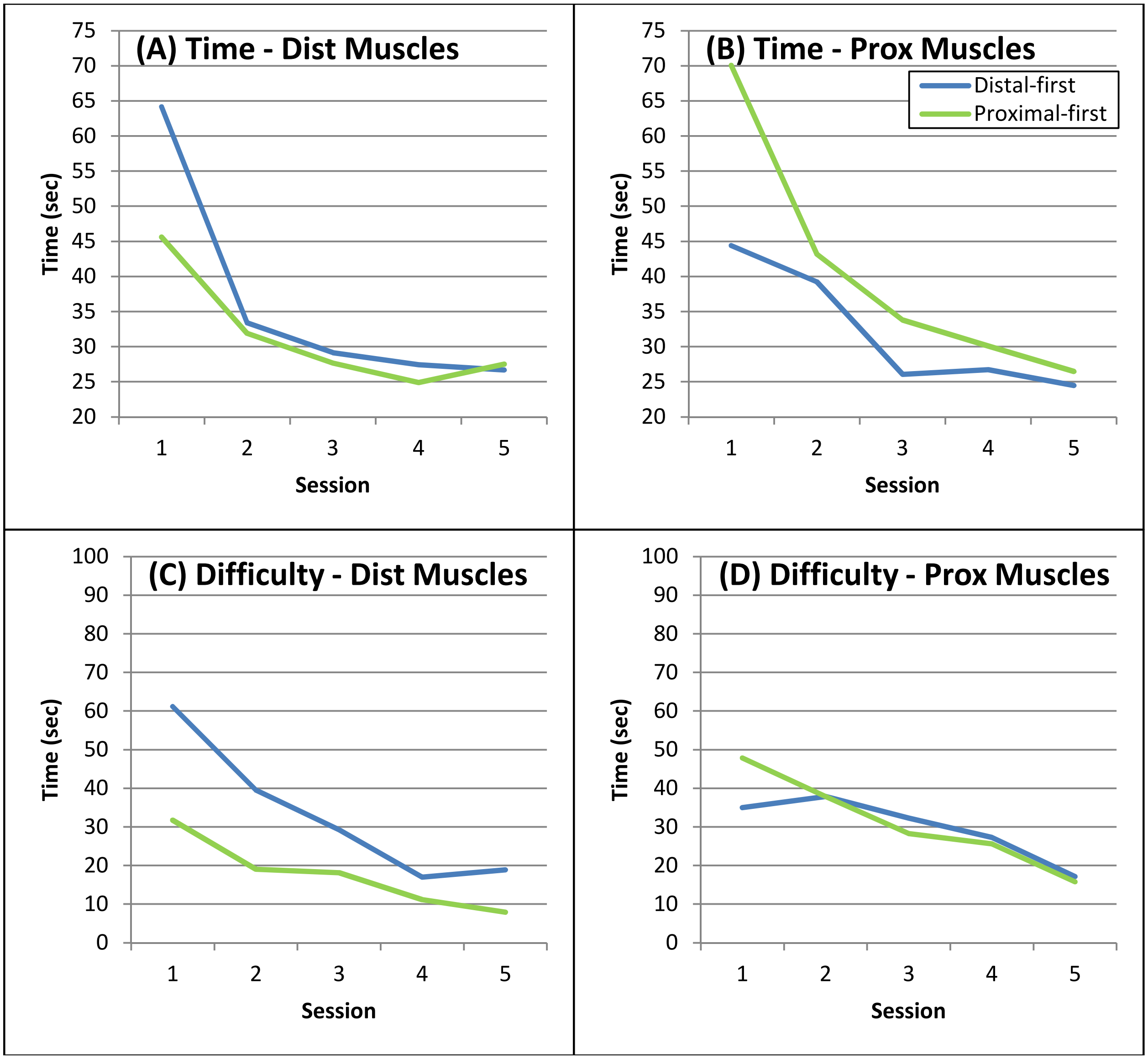

Figure 19: Comparison of performance between the distal-first and proximal-first groups of subjects with respect to (A) time with the distal muscle group, (B) time with the proximal muscle group, (C) reported difficulty with the distal muscle group, and (D) reported difficulty with the proximal muscle group.

3.2 – Difficulty Data

Figure 20 shows the results for the average reported difficulty for each session. A repeated measures ANOVA test with a Greenhouse-Geisser correction showed that the mean difficulty differed statistically significantly between sessions ($F(2.145, 25.741) = 46.062$, $P < 0.0005$). Post hoc tests with the Bonferroni correction showed that the myoelectric training elicited a statistically significant ($p < 0.0005$) decrease in the reported difficulty between the first and last session (46.96 ± 22.25 *vs.* 18.00 ± 14.79). This represents a 62% decrease in the average difficulty over the course of the training.

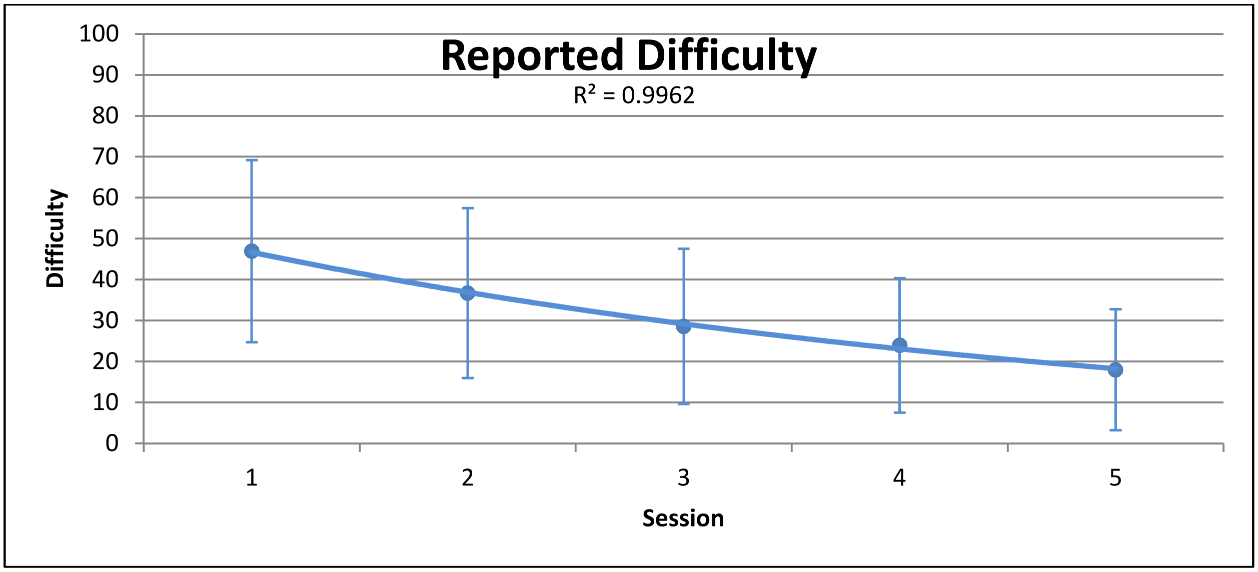

Figure 20: Average difficulty reported by visual analog scale with respect to how many sessions had been completed. The solid line represents an exponential best-fit function of the data.

Both the distal-first and the proximal-first groups of subjects demonstrated a steady decrease in the difficulty reported on the visual analog scale. The distal-first subjects reported a higher degree of difficulty on average, but the difference was not great enough to be statistically significant. As Figure 19 shows, the distal-first group of subjects reported the highest degree of difficulty with using the distal group of muscles in each session, the lowest degree of difficulty with using the proximal group of muscles in each session, and an intermediate degree of difficulty with using the medial group of muscles. The proximal-first group of subjects reported that the distal group of muscles was the least difficult to use in each session and the proximal group of muscles were more difficult to use in each session, but in each session they reported that the medial group of muscles was the most difficult to control the car with. The difference between the reported difficulties of the different muscle groups was also greater in the proximal-first group than in the distal-first group. There was found to be no statistically significant difference in performance between the distal-first and proximal-first groups of subjects with respect to the average difficulty reported, but the difference in performance with the distal and proximal muscle groups between the groups of subjects was found to be statistically significant ($P = 0.04$). These findings show a trend of subjects having less difficulty using the muscle groups that they use last in each session.

3.3 – Errors Data

Figure 21 shows the results for the average number of errors per trial for each session. A repeated measures ANOVA test with a Greenhouse-Geisser correction showed that the mean number of errors differed statistically significantly between sessions ($F(3.029, 36.347) = 23.925$, $P < 0.0005$). Post hoc tests with the Bonferroni correction showed that the myoelectric training elicited a statistically significant ($p < 0.0005$) decrease in the number of errors per trial between the first and last session (3.78 ± 1.53 errors *vs.* 1.92 ± 0.88 errors). This represents a 49% decrease in the mean errors per trial over the course of the training.

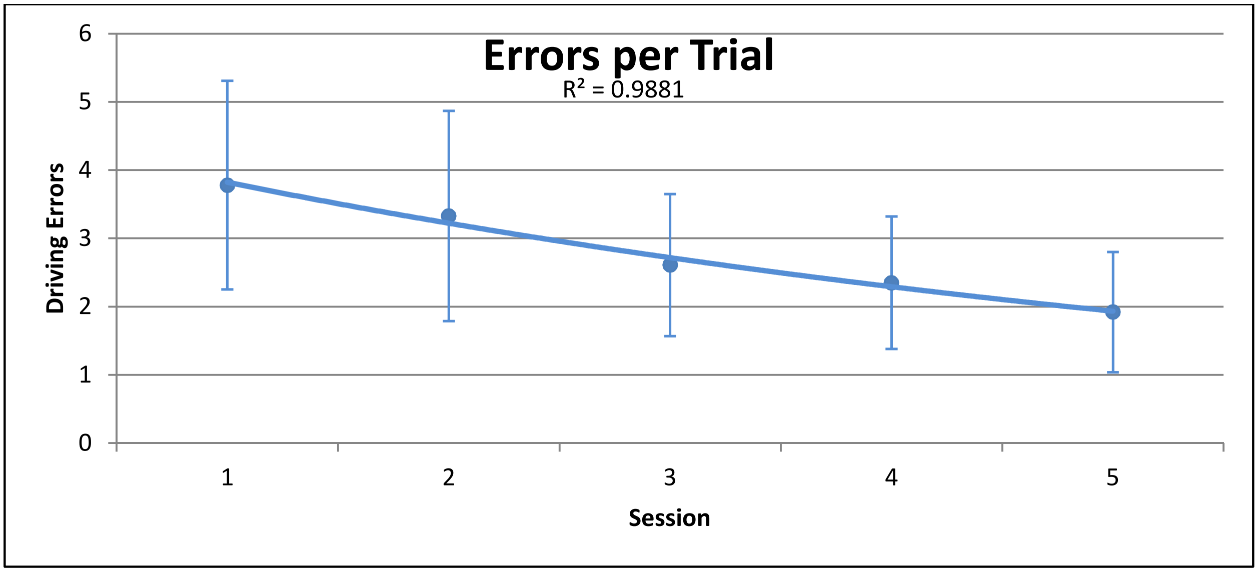

Figure 21: Average number of errors per trial with respect to how many sessions had been completed. The solid line represents an exponential best-fit function of the data.

Both the distal-first and the proximal-first groups of subjects demonstrated a steady decrease in the number of errors committed per trial as they progressed through each session. As Figure 22 shows, the distal-first group of subjects demonstrated the greatest amount of errors per trial while they were using the distal muscle group and the smallest amount of errors per trial while they were using the proximal muscle group, while the number of errors per trial for the medial muscle group fell between the other two groups. The proximal-first group of subjects demonstrated the greatest number of errors per trial while they were using the proximal muscle group and the lowest number of errors per trial while they were using the distal muscle group, while the amount of errors per trial for the medial muscle group fell in between the other groups.

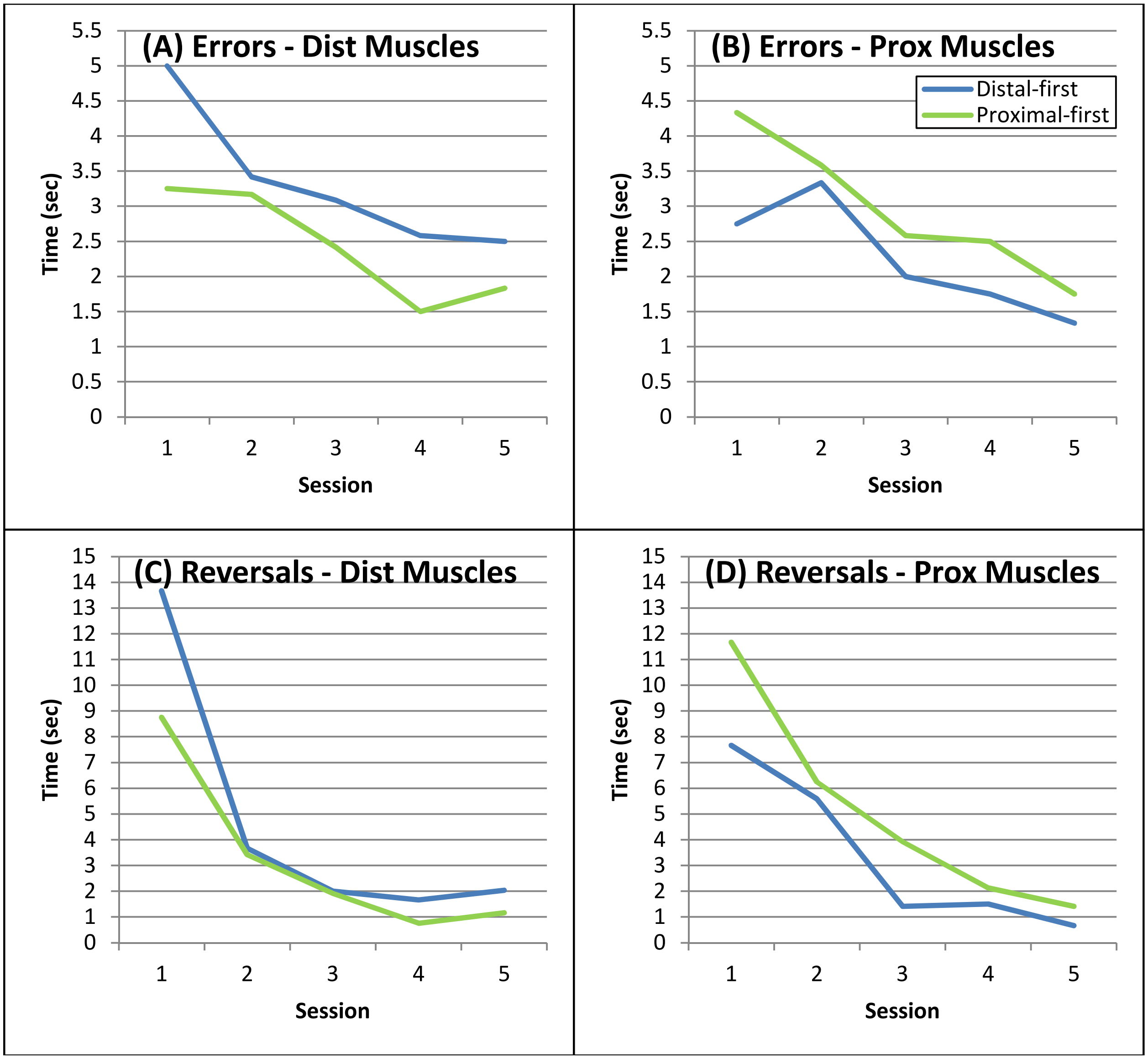

Figure 22: Comparison of performance between the distal-first and proximal-first groups of subjects with respect to (A) errors with the distal muscle group, (B) errors with the proximal muscle group, (C) reversals with the distal muscle group, and (D) reversals with the proximal muscle group.

It was also noted that subjects demonstrated more errors on the four more widely spaced middle turns than on the four more narrowly spaced turns at the beginning and end of the course, on average demonstrating an error on 44% of the trials with each of the wide turns compared to of 26% of the trials with each of the narrow turns, as shown in Figure 23. These findings show a trend of subjects demonstrating less errors with the muscle groups that they used later in each session. There was found to be no statistically significant difference in performance between the distal-first and proximal-first groups of subjects with respect to the average number of errors per trial, but the difference in performance with the distal and proximal muscle groups between the groups of subjects was found to be statistically significant (P = 0.04).

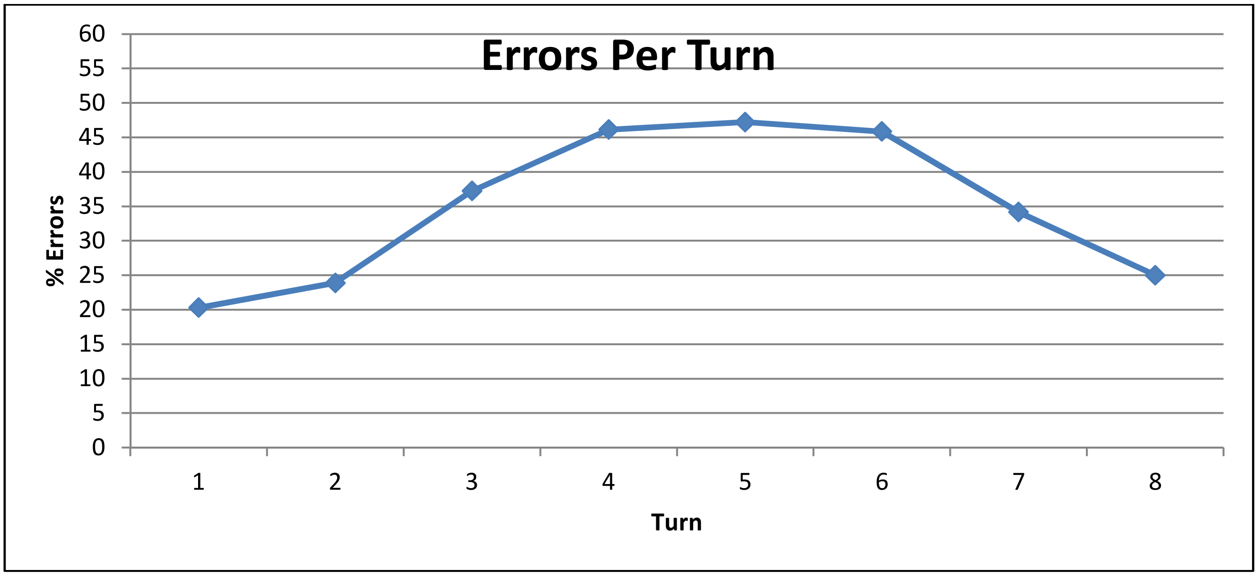

Figure 23: Percentage of trials that an error occurred on each turn of the study course.

3.4 – Reversals Data

Figure 24 shows the results for the average number of reversals per trial for each session. A repeated measures ANOVA test with a Greenhouse-Geisser correction showed that the mean reversals differed statistically significantly between sessions ($F(1.392, 16.702) = 34.979$, $P < 0.0005$). Post hoc tests with the Bonferroni correction showed that the myoelectric training elicited a statistically significant ($p < 0.0005$) decrease in the reversals per trial between the first and last session (10.93 ± 9.06 reversals *vs.* 1.44 ± 1.52reversals). This represents an 87% decrease in the mean number of reversals over the course of the training.

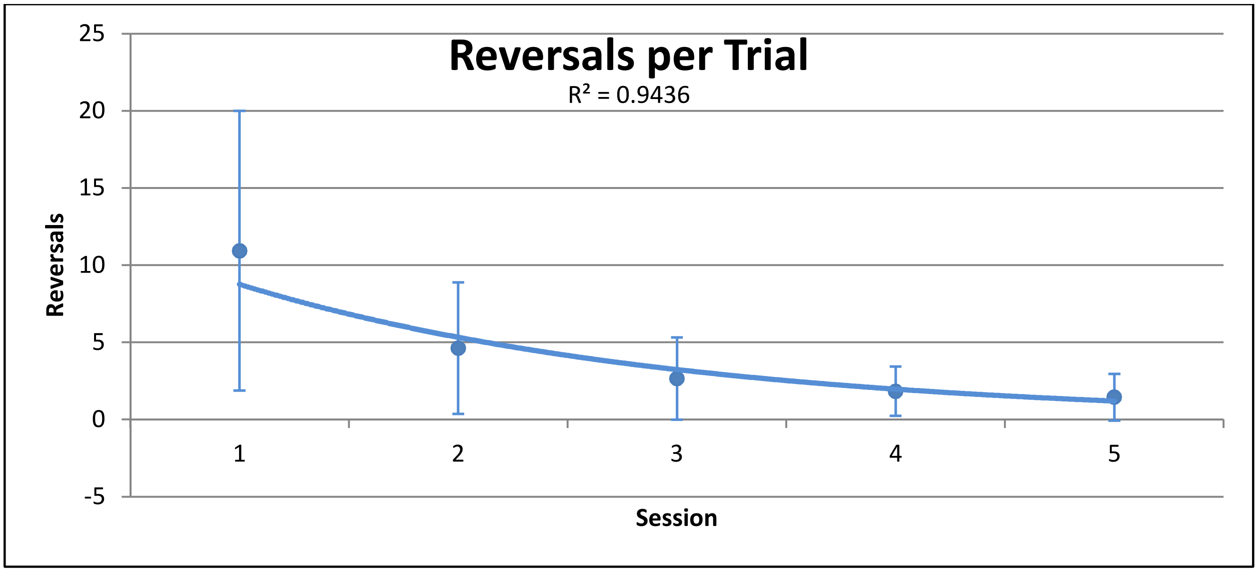

Figure 24: Average number of reversals required to navigate the course with respect to how many sessions had been completed. The solid line represents an exponential best-fit function of the data.

Both the distal-first and the proximal-first groups of subjects demonstrated a steady decrease in the number of reversals required to complete each trial as they progressed through each session. As Figure 22 shows, the distal-first group of subjects was found to require more reversals to complete a trial while they were using the distal muscle group than while they were using the proximal muscle group, while the number of reversals required to complete a trial while using the medial muscle group fell between the other two groups. The proximal-first group of subjects was found to require more reversals to complete a trial while they were using the proximal muscle group than while they were using the distal muscle group, while the number of reversals required to complete a trial while using the medial muscle group fell between the other two groups. There was found to be no statistically significant difference in performance between the distal-first and proximal-first groups of subjects with respect to the average number of reversals necessary to complete a trial, but the difference in performance with the distal and proximal muscle groups between the groups of subjects was found to be statistically significant ($P = 0.04$).

3.5 – Effect of Training Order

Overall there was no statistically significant difference between the performance of subjects who trained with the distal group of muscles first and those who trained with the proximal group of muscles first, as can be seen in Figure 25. However, there was a statistically significant difference when comparing the two groups' performance with just the distal muscle group and just the proximal muscle group, as can be seen in Figure 19 and Figure 22. Subjects in both groups tended to perform worst with the first muscle group that they trained with and best with the last muscle group that they trained with in each session. The distal-first subjects demonstrated their best performance with the proximal group of muscles and the worst performance with the distal set of muscles, while the proximal-first subjects demonstrated their best performance with the distal group of muscles and their worst performance with the proximal group of muscles.

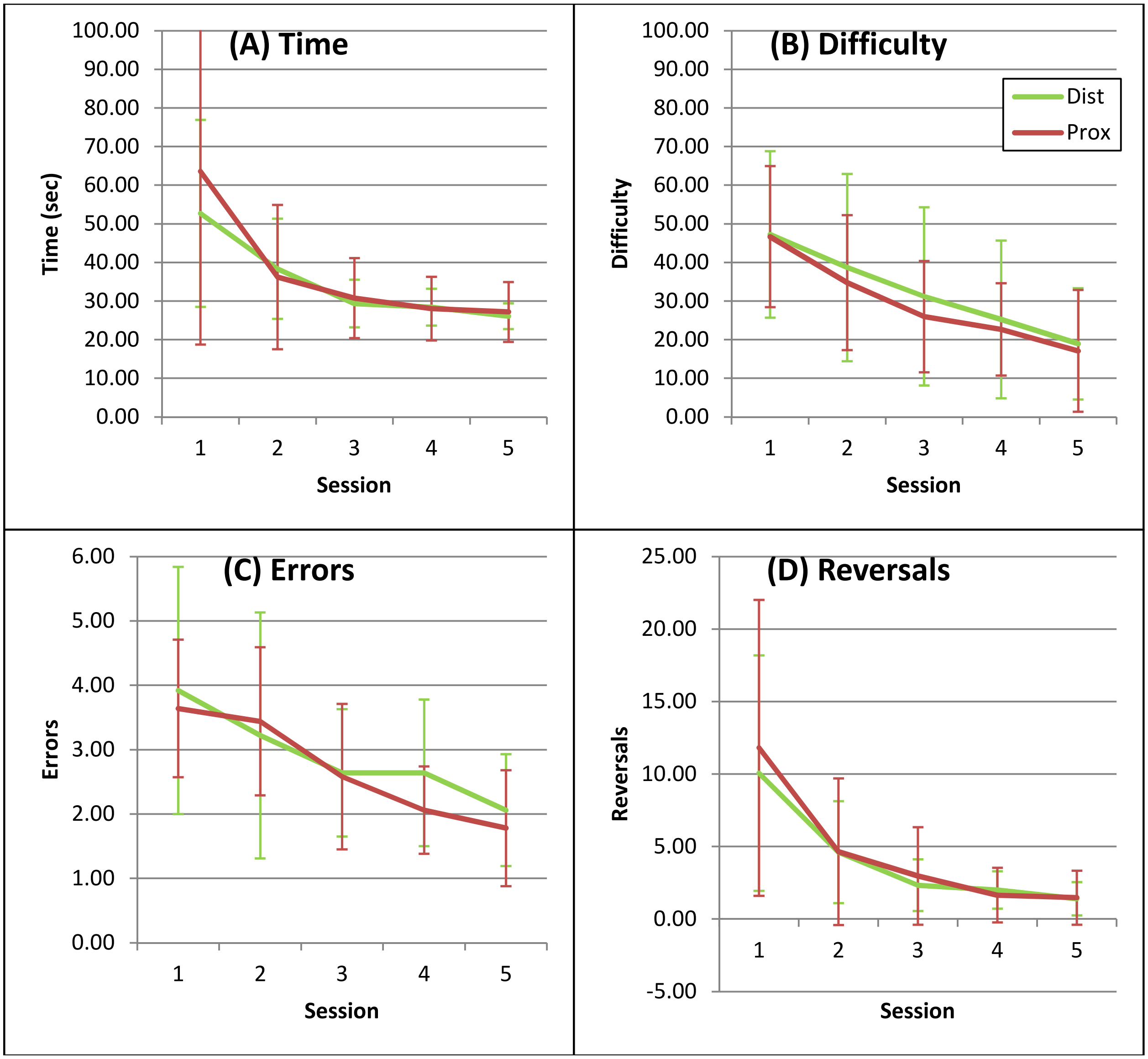

Figure 25: Comparison of overall performance between subjects assigned to the distal-first and proximal-first training orders with respect to (A) time per trial, (B) reported difficulty, (C) errors per trial, and (D) reversals per trial.

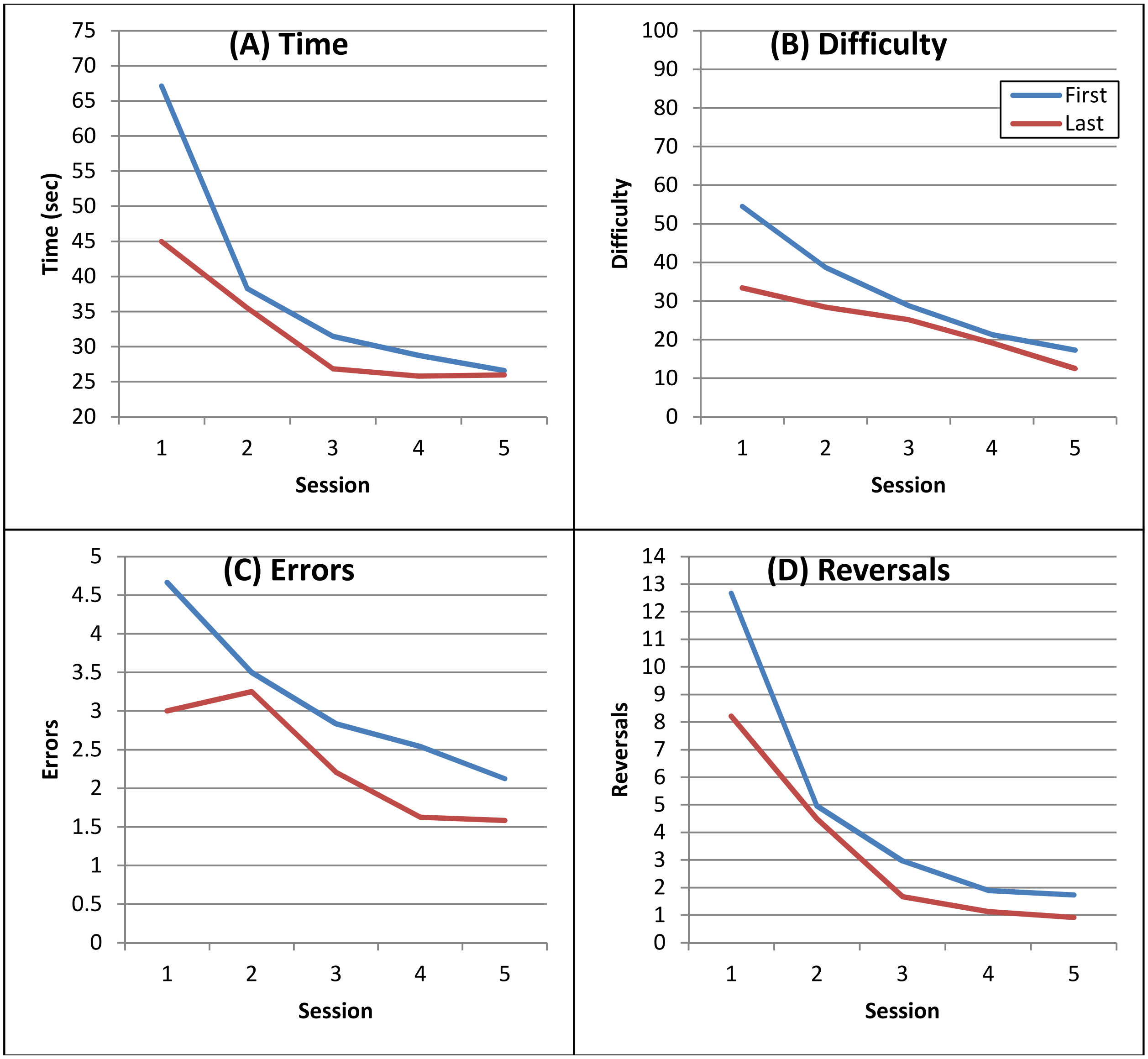

Figure 26: Comparison of the first and last muscle groups used in each session with respect to (A) time, (B) reported difficulty, (C) errors per trial, and (D) reversals per trial.

This relationship is reinforced by Figure 26, which shows that the difference in performance demonstrated by the first and last muscle group used by each subject. As it is unlikely that training with one muscle group could improve a subject's volitional control of the EMG signals of an unrelated muscle group, this result supports the idea that subjects benefitted from the experience with the earlier muscle groups in learning how to better perform the tasks of the study. This result again demonstrates that the training device can function as an effective training tool independent of which muscle groups it is used with.

3.6 – Effect of Gender

While data analysis revealed that neither the muscle group used nor the order a subject was trained to use the three muscle groups made a statistically significant difference in performance, the gender of subjects did have a significant effect on the outcome, as seen in Figure 27. The average time per trial was significantly different between the male and female subjects (P = 0.01), with the male subjects achieving times 35.6% lower than the female subjects on average. The average reported difficulty was significantly different between the male and female subjects (P = 0.005), with the male subjects reporting difficulties 39.3% lower than the female subjects on average. The average errors per trial was significantly different between the male and female subjects (P = 0.05), with the male subjects demonstrating 32.7% fewer errors than the female subjects on average. The average reversals per trial was significantly different between the male and female subjects (P = 0.002), with the male subjects requiring 65.9% fewer reversals to complete the course than the female subjects on average. The summarizing data can be found in Table 2.

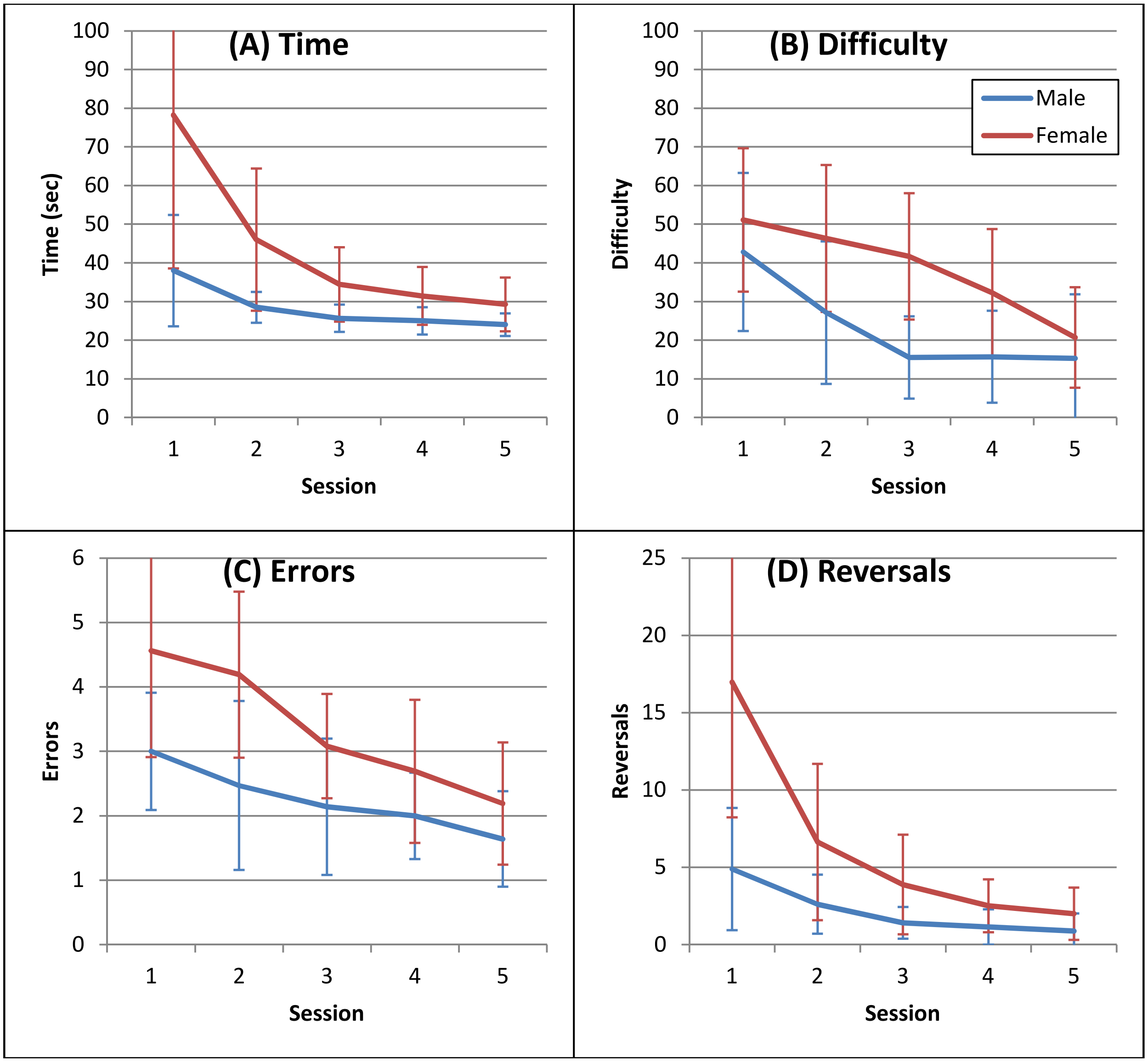

Figure 27: Comparison of performance between male and female subjects with respect to (A) time per trial, (B) reported difficulty, (C) errors per trial, and (D) reversals per trial.

	Male		Female		
	Mean	SD	Mean	SD	% Difference
Time	28.23	5.71	43.87	20.28	35.6
Difficulty	23.30	12.02	38.39	12.11	39.3
Errors	2.25	0.51	3.34	1.00	32.7
Reversals	2.19	1.65	6.40	6.18	65.9

Table 2: Comparison of collected data between male and female subjects.

The greatest statistically significant correlation observed between subjects and their performance was the relationship between subjects' gender and their performance. The male subjects performed significantly better in all measured areas, achieving lower average times to complete a trial, reporting lower average difficulty, demonstrating fewer errors per trial on average, and requiring fewer reversals to complete a trial on average than the female subjects. While this difference in performance greatly decreased over the course of the study, the difference between these two groups of subjects is still quite striking, as can be seen in Figure 27. Because this correlation was noticed while the trial was still in progress, it was deemed prudent to look into factors that could help to explain this phenomenon.

It has been demonstrated in previous studies that the use of video games can cause an increase in the spatial skill of subjects, allowing them to more easily complete novel spatial tasks, and that training in this manner could virtually eliminate the observed difference in spatial skill between male and female subjects. (7) Because of this, it was hypothesized that this type of effect could be influencing the results of this study. To determine whether this could be an influencing factor, upon the completion of their final session of the study each subject was asked if they had any significant experience with playing video games. Five of the eight subjects responded positively that they had played a significant amount of video games, including all four of the male subjects as well as one of the female subjects. The result of dividing subjects into groups of "gamers" and "non-gamers" is even more pronounced than the difference in performance between genders, as can be seen in Figure 28.

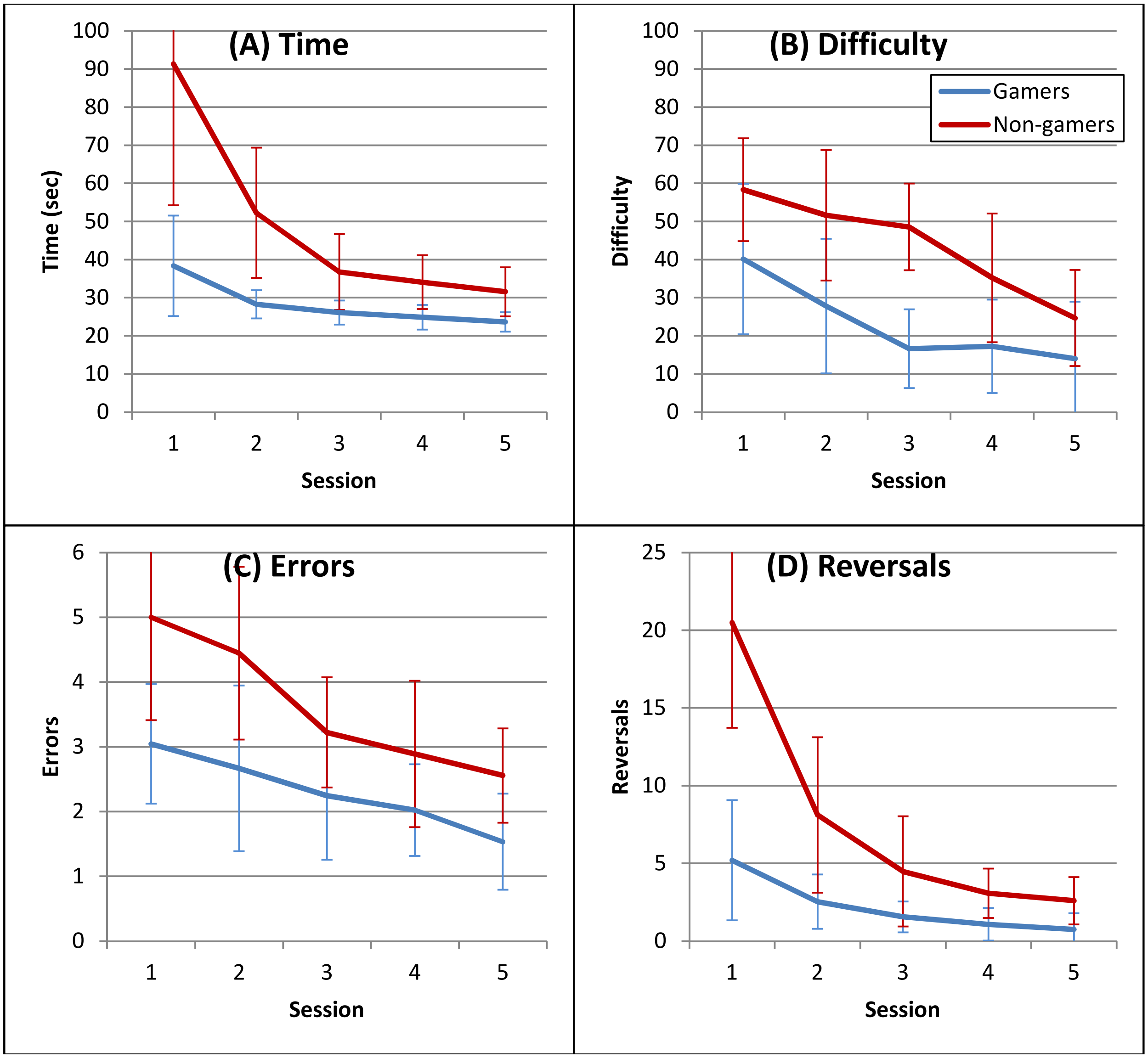

Figure 28: Comparison of performance between subjects who did and did not have a significant amount of experience with video games with respect to (A) time per trial, (B) reported difficulty, (C) errors per trial, and (D) reversals per trial.

The gamer subjects demonstrated a significantly better performance than the non-gamer subjects, although the difference in performance decreased as the study progressed. It was noted that the one female gamer subject had demonstrated significantly better performance than the other three female subjects who responded that they had not played video games, and she was actually the subject that achieved the fastest single run on the course. This subject's performance was found to be closer to the performance demonstrated by the male subjects than to the performance demonstrated by the other female subjects. This data supports the results found in studies concerning video game usage and spatial skill, as well as raising the question of whether this training device could be used as another method of increasing a subject's spatial skill.

Chapter 4

Discussion

4.1 – Design Validation

The primary objective of this study was to design and validate the design of a novel training system for myoelectric prosthetic limbs. The design allowed novice users to begin driving a remote control car through myoelectric control within a few minutes of the start of training, and their skill with controlling the car improved steadily over time. The ability of the design to facilitate learning to use myoelectric signals to control an object was tested by asking subjects to use the system to drive the car though a slalom course while their performance was being monitored for four indicators of learning.

Subjects' time to complete the course was measured, and it was found to decrease both between testing sessions as well as between sequential muscle groups within a single session. The number of times that subjects demonstrated an error, in the form of passing to either side of the marked gates rather than through them, was recorded, and subjects were found to demonstrate fewer errors both between testing sessions as well as between sequential muscle groups within a single session. The number of times subjects were required to reverse the car in order to successfully navigate the course was also measured and was found to decrease both between testing sessions as well as between sequential muscle groups within a single session. Finally, subjects' assessment of the difficulty of controlling the car was assessed through the use of a visual analog scale, and their assessment of the difficulty was found to decrease both between testing sessions as well as between sequential muscle groups within a single session. All of these indicators demonstrate that through using this training system subjects became more adept at using a myoelectric control scheme that is commonly used in commercial myoelectric prosthetic limbs.

These results are consistent with the results found in other studies, providing additional validation of this training device compared to other training devices that have been created. Other research has shown that subjects' time to complete tasks with the myoelectric training devices decreased over the course of the study asymptotically, with the greatest increase in performance occurring at the beginning of the study, similarly to the data collected in this study. The similar nature of the data collected in this study is taken as verification that the training device can be used as an effective form of control training for myoelectric prosthetic devices. (6, 18)

Additionally, the majority of subjects were noted to have spontaneously remarked that they considered using the training device to be fun after at least one of the training sessions. Because these statements were made while subjects had only used the training device in a strictly controlled experimental setting, this is considered a good indicator that the training device could offer an improvement over the currently available myoelectric training systems by being more enjoyable to use. A more realistic usage scenario for the training device would likely involve giving more freedom to drive the car wherever they like or simply providing them with obstacles to navigate around as they saw fit, which would likely be more enjoyable than the strictly regimented form of usage found in this study. This type of training could be particularly effective in training young children to use prosthetic limbs due to the trainer being more likely to hold their attention than the repetitive tasks of the current generation of training devices.

4.2 – Trainer design

While the training system has shown to be a successful proof of concept device, the current design is not without certain limitations. First, the training system was specifically designed to provide training for a two-site three-state control scheme because the simple nature of the control scheme was thought to provide a better example as a proof of concept for the efficacy of the device. The downside of this approach is that the trainer is not currently suitable to provide training for newer myoelectric prosthetic arms that have more advanced pattern based control schemes used to control more complex movements like articulated wrists in addition to the movement of the hand. The system could easily be adapted to accommodate training for additional models of prosthetic arms by altering the current control algorithms to include additional control schemes. Second, while many commercial myoelectric prosthetics are moving from digital controls to proportional controls, the training system is currently limited to using only digital control schemes due to the fact that the remote control car used in the study is only capable of responding in a digital fashion. Overcoming this limitation would again require modifications to the control algorithms, but it would additionally require a remote control car capable of responding to proportional commands and modifications to the circuit to relay commands from the microcontroller to the car's remote. Finally, due to its experimental nature, the training system is not very portable or user friendly due to its relatively large size, need for an external power supply, and dependence on an existing EMG amplifier system. These limitations are the most challenging to overcome, as making the trainer into a more user friendly system would require redesigning the circuit to be smaller and incorporate an EMG amplifier, radio transmitter, and battery supply in order to make it fully self-contained and portable.

4.3 – Functional Electrical Stimulation

Another potential application of this type of myoelectric training device is training for myoelectrically controlled Functional Electrical Stimulation (FES) devices. It is estimated that there are 400,000 individuals suffering from spinal cord injuries in the United States, with another 11,000 more injuries occurring each year, often leaving the victims partially paralyzed and able to control their arms but not their hands. (12) FES devices are neuroprostheses designed to restore function to patients with spinal cord injuries by electrically stimulating selected muscles to contract in a predetermined pattern in order to achieve a desired movement in a paralyzed limb or muscle. These devices have been used to help restore function or control to the upper and lower extremities, bladder and bowels, and even to the diaphragm to help maintain breathing. (14, 19)

Patients who experience a spinal cord injury in the C5/C6 region of the spine are often left with control of proximal muscles of the arms but lose the ability to use distal muscles, allowing them to retain control the position of the arm but leaving them unable control the hand. To rectify this issue, systems have been developed to provide stimulation to the muscles controlling hand movement in order to restore some function and aid tetraplegic patients in accomplishing activities of daily living. An increasing number of systems are available that use myoelectric signals as the basis to control the stimulation of the hand muscles, allowing tetraplegic patients to achieve more natural use of the hand than with older systems involving physical buttons or other methods to control hand motions. (5, 23) The myoelectric training device used in this study could be used with tetraplegic patients in a similar fashion to limb-loss patients, providing training with myoelectric control before a FES system is provided or electrode implantation is undertaken, or aiding in validation of the patient's viability for myoelectric control schemes.

Chapter 5

Conclusion

The specific aims of this study were to design a novel training device to assist in the control training phase of myoelectric prosthetic training, to evaluate the performance of the device, and to investigate the ability of distal or proximal muscle groups to control myoelectric devices. A training device was developed which allows EMG signals from surface electrodes to be collected and used to drive a toy remote control car. This training system was employed to implement signal training and control training phases of myoelectric training in able bodied subjects using both proximal and distal muscle groups to control the car. Subjects demonstrated an improvement in performance similar to the results of other studies on the learning of myoelectric control schemes. While there was no significant difference in subjects' performance using proximal or distal muscle groups, subjects demonstrated their best performance with the last muscle group they trained to use. Additionally, a subject's level of spatial skill appears to have a significant effect on their performance with the training system, with subjects that had previous experience with using types of video games demonstrating better performance than those with no experience. The training system appears to be successful in imparting learning in the use of a myoelectric control scheme, but more research and development is necessary before it will be ready for wider usage.

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Literature Cited

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Appendices

Appendix A

Driving Data

Subject	Muscle	Group	Gender	Time1	Time2	Time3	Time4	Time5
1	Dist	Dist	Female	85.18	35.18	32.31	28.08	27.63
1	Med	Dist	Female	78.09	66.92	44.02	39.32	32.88
1	Prox	Dist	Female	60.03	44.23	28.20	26.48	26.21
2	Dist	Dist	Female	92.11	37.65	31.19	29.25	29.06
2	Med	Dist	Female	62.98	49.46	36.87	31.31	25.06
2	Prox	Dist	Female	63.85	54.03	26.91	30.50	25.90
3	Dist	Prox	Female	32.13	28.36	29.15	23.31	22.63
3	Med	Prox	Female	36.47	24.98	27.48	23.01	21.45
3	Prox	Prox	Female	49.09	29.39	26.24	26.78	22.94
4	Dist	Prox	Female	72.68	48.75	32.09	32.28	43.65
4	Med	Prox	Female	143.87	43.85	40.70	42.97	35.43
4	Prox	Prox	Female	163.02	90.34	58.65	46.34	38.17
5	Dist	Dist	Male	33.21	32.02	30.37	28.81	25.87
5	Med	Dist	Male	28.43	29.53	27.79	32.91	28.74
5	Prox	Dist	Male	26.31	33.67	24.88	28.17	24.32
6	Dist	Dist	Male	46.17	28.69	22.62	23.61	24.17
6	Med	Dist	Male	29.71	22.55	23.13	21.88	21.70
6	Prox	Dist	Male	27.38	25.08	24.17	21.72	21.42
7	Dist	Prox	Male	49.58	23.94	27.02	22.07	22.25
7	Med	Prox	Male	76.38	32.79	32.52	25.77	23.03
7	Prox	Prox	Male	32.41	28.99	22.35	22.13	22.54
8	Dist	Prox	Male	28.01	26.39	22.34	21.86	21.53
8	Med	Prox	Male	44.50	33.49	23.46	25.45	29.67
8	Prox	Prox	Male	35.76	23.99	27.98	25.05	22.27

Subject	Muscle	Group	Gender	Difficulty1	Difficulty2	Difficulty3	Difficulty4	Difficulty5
1	Dist	Dist	Female	57.0	29.0	38.5	7.0	12.0
1	Med	Dist	Female	60.0	60.5	59.5	46.0	24.0
1	Prox	Dist	Female	40.0	50.0	54.5	33.0	20.0
2	Dist	Dist	Female	85.0	67.0	56.5	41.0	47.0
2	Med	Dist	Female	64.0	62.5	45.0	57.5	34.0
2	Prox	Dist	Female	64.0	77.5	59.0	56.0	38.0
3	Dist	Prox	Female	13.0	16.0	12.0	9.0	6.0
3	Med	Prox	Female	42.0	25.5	20.0	23.5	8.0
3	Prox	Prox	Female	33.0	50.0	31.0	37.5	12.0
4	Dist	Prox	Female	41.0	27.0	24.5	17.0	9.5
4	Med	Prox	Female	53.0	40.5	47.0	28.0	15.5
4	Prox	Prox	Female	61.0	50.5	52.5	31.0	22.0
5	Dist	Dist	Male	41.0	22.0	9.0	4.0	3.0
5	Med	Dist	Male	20.5	14.0	5.0	10.5	18.0
5	Prox	Dist	Male	12.0	4.0	1.5	2.0	2.0
6	Dist	Dist	Male	61.5	40.0	13.0	16.0	13.5
6	Med	Dist	Male	38.0	17.5	19.0	12.0	7.0
6	Prox	Dist	Male	24.0	20.0	14.0	18.0	8.5
7	Dist	Prox	Male	48.0	18.0	30.0	14.5	6.0
7	Med	Prox	Male	81.5	65.0	38.0	36.0	23.0
7	Prox	Prox	Male	51.5	24.0	10.5	8.0	14.0
8	Dist	Prox	Male	25.0	15.0	6.0	4.0	10.0
8	Med	Prox	Male	65.0	59.0	21.0	37.5	64.0
8	Prox	Prox	Male	46.0	27.0	19.0	26.0	15.0

Subject	Muscle	Group	Gender	Errors1	Errors2	Errors3	Errors4	Errors5
1	Dist	Dist	Female	6.33	3.00	3.00	1.67	3.00
1	Med	Dist	Female	4.33	4.00	3.33	4.00	2.33
1	Prox	Dist	Female	3.00	3.33	2.33	1.67	1.33
2	Dist	Dist	Female	6.33	5.33	4.67	3.67	2.67
2	Med	Dist	Female	7.33	5.67	4.00	5.00	3.67
2	Prox	Dist	Female	4.33	6.67	2.33	2.67	2.00
3	Dist	Prox	Female	2.00	4.00	3.00	1.00	1.67
3	Med	Prox	Female	3.33	2.33	3.00	2.33	0.33
3	Prox	Prox	Female	4.33	4.00	2.00	3.00	1.33
4	Dist	Prox	Female	3.33	5.00	3.00	2.00	2.67
4	Med	Prox	Female	3.67	2.67	2.33	2.67	2.00
4	Prox	Prox	Female	6.33	4.33	4.00	2.67	3.33
5	Dist	Dist	Male	4.00	2.67	3.00	2.33	2.67
5	Med	Dist	Male	2.67	1.67	2.00	3.00	2.33
5	Prox	Dist	Male	2.33	1.00	1.33	1.00	1.00
6	Dist	Dist	Male	3.33	2.67	1.67	2.67	1.67
6	Med	Dist	Male	1.67	0.33	2.00	2.33	1.00
6	Prox	Dist	Male	1.33	2.33	2.00	1.67	1.00
7	Dist	Prox	Male	4.33	1.67	2.33	1.00	1.00
7	Med	Prox	Male	3.67	5.00	4.33	1.33	1.67
7	Prox	Prox	Male	3.67	3.00	0.67	1.67	0.67
8	Dist	Prox	Male	3.33	2.00	1.33	2.00	2.00
8	Med	Prox	Male	2.67	4.33	1.33	2.33	3.00
8	Prox	Prox	Male	3.00	3.00	3.67	2.67	1.67

Subject	Muscle	Group	Gender	Reversals1	Reversals2	Reversals3	Reversals4	Reversals5
1	Dist	Dist	Female	17.00	1.67	2.00	1.33	2.00
1	Med	Dist	Female	14.00	9.33	5.67	4.00	3.00
1	Prox	Dist	Female	10.33	4.67	1.33	1.00	0.67
2	Dist	Dist	Female	25.67	5.33	2.33	2.00	3.67
2	Med	Dist	Female	17.00	7.67	6.00	3.33	0.67
2	Prox	Dist	Female	17.67	11.67	2.00	3.00	1.33
3	Dist	Prox	Female	2.00	2.67	2.33	0.67	0.33
3	Med	Prox	Female	7.67	1.00	2.67	0.33	0.00
3	Prox	Prox	Female	9.67	3.00	1.33	1.50	0.33
4	Dist	Prox	Female	25.00	8.00	3.00	2.33	4.00
4	Med	Prox	Female	29.67	5.67	5.33	5.33	3.00
4	Prox	Prox	Female	28.00	19.00	12.67	5.33	5.00
5	Dist	Dist	Male	5.67	5.67	3.00	2.00	1.50
5	Med	Dist	Male	2.67	1.33	2.00	3.67	2.33
5	Prox	Dist	Male	2.00	3.33	1.00	2.00	0.67
6	Dist	Dist	Male	6.33	2.00	0.67	1.33	1.00
6	Med	Dist	Male	1.67	0.00	0.67	0.33	0.00
6	Prox	Dist	Male	0.67	2.67	1.33	0.00	0.00
7	Dist	Prox	Male	6.00	0.67	2.00	0.00	0.33
7	Med	Prox	Male	15.33	4.67	3.33	1.00	0.67
7	Prox	Prox	Male	3.33	2.33	0.00	0.00	0.00
8	Dist	Prox	Male	2.00	2.33	0.33	0.00	0.00
8	Med	Prox	Male	7.33	5.67	1.00	1.67	3.67
8	Prox	Prox	Male	5.67	0.67	1.67	1.67	0.33

Appendix B

Script read to subjects in study

1. Introduction

In this experiment I am going to use an EMG, which senses the electrical activity of your muscles, to allow you to drive a remote control car. I will place pairs of electrodes over muscles in your lower arm, upper arm, and shoulder, and then ask you to contract those muscles in order to control the toy car and drive it through a course I have prepared. If you are ready now, I will begin placing the electrodes on your arm.

2. Calibration

With the electrodes now in place, we are going to calibrate the system. I will brace your arms so that the muscles will be in a constant position while we conduct the trial, and I am going to ask you to slowly contract each of the muscles we are using as hard as you can and then relax it in order to get a baseline reading for the system.

3. Signal training

I am now going to show you two live displays of the signals from your arms. Your dominant arm will be used to control the turning of the car, while your other arm will be used to control the forward and backward motion of the car.

The diagonal lines on the display represent the level of muscle contraction necessary to activate a control for the car, such as turning left or right on this first display and driving forward or back in the next display I will show you. The space between the lines represents the neutral actions of turning straight and stopping. As you contract the muscles of each arm, the dot on the screen will move up or to the right depending on which muscle you contract.

You may now try moving your arm to move the red dot around; when you are comfortable moving the dot into each area of the display we will move on.

I am now going to ask you to contract each muscle one at a time, attempting to move the red dot into each area of the display and holding it there for five seconds. When you are done, we will move on to the next step.

4. Control Training

I am now going to place the car inside this box. In order to learn to drive the car using these muscles, I am going to ask you to drive the car through a full 360° of rotation, either from one full turn in one direction or from two half turns in opposite directions. Please let me know if you feel that any adjustments should be made to the sensitivity of the controls. When you have completed this we will move on to the driving course.

5. Functional Training/Testing

When I tell you to begin, I want you to drive the car to the end of the course, alternating going to the right or left of each cone, beginning with going to the right of the first cone. I want you to try to complete the course as quickly as possible, and to drive as close to each cone as you can without hitting it on each turn. When you have completed the course, I will reset and we will conduct another trial.

6. Visual Analog Scale

Now that you have completed the course using this set of muscles, on a scale ranging from "very easy" to "very hard" please mark on this line how difficult you felt this task was.

Appendix C

Data Sheet used to collect study data

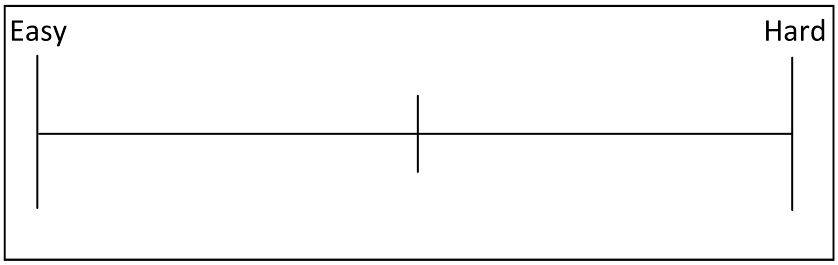
Subject Initials:__________ Age:_____ Handed:_____ Date:__________

Group:__________ Start Time:__________ End Time:__________

Turn	Trial 1		Trial 2		Trial 3	
	wall	cone	wall	cone	wall	cone
Distal						
1.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
2.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
3.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
4.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
5.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
6.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
7.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
8.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Time	________		________		________	
Medial						
1.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
2.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
3.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
4.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
5.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
6.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
7.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
8.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Time	________		________		________	
Proximal						
1.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
2.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
3.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
4.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
5.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
6.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
7.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
8.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Time	________		________		________	

Appendix D

Visual Analog Scale used in study



Appendix E

Code used by trainer device during study

```
//EMG Steering Program v. 2.6

#include "mbed.h"
#include "ConfigFile.h"

//Declarations
DigitalOut light1(LED1), light2(LED2), light3(LED3), light4(LED4);
DigitalOut reset(p10), carForward(p11), carBack(p12), carLeft(p13),
      carRight(p14);
AnalogIn leftInput(p15), rightInput(p16), forwardInput(p17), backInput(p18);
Serial pc(USBTX, USBRX);
LocalFileSystem local("local");
ConfigFile settings;
Timer timer1, timer2, t, l;

const int windowSize=100, baselineWindow=10, LEFT=1, RIGHT=2, FORWARD=3,
      BACK=4;
int thresholdTime;
float timeOffset=0;
bool fileOpen=false, collect=false, liveOut=false, override=true;
FILE *data;

class Input {
public:
    int input;
    float raw[3], filt[3], baseline[baselineWindow], rect[windowSize],
      baselineTotal, mid, rectTotal, smooth, amp, min, onThresh, offThresh;
    Input() {};
    Input(int num) {
        input=num;
        raw[0]=0;
        raw[1]=0;
        raw[2]=0;
        filt[0]=0;
        filt[1]=0;
        filt[2]=0;
        smooth=0;
        baselineTotal=0;
        rectTotal=0;
    };
```

```
};

void rectifier(int& i, Input& input);
void threshold(Input& left, Input& right, Input& forward, Input& back, bool
      override);
void printMenu();
void menu(Input& left, Input& right, Input& forward, Input& back);
void calibrateTurn(Input& left, Input& right);
void calibrateDrive(Input& forward, Input& back);
void editThresholds(Input& left, Input& right, Input& forward, Input& back);
void record(Input& left, Input& right, Input& forward, Input& back);
void display(Input& left, Input& right, Input& forward, Input& back);
void readSettings(Input& left, Input& right, Input& forward, Input& back);
void writeSettings(char* key, float value);
void driveLeft();
void driveRight();
void driveCenter();
void driveForward();
void driveBack();
void driveStop();
void reboot();

int main() {
    //Startup procedures - load settings from file and prime the arrays
    pc.baud(921600);
    timer1.start();
    timer2.start();
    l.start();
    Input left(LEFT), right(RIGHT), forward(FORWARD), back(BACK);
    readSettings(left, right, forward, back);
    for (int x=0; x<windowSize; x++) {
        left.baseline[x]=0;
        right.baseline[x]=0;
        forward.baseline[x]=0;
        back.baseline[x]=0;
        left.rect[x]=0;
        right.rect[x]=0;
        forward.rect[x]=0;
        back.rect[x]=0;
    }
    printMenu();

    //Main program loop
    while (1) {
        for (int i=0; i<windowSize; i++) {
            //Input raw data, filter, rectify, and smooth
            rectifier(i, left);
            rectifier(i, right);
            rectifier(i, forward);
```

```
            rectifier(i, back);

            //Threshold outputs from data
            threshold(left, right, forward, back, override);

            //Check for control commands
            menu(left, right, forward, back);

            //Write data to file
            record(left, right, forward, back);

            //Output for live data display
            if (i%50==0) display(left, right, forward, back);

            //Hold recording rate at 1000 Hz
            while (l.read_us()<999) {};
            l.reset();
        }
    }
}

void rectifier(int& i, Input& input) {
//Samples, 200 Hz 2nd order butterworth low-pass filters, rectifies, smooths,
      and normalizes incoming data
    input.raw[0]=input.raw[1];
    input.raw[1]=input.raw[2];
    input.filt[0]=input.filt[1];
    input.filt[1]=input.filt[2];
    if (input.input==LEFT) input.raw[2] = leftInput.read();
    else if (input.input==RIGHT) input.raw[2] = rightInput.read();
    else if (input.input==FORWARD) input.raw[2] = forwardInput.read();
    else if (input.input==BACK) input.raw[2] = backInput.read();
    input.filt[2]=(input.raw[0]+input.raw[2]+2*input.raw[1]-
      0.196*input.filt[0]+0.369*input.filt[1])/4.173;
    input.baselineTotal-=input.baseline[i%baselineWindow];
    input.baseline[i%baselineWindow]=input.filt[2];
    input.baselineTotal+=input.baseline[i%baselineWindow];
    input.mid=input.baselineTotal/baselineWindow;
    input.rectTotal-=input.rect[i];
    input.rect[i]=abs(input.filt[2]-input.mid);
    input.rectTotal+=input.rect[i];
    input.smooth=abs((input.rectTotal/windowSize-input.min)/(input.amp-
      input.min));
}

void threshold(Input& left, Input& right, Input& forward, Input& back, bool
      override) {
//Applies the thresholds to the incoming data to decide to turn left, right,
      or center and forward, back, or stop
```

```
    if (!override) {
        float turn=right.smooth-left.smooth;
        if (turn>right.onThresh) {
            driveRight();
            timer1.reset();
        } else if (turn<left.onThresh) {
            driveLeft();
            timer1.reset();
        } else if (carRight) {
            if (turn>right.offThresh) timer1.reset();
            else if (timer1.read_ms()>thresholdTime) driveCenter();
        } else if (carLeft) {
            if (turn<left.offThresh) timer1.reset();
            else if (timer1.read_ms()>thresholdTime) driveCenter();
        }
        float drive=forward.smooth-back.smooth;
        if (drive>forward.onThresh) {
            driveForward();
            timer2.reset();
        } else if (drive<back.onThresh) {
            driveBack();
            timer2.reset();
        } else if (carForward) {
            if (drive>forward.offThresh) timer2.reset();
            else if (timer2.read_ms()>thresholdTime) driveStop();
        } else if (carBack) {
            if (drive<back.offThresh) timer2.reset();
            else if (timer2.read_ms()>thresholdTime) driveStop();
        }
    }
}

void printMenu() {
//Prints the options for the main menu
    pc.printf("\n\n\n");
    pc.printf("Main Menu\n");
    pc.printf(" space - toggle data recording\n");
    pc.printf(" C     - begin calibration\n");
    pc.printf(" T     - edit threshold levels\n");
    pc.printf(" O     - toggle car control override\n");
    pc.printf(" R     - reset\n\n");
}

void menu(Input& left, Input& right, Input& forward, Input& back) {
//Menu for keyboard control by serial connection
    if (pc.readable()) {
        char cal=pc.getc();
        if (cal==' ') {
            collect=!collect;
```

```
            if (collect) {
                override=false;
                pc.printf("\nCar control: USER\n");
            } else {
                override=true;
                driveStop();
                driveCenter();
                pc.printf("\nCar control: KEYBOARD\n");
            }
        } else if (cal=='c') {
            pc.printf("\n  1 - Calibrate turning\n  2 - Calibrate driving\n
      ");
            cal=pc.getc();
            if (cal=='1') calibrateTurn(left, right);
            else if (cal=='2') calibrateDrive(forward, back);
            printMenu();
        } else if (cal=='r') {
            reboot();
        } else if (cal=='x') {
            liveOut=!liveOut;
            if (liveOut) {
                l.start();
                l.reset();
            }
        } else if (cal=='t') {
            editThresholds(left, right, forward, back);
            printMenu();
        } else if (cal=='o') {
            override=!override;
            if (override) {
                driveStop();
                driveCenter();
                pc.printf("\nCar control: KEYBOARD\n");
            } else pc.printf("\nCar control: USER\n");
        }
        if (override) {
            if (cal=='w') driveForward();
            else if (cal=='a') driveStop();
            else if (cal=='s') driveBack();
            if (cal=='j') driveLeft();
            else if (cal=='k') driveCenter();
            else if (cal=='l') driveRight();
        }
    }
}

void calibrateTurn(Input& left, Input& right) {
//sets the values used for scaling incoming data for the left-right inputs
    left.amp=0.0;
```

```
    right.amp=0.0;
    left.min=1.0;
    right.min=1.0;
    pc.printf("\nLeft/Right Calibration\n Press any key to begin\n");
    pc.getc();
    pc.printf("\nCalibration in progress\n Press any key to finish\n");
    float leftAmp, rightAmp, leftRaw=0, rightRaw=0;
    while (!pc.readable()) {
        for (int x=0; x<windowSize; x++) {
            rectifier(x, left);
            rectifier(x, right);
        }
        if (abs(left.filt[2]-left.mid)>leftRaw) leftRaw = 2*abs(left.filt[2]-
      left.mid);
        if (abs(right.filt[2]-right.mid)>rightRaw) rightRaw =
      2*abs(right.filt[2]-right.mid);
        leftAmp=left.rectTotal/windowSize;
        rightAmp=right.rectTotal/windowSize;
        if (leftAmp > left.amp) left.amp = leftAmp;
        if (leftAmp < left.min) left.min = leftAmp;
        if ( rightAmp > right.amp) right.amp = rightAmp;
        if ( rightAmp < right.min) right.min = rightAmp;
    }
    pc.getc();
    pc.printf("Calibration complete\n  Left: %.2f\n  Rght: %.2f\n", leftRaw,
      rightRaw);
    writeSettings("leftAmp", left.amp);
    writeSettings("rightAmp", right.amp);
    writeSettings("leftMin", left.min);
    writeSettings("rightMin", right.min);
}

void calibrateDrive(Input& forward, Input& back) {
//sets the values uesd for scaling incoming data for the forward-back inputs
    forward.amp=0.0;
    back.amp=0.0;
    forward.min=1.0;
    back.min=1.0;
    pc.printf("\nForward/Back Calibration\n Press any key to begin\n");
    pc.getc();
    pc.printf("\nCalibration in progress\n Press any key to finish\n");
    float forwardAmp, backAmp, forwardRaw=0, backRaw=0;
    while (!pc.readable()) {
        for (int x=0; x<windowSize; x++) {
            rectifier(x, forward);
            rectifier(x, back);
        }
        if (abs(forward.filt[2]-forward.mid)>forwardRaw) forwardRaw =
      2*abs(forward.filt[2]-forward.mid);
```

```
        if (abs(back.filt[2]-back.mid)>backRaw) backRaw = 2*abs(back.filt[2]-
      back.mid);
        forwardAmp=forward.rectTotal/windowSize;
        backAmp=back.rectTotal/windowSize;
        if (forwardAmp > forward.amp) forward.amp = forwardAmp;
        if (forwardAmp < forward.min) forward.min = forwardAmp;
        if (backAmp > back.amp) back.amp = backAmp;
        if (backAmp < back.min) back.min = backAmp;
    }
    pc.getc();
    pc.printf("Calibration complete\n  Fwd:  %.2f\n  Back: %.2f\n",
      forwardRaw, backRaw);
    writeSettings("forwardAmp", forward.amp);
    writeSettings("backAmp", back.amp);
    writeSettings("forwardMin", forward.min);
    writeSettings("backMin", back.min);
}

void editThresholds(Input& left, Input& right, Input& forward, Input& back) {
//Interface to change the threshold settings from the command window
    bool loop=true;
    int input=1, thresh=1;
    while (loop) {
        pc.printf("\n\n\n\n\n\n\n\n\n\n\n\n\n\n\nThreshold Levels\n\n");
        pc.printf("     L-1  R-2  F-3  B-4\n");
        pc.printf("on  %.2f %.2f %.2f %.2f\n", left.onThresh*-1.0,
      right.onThresh, forward.onThresh, back.onThresh*-1.0);
        pc.printf("off %.2f %.2f %.2f %.2f\n\n", left.offThresh*-1.0,
      right.offThresh, forward.offThresh, back.offThresh*-1.0);
        char in=pc.getc();
        if (in=='1') input=LEFT;
        else if (in=='2') input=RIGHT;
        else if (in=='3') input=FORWARD;
        else if (in=='4') input=BACK;
        else if (in=='q') thresh=1;
        else if (in=='a') thresh=2;
        else if (in=='-') {
            if (thresh==1) {
                if (input==LEFT) {
                    left.onThresh+=0.05;
                    writeSettings("leftOnThresh", left.onThresh*-1.0);
                }
                if (input==RIGHT) {
                    right.onThresh-=0.05;
                    writeSettings("rightOnThresh", right.onThresh);
                }
                if (input==FORWARD) {
                    forward.onThresh-=0.05;
                    writeSettings("forwardOnThresh", forward.onThresh);
```

```
            }
            if (input==BACK) {
                back.onThresh+=0.05;
                writeSettings("backOnThresh", back.onThresh*-1.0);
            }
        } else if (thresh==2) {
            if (input==LEFT) {
                left.offThresh+=0.05;
                writeSettings("leftOffThresh", left.offThresh*-1.0);
            }
            if (input==RIGHT) {
                right.offThresh-=0.05;
                writeSettings("rightOffThresh", right.offThresh);
            }
            if (input==FORWARD) {
                forward.offThresh-=0.05;
                writeSettings("forwardOffThresh", forward.offThresh);
            }
            if (input==BACK) {
                back.offThresh+=0.05;
                writeSettings("backOffThresh", back.offThresh*-1.0);
            }
        }
    } else if (in=='=') {
        if (thresh==1) {
            if (input==LEFT) {
                left.onThresh-=0.05;
                writeSettings("leftOnThresh", left.onThresh*-1.0);
            }
            if (input==RIGHT) {
                right.onThresh+=0.05;
                writeSettings("rightOnThresh", right.onThresh);
            }
            if (input==FORWARD) {
                forward.onThresh+=0.05;
                writeSettings("forwardOnThresh", forward.onThresh);
            }
            if (input==BACK) {
                back.onThresh-=0.05;
                writeSettings("backOnThresh", back.onThresh*-1.0);
            }
        } else if (thresh==2) {
            if (input==LEFT) {
                left.offThresh-=0.05;
                writeSettings("leftOffThresh", left.offThresh*-1.0);
            }
            if (input==RIGHT) {
                right.offThresh+=0.05;
                writeSettings("rightOffThresh", right.offThresh);
```

```
                }
                if (input==FORWARD) {
                    forward.offThresh+=0.05;
                    writeSettings("forwardOffThresh", forward.offThresh);
                }
                if (input==BACK) {
                    back.offThresh-=0.05;
                    writeSettings("backOffThresh", back.offThresh*-1.0);
                }
            }
        } else if (in=='0') loop=false;
    }
}

void record(Input& left, Input& right, Input& forward, Input& back) {
//Record data to local file
    if (collect) {
        if (!fileOpen) {
            data = fopen("/local/data.dat", "w");
            pc.printf("File open\n");
            fileOpen=true;
            timeOffset=0;
            t.start();
            t.reset();
        }
        fprintf(data, "%.2f%.2f%.2f%.2f\n", left.smooth, right.smooth,
      forward.smooth, back.smooth);
        if (l.read_us()>999) timeOffset+=l.read()-0.001;
    } else if (fileOpen) {
        t.stop();
        float x=t.read();
        fprintf(data, "\n%f\n%f\n", x, x-timeOffset);
        fclose(data);
        pc.printf("File closed\n");
        fileOpen=false;
    }
}

void display(Input& left, Input& right, Input& forward, Input& back) {
//Output for live display of data
    if (liveOut) pc.printf("%.2f%.2f%.2f%.2f!", left.smooth, right.smooth,
      forward.smooth, back.smooth);
}

void readSettings(Input& left, Input& right, Input& forward, Input& back) {
//reads in the program values stored in the settings file
    char value[BUFSIZ];
    settings.read("/local/settings.cfg");
```

```
    if (settings.getValue("leftAmp", &value[0], sizeof(value))) left.amp =
      atof(value);
    if (settings.getValue("rightAmp", &value[0], sizeof(value))) right.amp =
      atof(value);
    if (settings.getValue("forwardAmp", &value[0], sizeof(value)))
      forward.amp = atof(value);
    if (settings.getValue("backAmp", &value[0], sizeof(value))) back.amp =
      atof(value);
    if (settings.getValue("leftMin", &value[0], sizeof(value))) left.min =
      atof(value);
    if (settings.getValue("rightMin", &value[0], sizeof(value))) right.min =
      atof(value);
    if (settings.getValue("forwardMin", &value[0], sizeof(value)))
      forward.min = atof(value);
    if (settings.getValue("backMin", &value[0], sizeof(value))) back.min =
      atof(value);
    if (settings.getValue("thresholdTime", &value[0], sizeof(value)))
      thresholdTime = atoi(value);
    if (settings.getValue("leftOnThresh", &value[0], sizeof(value)))
      left.onThresh = atof(value)*-1.0;
    if (settings.getValue("rightOnThresh", &value[0], sizeof(value)))
      right.onThresh = atof(value);
    if (settings.getValue("forwardOnThresh", &value[0], sizeof(value)))
      forward.onThresh = atof(value);
    if (settings.getValue("backOnThresh", &value[0], sizeof(value)))
      back.onThresh = atof(value)*-1.0;
    if (settings.getValue("leftOffThresh", &value[0], sizeof(value)))
      left.offThresh = atof(value)*-1.0;
    if (settings.getValue("rightOffThresh", &value[0], sizeof(value)))
      right.offThresh = atof(value);
    if (settings.getValue("forwardOffThresh", &value[0], sizeof(value)))
      forward.offThresh = atof(value);
    if (settings.getValue("backOffThresh", &value[0], sizeof(value)))
      back.offThresh = atof(value)*-1.0;
}

void writeSettings(char* key, float value) {
//writes a value to the settings file
    char buffer[10];
    sprintf(buffer, "%f", value);
    settings.setValue(key, buffer);
    settings.write("/local/settings.cfg");
}

void driveLeft() {
//turn left
    carRight=0;
    light2=0;
    carLeft=1;
```

```
    light1=1;
}

void driveRight() {
//turn right
    carLeft=0;
    light1=0;
    carRight=1;
    light2=1;
}

void driveCenter() {
//turn straight
    carLeft=0;
    light1=0;
    carRight=0;
    light2=0;
}

void driveForward() {
//drive forward
    carBack=0;
    light4=0;
    carForward=1;
    light3=1;
}

void driveBack() {
//drive back
    carForward=0;
    light3=0;
    carBack=1;
    light4=1;
}

void driveStop() {
//stop driving
    carForward=0;
    light3=0;
    carBack=0;
    light4=0;
}

void reboot() {
//reboots controller
    pc.printf("Resetting\n");
    reset=0;
    wait(.25);
    reset=1;
```

```
    wait(.25);
}

/*
Version History:
1.0 - First functional two input program for steering the remote control car
2.0 - Reworked organization of EMG collection algorithm
        - switched to triangle smoothing algorithm instead of rectangular
        - reworked calibration from manually activated function to first five
      seconds of program running
    - Added serial connection to PC via USB for data collection and control
2.1 - Implement file access and computer control
        - Startup variables stored in file rather than hard-coded
        - Enable restart without recalibration
        - Variables modifiable by serial menu
    - Reworked rectifier to detect high frequency noise and resample
2.2 - Modified to use four inputs to control forward and back as well as left
      and right
    - Removed non-essential diagnostic output functions
    - Fixed bugs with noise detection and smoothed signal windowing
    - Moved from a one stage calibration to a two stage calibration as well
      as minor improvements in calibration algorithm
    - Switched back to rectangular smoothing algorithm
    - Modified thresholding to use an upper threshold to trigger output and a
      lower threshold with a time delay to turn it off
2.3 - Modified rectifying algorithm from using min and max to find the mean
      and scaling factor to having a fixed mean and using amplitude
    - Added EMG data collection to local storage
    - Changed filtering to a second order Butterworth low pass filter with a
      200 Hz cutoff
    - Optimized for a 100 sample window to yield a 1000 Hz sampling rate and
      100 ms smoothing window while recording
    - Switched to using an object to hold all of the variables associated
      with an input channel
    - Modified thresholding to remove bias toward one muscle group
    - Modified calibration from a button activated automation to keyboard
      operation
    - Added code to remove the DC offset from the smoothed signal
2.4 - Added output for real time EMG display and associated control
    - Reworked collection algorithm to remove baseline wander during
      rectification
    - Optimization of algorithm to use a running total for smoothing instead
      of continuously recalculating
    - Made settings to control on and off thresholds separately
    - Added override capability for keyboard control of car
    - Removed normalization after rectification, using single normalization
      after smoothing only - single step calibration
2.5 - Set sampling rate at 1000 Hz using timers
    - Changed live output to static 20 Hz
```

```
    - Reorganized program layout
    - Added threshold editing interface
2.6 - Changes to displayed menus
*/
```

Appendix F

Code for live display of subject EMG levels

```
Imports System.IO.Ports
Imports Excel = Microsoft.Office.Interop.Excel
Public Class Form1
    Dim excelApp As Excel.Application
    Dim excelBook As Excel.Workbook
    Dim excelSheet As Excel.Worksheet
    Dim WithEvents serial As New SerialPort
    Dim stream As String = "0.000.000.000.00"
    Dim fileOpen As Boolean = False

    Private Sub Form1_Load(ByVal sender As Object, ByVal e As System.EventArgs) Handles
Me.Load
        If serial.IsOpen = True Then serial.Close()
        With serial
            .PortName = "COM14"
            .BaudRate = 921600
            .DataBits = 8
            .Parity = Parity.None
            .StopBits = StopBits.One
            .Handshake = Handshake.None
            .NewLine = "!"
        End With
        'serial.ReceivedBytesThreshold = 1
        StatusLabel.Text = "Status: Ready"
    End Sub

    Private Sub AcquireDataButton_Click() Handles AcquireDataButton.Click
        If IsNothing(excelBook) Then
            StatusLabel.Text = "Open file first."
        Else
            If serial.IsOpen = False Then
                StatusLabel.Text = "Status: Acquiring"
                Try
                    serial.Open()
                    serial.DiscardInBuffer()
                    excelSheet.Range("A1:A300").Clear()
                    serial.Write("x")
                Catch ex As Exception
                    StatusLabel.Text = "Error: Serial port in use."
                End Try
            Else
                serial.ReadLine()
            End If
        End If
    End Sub
```

```
    Private Sub StopButton_Click() Handles StopButton.Click
        Try
            serial.Write("x")
        Catch
        End Try
        If serial.IsOpen = True Then serial.Close()
        StatusLabel.Text = "Status: Stopped"
    End Sub

    Private Sub serial_datareceived(ByVal sender As Object, ByVal e As
System.IO.Ports.SerialDataReceivedEventArgs) Handles serial.DataReceived
        Try
            excelSheet.Cells(1, 1) = serial.ReadLine()
        Catch
        End Try
    End Sub

    Private Sub OpenFileButton_Click() Handles OpenFileButton.Click
        If fileOpen = False Then
            excelApp = New Excel.Application
            excelApp.Visible = True
            excelApp.UserControl = True
            excelBook = excelApp.Workbooks.Open("C:\Dropbox\BME Research\mBed\Serial
Display\EMG Display.xlsx")
            excelSheet = excelBook.Worksheets("Sheet1")
            fileOpen = True
        End If
    End Sub

    Private Sub CloseFileButton_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles CloseFileButton.Click
        If fileOpen = True Then
            Try
                excelBook.Save()
                excelBook.Close()
                excelApp.Quit()
                excelApp = Nothing
                excelBook = Nothing
                excelSheet = Nothing
            Catch
            End Try
            fileOpen = False
        End If
    End Sub

    Private Sub ResetButton_Click(sender As System.Object, e As System.EventArgs) Handles
ResetButton.Click
        Try
            serial.Open()
            serial.DiscardInBuffer()
            serial.Write("r")
            serial.Close()
        Catch
            StatusLabel.Text = "Error: Serial port in use."
        End Try
    End Sub
End Class
```