Development of a software program to train individuals to use myoelectric prostheses

by

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Signatures have been redacted for privacy
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Computer Testing

Computer Test 1: Arm up, relax to freeswing
Computer Test 2: Arm up, force down with triceps
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In today’s technological world, there is a push toward using computers to help with instruction and training. In 1990, a computer software program was developed and tested to train children how to control myoelectric motors. In this thesis the development of a software program that trains adults to control myoelectric prostheses is discussed. An inverting circuit, a microprocessor, and other electronics help send electromyographic (EMG) signals from electrodes connected to the arm to a personal computer to be processed by the Myotrain software program.

Using Motion Control's training procedures for training individuals to use the Utah Arm, the software program models the Utah Arm 2 and teaches individuals how to control an above-elbow myoelectric prosthesis. The software uses training instructions and feedback, and gives ample time for learning and practice.

Five experimental subjects were instructed on operating a myoelectric prosthesis using the software program. Five control subjects were instructed on the use of the Utah Arm at-elbow as is currently done for training new prosthetic users. After two days of training, all ten subjects returned a third day and were tested on the Utah Arm and on the software to determine success levels by each subject.

All subjects showed improvement of skill over time. Users trained only on the software were able to control a myoelectric prosthesis when tested on the third day. The software was successful in teaching adults to move the Utah Arm. There was no significant difference between the abilities of the control and experimental groups in controlling the Utah Arm.

This study shows that software trainers can be used to train adults to use myoelectric prostheses. With this innovation, potential myoelectric users will be able to practice using a prosthesis before they are fitted with one.
INTRODUCTION

History of Prostheses

For centuries, prosthetic devices for upper-limb amputees or individuals with upper-limb defects have been needed. During the Medieval Period, surgeons tried to transplant limbs so that amputees could have an “artificial” limb [10]. In 16th century Rome, individuals were fitted with an artificial bronze arm [10]. Since that time, many technological advances have occurred which help individuals without limbs to live a more normal lifestyle.

Lighter materials such as composite plastics and graphite composites have replaced the heavier metals that were used for earlier prostheses. These lighter materials enable prosthetic users to have more mobility and a more life-like artificial arm. In the 1950s body powered prostheses were common for prosthetic users [19] [20]. These limbs typically consist of a cable that is attached to a shoulder harness (Fig. 1). When the user moves his or her shoulder forward, the terminal device (TD) on the end of the arm opens. This TD is usually a hook used for grasping purposes. These devices are still common and it is estimated that 90% of upper-limb amputees wear this type of conventional device [11].

Since the 1950s, researchers have tried to find ways to interface biological muscle and nerve signals to control artificial arms. Wiener in 1948 suggested, in his book

![Front View Back View](image-url)

**Figure 1.** Since the 1950s, shoulder harnesses have been common in artificial arms to help control a terminal device (TD) such as a hook.
Cybernetics, that biological signals could be used to control devices. Rieter was the first to develop a hand that was controlled by electromyographic (EMG) signals [4] [22]. Since Rieter’s development, many other advances have been made. Jacobsen and others named a few of the advances that occurred: IBM arm, Russian EMG controlled hand, Viennatone hand, Boston elbow from Massachusetts Institute of Technology, Veterans Administration elbow, Boston elbow from Liberty Mutual Insurance Company Research Center, Otto Bock hand, Fidelity hand, Italian arm, New York University elbow, Variety Village elbow, Utah arm, Japanese research, Otto Bock pincer [4].

Each of these advances and developments created devices that were controlled by myoelectric signals. The EMG signals controlled motors in the elbow joint of the prosthesis, or in the hand or terminal device of the arm. Since the initial research developments of the 1950s, more commercial myoelectric devices have been placed on the market for amputees to use. Three examples include: the Utah Arm (Fig. 2), the Boston Elbow, and the ProControl Arm (Fig.

Figure 2. The Utah Arm 2 is one of the commercial arms that has been available to above-elbow amputees since the 1980s. Used by permission from Motion Control.
Motion Control in Salt Lake City, Utah manufactures the Utah Arm and the ProControl Arm, while Liberty Mutual Insurance Company manufactures the Boston Elbow. Each of these prosthetic limbs targets upper-limb amputees. These amputees are either above-elbow or below-elbow amputees, depending on the location of the arm amputation with respect to the elbow. (Reference to amputee in this thesis will address individuals who have lost use of their arm due to amputation, birth defect, or other causes.)

![Figure 3.](image)

**Figure 3.** This below-elbow myoelectric prosthesis is known as the ProControl 2 Arm. It has both a hand and wrist motor with myoelectric control. *Used by permission from Motion Control.*

The basic function of the externally powered myoelectric prosthesis is to control motors in the prosthesis with the contraction of remnant muscles. The commercial myoelectric arms mentioned use this approach to control the movements of the individual's prosthesis. One method of control for a myoelectric arm uses a set of electrodes placed over opposing muscle groups, such as the biceps and triceps. When the user contracts either muscle group, the motors in the arm will move forward or backward depending on the muscle group contracted, and the strength and timing of the signal. Microprocessors and electronic controls in the prosthetic arm facilitate the operation of the motors and allow the arm to be controlled in a set fashion. Most arms, whether
above-elbow or below-elbow, will provide control for at least two motors. Typically, an above-elbow prosthesis (Fig. 2) controls an elbow motor to bend the elbow up and down and a hand motor to open and close the hand. A below-elbow prosthesis (Fig. 3) will usually have a hand motor and a wrist motor. The latter will cause the wrist to rotate. To rotate the wrist on an above-elbow prosthesis that is not equipped with a wrist motor, the user must manually turn the wrist to the desired position before opening or closing the hand.

There are about 10,000 new upper extremity amputees each year [20], but only about 5,000 receiving some type of prosthetic device to replace their arm [12]. These 5,000 individuals represent about 5% of the work performed by prosthetists in the United States [13]. The market for upper-limb prostheses is not one of high-volume demand; therefore, many investors and researchers do not spend as much time and money in this industry as in lower-limb industries [13] [4]. As mentioned before, 90% of prosthesis users use body-powered prostheses instead of myoelectric prostheses [11] [21].

**History of Training**

Even with the small number of myoelectric users each year and few myoelectric arms on the market, there exists a need to train users to control a myoelectric prosthesis. A prosthetist and therapist are involved in training an individual to control the prosthesis. The training procedure and amount of time taken to train individuals depend on many variables such as user motivation, training protocol, and ease of learning by the user [14]. The therapist usually does the majority of the training with the individuals and usually sits at-elbow with him or her to provide immediate feedback and assistance.

Three steps are normally taken in the training procedure: basic control training, use training, and activities of daily living (ADL) training [9] [14]. First, therapists and prosthetists teach the individual how to create the best difference between opposing EMG signals and find the optimal location for the electrodes.
Following this procedure, the individual is trained on the basic control features of a prosthesis, such as flexing and extending the elbow. Use training includes instructing the user on how to control the prosthesis to pick up objects, place objects, or to pre-position the arm for different functions. The final part of training is teaching the user to utilize the arm in scenarios that are part of his or her daily routine. Some examples may include hammering a nail, cracking an egg, or saddling a horse.

There is no standard training protocol that is documented for all therapists to use. The only standard for training that exists is the accreditation of the different orthotic and prosthetic (O&P) educational programs by The National Commission on Orthotic and Prosthetic Education (NCOPE). NCOPE certifies the different educational programs to make sure that they are teaching future prosthetists and orthotists the necessary information to be thorough and efficient in their profession.

Over the years of myoelectric prosthesis use, there have been some advances in training that take advantage of growing computer technologies. A microcomputer trainer was developed by Lovely to help trainers combine the functions of many prosthetic devices into one computerized trainer. [17]. In 1990, D.F. Lovely and others published results on a computer-aided training system for helping young children learn to control myoelectric devices. Their computer program included games that allowed children to control a computer screen cursor with both a joystick and myoelectric signals. Other innovative trainers include a visual feedback trainer created by scientists in Australia which gives feedback via light emitting diodes (LEDs) depending on the sequences of contractions and operations of the arm [15]. Motion Control has created a software trainer that will allow a user to see the contractions and signals coming directly from their ProControl arm as they are using it. The software also allows a user to set certain controls through a computer rather than having to turn manual dials on the arm [7] [13].
The main aim for those trying to develop more advanced training systems is to help the users have a more natural, efficient, and effective way to learn to use a myoelectric prosthesis [13].

Software Trainer

As automation and computer use increase, there is a push in the myoelectric industry to create devices that will help train individuals to control myoelectric prostheses. Lovely’s software program that taught children to use myoelectric signals to control a cursor on a computer monitor [16] was a step toward computer-based training. Since their work, there has been little progress in the way of computer-based training. Motion Control’s new ProControl 2 system allows users to see signals produced from muscle contractions and arm movements, but it does not take them through a training procedure to learn to use and control the prosthetic device [7].

A computer-based myotrainer would be useful to prosthetic users because they would be able to learn to use a myoelectric prosthesis before they are fitted for one. Learning how to read and understand EMG signals and their function in control sequences can help the user to decide if a myoelectric prosthesis would be appropriate for his or her needs. With a computer program, potential myoelectric users could be trained while waiting for the arm to be fitted, saving time by decreasing the amount of time spent testing and learning at-elbow with a therapist. A trainer of this type will not replace the therapist, but serve as a supplement to reinforce the principles used in training for myoelectric use. Ultimately, the software trainer may help the user become more independent, reduce costs associated with training and fitting, and allow a user to obtain feedback when a prosthetist or therapist is not present during the personalized training.
Thesis Statement

A personal computer with an appropriate software trainer and arm model can teach adults how to control a myoelectric prosthesis. This thesis describes the development of such a trainer and shows its effectiveness by comparing the results of subjects trained with the software trainer and subjects trained by traditional methods.
METHODS AND MATERIALS

Four parts were involved in developing the software trainer: electronics, software programming, training procedure protocols, and experimental setup. The following part of this thesis will explain how these four areas were developed and prepared for experimental use.

Electronics

The electronic setup of the experiment consisted of interfacing the myoelectric potentials in the user’s muscles with the serial port of the PC where the software trainer was loaded (Fig. 4). The hardware between the muscles and the PC included:

![Diagram of experimental setup](image)

**Figure 4.** Five components of the experimental setup. The electrodes carried the EMG signal to the Myolab II for analog processing. The inverting circuit and Handy Board further processed the signal and converted it to a digital signal that was serially sent to the PC and interpreted by the Myotrain software program.
- Myolab II myotester with electrodes and preamplifiers
- Inverting circuit
- Handy Board for analog to digital (A/D) conversion

This equipment read the EMGs when the user contracted his or her arm muscles and converted them into digital signals that could be read by the PC software trainer.

**Myolab II**

A Myolab II (Motion Control, Salt Lake City, UT) (Fig. 5) was used to read the analog signals from the electrodes. It is a myotester that is used by some therapists to help train individuals to find optimal EMG sites for electrode placement to control a myoelectric arm. The Myolab II consists of electrodes (input), analog display dials (output), muscle frequency sound outputs, and a signal output line.

**Electrodes**

Included with the Myolab II myotester was a pair of horizontal bar electrodes, each containing three stainless-steel electrodes for positive (+), negative (-) and ground leads (Fig. 6). Each bar can be placed over an opposing muscle group such as the flexor and extensor muscles of the forearm and used to control the myoelectric arm. The two end electrodes pick up electrical potentials.
that occur in the muscles during contraction. The middle electrode is a ground or reference electrode for the other two [8].

Electrodes are ideally placed on antagonist muscles (i.e., biceps and triceps) in order to control the prosthesis [19]. One muscle’s signal will cause the prosthesis joint to flex. The other muscle’s EMG will cause the joint to extend. The three electrodes on the horizontal bar are similar to electrode placement inside the socket of most prosthetic devices (Fig. 7). The electrodes used in the experiment were connected to preamplifiers to help amplify the weak EMG signals (Fig. 6).
Two horizontal bars of electrodes were used on the subjects, one on each muscle group (Fig. 8). The electrodes were placed over the muscles, and contractions were induced to produce EMG signals. These signals were evaluated until the best difference between biceps and triceps contractions was found. This difference was necessary to be able to control the Utah Arm efficiently. When strong signals were located with the electrodes, these locations were marked as optimal sites for EMG measurements.

**Preamplifiers**

Normally the signal frequency for EMG signals ranges from 25 Hz to several kilohertz (kHz) and the voltage ranges from 100 µV to 90 mV [1]. These voltages are normally too small to be detected and seen clearly; therefore, most EMG signals are amplified. The Myolab II’s preamplifiers, mounted inside the horizontal bar, allowed the signal to be amplified at a gain of about 375 at 300 Hz [25]. This gain produces a signal in the range of 0.1-1.0 V in the Myolab.

The basic configuration of the electrodes allows the user to hold the electrode bar to his or her arm while muscles are contracted. Voltage potentials from the contracting muscles are picked up by the electrodes and amplified by...
the preamplifiers. From the preamplifiers, the signal is differenced with the opposing muscle's signal and the differentiated signal is amplified. This final signal is seen on the Myolab II's analog dial display. It can also be detected as a voltage on the output line of the Myolab (Fig. 9).

**Figure 9.** Explanation of the Myolab II's ports found in the battery component of the myotester. Ports 4, 5, 6 were used for the output signal to the inverting circuit.

**Signal from the Myolab II output**

The output port used on the Myolab II is normally used by therapists to control one of Motion Control's myoelectric arms during training and troubleshooting exercises with a client. The port allows a user to read the signals that are coming into the Myolab II from the electrodes. Two of the signals that come out of the Myolab II output port are processed signals for each channel (A and B). The processed signals are inverted with a range from 0 to -2 V when the Myolab II gain dials are set at 10. The needle on the front of the Myolab measures the signal from the electrodes and preamplifiers with a range from 0 to 200%, but only 0 to 100% is displayed on the dial.
The Myolab II also has gain controls to fine-tune the strength of signal in each muscle group. The gains range from 0-12, with the “normal” setting being 10 [25]. This gain setting of 10 produces a reading of −1 V from the output port during a contraction that reached 100% on the dials of the analog output display on the front of the Myolab II. When the gain is set at 10 and a contraction is showing 100 on the display, this would correspond to 100 µV coming from the electrodes and preamplifiers (a factor of 1/1000 of the processed signal). An additional electrical circuit (Fig. 10) was created to invert the Myolab II's signal and amplify it for reading the signal on the A/D converter of the Motorola 68HC11 microcontroller (Fig. 11).

Figure 10. Inverting circuit used for both EMG channels. The circuit inverted the Myolab II's output signal and amplified it by a gain of 2 so that the Handy Board’s A/D converter could process the analog signal.
The analog signal from the Myolab II was ultimately read by an A/D converter on the Handy Board, a microcontroller based on the Motorola 68HC11 chip and created by Fred Martin [5]. The negative voltage from the Myolab had to be inverted and amplified by a separate circuit (Fig. 10) to achieve optimal reading by the A/D converter. The circuit was a standard amplification circuit using an LM741 operational amplifier (op amp), a 220 KΩ resistor, and a 500 KΩ potentiometer. The op amp was powered by ± 5 V, supplied by the combination of two 9 V batteries and two LM 7805 voltage regulators (Fig. 12). The voltage to the op amp was kept at 5 V because the highest recommended voltage entering the A/D converter of the 68HC11 microcontroller was 6 V [27].

Using the inverting circuit also reduced the risk of electrical shock to the individual because it was another path through which an unexpected and unlikely voltage spike from the PC’s alternating current (AC) would have to travel before it reached the electrodes on the individual. Furthermore, by using 9 V batteries, the use of an AC power adapter to power the circuit was avoided. An AC power adapter could potentially introduce unwanted voltages and threaten electrical shock.
Handy Board and Motorola controller

The A/D converter on the Handy Board sent the digital values of the myoelectric signals over the serial port to the PC. The Handy Board was programmed for A/D conversion and serial communication using Interactive C (IC), a computer language similar to C.

The Handy Board's A/D converter has a range from 0 to 5 V (0 V = 0 bits, 5 V = 255 bits) [5]. Since the signal output from the Myolab II ranges from 0 to -2 V, the inverting circuit used in the experiment amplified the signal with a gain of 2. This amplification gave a signal of 0 to 4 V from the inverting circuit to the A/D converter. This range of analog voltage corresponded to digital values in the range of 0 to 204.10, or a resolution of 19.6 mV per bit (Table 1) [26]. The remaining 41 bits not used in the A/D conversion could be used in the future for finer resolution or control signals and applications between the controller and the PC.
Table 1. Conversion table for determining voltage and relative strengths of contraction. Resolution of the analog to digital converter is 1 bit = 19.6 mV. The Myolab II displayed a relative range from 0 to 2 V and the Myotrain software displayed a range from 0 to 4 V.

<table>
<thead>
<tr>
<th>Volts</th>
<th>Digital Bits</th>
<th>Myolab II Display</th>
<th>Myotrain Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>0.50</td>
<td>25</td>
<td>25%</td>
<td>13%</td>
</tr>
<tr>
<td>1.00</td>
<td>51</td>
<td>50%</td>
<td>25%</td>
</tr>
<tr>
<td>1.50</td>
<td>76</td>
<td>75%</td>
<td>38%</td>
</tr>
<tr>
<td>2.00</td>
<td>102</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td>2.50</td>
<td>127</td>
<td>100%</td>
<td>63%</td>
</tr>
<tr>
<td>3.00</td>
<td>153</td>
<td>100%</td>
<td>75%</td>
</tr>
<tr>
<td>3.50</td>
<td>178</td>
<td>100%</td>
<td>88%</td>
</tr>
<tr>
<td>4.00</td>
<td>204</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>4.50</td>
<td>229</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>5.00</td>
<td>255</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Analog signals from each electrode (Fig. 13) were input to the analog ports 0 and 1 of the Handy Board (Fig. 11). A program was written by Scott Openshaw to read the analog signals and convert them to digital. Once in digitized form, values were sent serially to the PC to be read and processed by the Myotrain software.

Handy Board

Inverting Circuit

Myolab II

Electrodes from arm

Figure 13. Path that the EMG signals took to be digitized and read by the PC.
Embedded software for the Handy Board

Figure 14 shows part of the program that read the analog signal, converted it to a digital signal, and then sent it to the serial port. To be able to communicate with the PC's serial port, extra code had to be added to the IC program written by Scott Openshaw. This additional code was created by Randy Sargent and published on the MIT web site [5].

Initially the PC had trouble reading the signals during contractions when either port on the Handy Board read a zero voltage signal. When the Myotrain software tried to read the zero value, it prevented the dial meter in the training window from moving. To solve this problem, a value of 1 bit was added to the serial_putchar function for both channels (Fig. 14). Because of this, each value read by the software was 1 bit greater than the true voltage reading.

```c
void main()
{
    int i;
    disable_pcode_serial();
    poke(0x1030,0x10);
    poke(0x1039,0x80);
    while(1)
    {
        while (!(peek(0x1030) & 0x80)); /* poll for a/d to say done */
        serial_putchar(255);
        i = peek(0x1031);
        serial_putchar(i+1);            /* send Channel A value to serial port */
        serial_putchar(peek(0x1032)+1); /* send Channel B value to serial port */
        poke(0x1030,0x10);
        poke(0x1039,0x80);
    }
    reenable_pcode_serial();
}
```

**Figure 14.** Code used for the Handy Board analog to digital conversion of EMG signals. The code is written in Interactive C (IC) language.
**Personal computer**

A Pentium II-266 MHz IBM-compatible computer was used to execute the software training program and to receive serial input from the Handy Board. The signals received over the serial port were used to control the logic for arm model and training. The PC also served as a graphical interface allowing the user to see visual information on a monitor and to run the necessary training procedures to learn to control a myoelectric prosthesis.

**Myotrain Software Program**

The Myotrain software program was developed and written by Jeremiah Patterson and Scott Openshaw. This software was the primary trainer of individuals using the PC training system to learn to use myoelectric prostheses. Programmed with Microsoft’s Visual C++, Myotrain gave the user a graphical user interface (GUI) with menus, instructions, training procedures, and feedback. The Myotrain software had a simple and basic model of the Utah Arm 2 built into the code to allow for effective feedback to the user.

**C++ software**

Microsoft’s Visual C++ was used because of its versatility and object-oriented programming capabilities [24]. With Visual C++, it was possible to program for easier control of myoelectric arm logic, graphical display of muscle contractions, versatility, and flexibility. C++ was also chosen because it is a common and widespread programming language used in today’s software market [23]. This would allow others to add to what was accomplished in this experiment.

**Software design considerations**

In designing this software program for training individuals, different elements of software design had to be taken into account. A training or
simulation software program cannot be setup without planning the educational content and strategies [2]. Although the Utah Arm training procedure has been used over the years in myoelectric training, interfacing these procedures with a software simulation needed to be done effectively so that there was educational value in the software training program.

Walker and Hess [2] compiled information that was presented at different symposia to show what was needed in Computer Aided Instruction (CAI) to make it more effective. Many of the ideas and procedures that were included in our software program were contained in their book *Instructional Software*. The most common types of CAI are: drill and practice, simulations, and tutorial [2]. The Myotrain program gives the myoelectric trainees an initial tutorial showing them how to use and control the arm. After the tutorial, they are given the chance to practice all the control procedures taught in the tutorial. The final part of the software program tests their proficiency in controlling the arm.

The Myotrain software program design was guided by the following considerations: visual display, instructions and feedback, and interaction. Each of these parts helped create a program that followed pedagogical principles.

**Program display and setup**

The Myotrain software was created with menus and various informational windows for ease in navigation through the program. The menus allowed users to choose where to begin when they started the program (Fig. 15). The three main areas of the training portion of the program included: Training (included

![Figure 15. Main Menu options given to the users when they started the Myotrain program.](image)
Testing EMG sites and Learn Procedures), Practicing, and Testing. Each of these will be discussed later because they are part of the training mechanism of the program, providing both written and graphical feedback to the user.

Various windows of dials and gauges on the screen provided the user with feedback during operation of the Myotrain program (Fig. 16). This information was provided to help in training and to reinforce successful operations, or to correct unsuccessful attempts. The feedback windows and text are similar to the information that a prosthetist or therapist would provide to the user during at-elbow training [9].

![Figure 16. The Myotrain program display used during training and testing. Each window is used in different ways to provide effective and essential feedback to the user.](image)

**Visual display**

Colors were selected for the visual display to create a contrast that helped the user focus on the important parts of the program and clearly see the information on the screen. In creating the layout, the different windows remained in one specific area in all parts of the program [2]. This consistency
allowed users to know where objects would be and not have to readjust each time that they went to another part of the program. Each screen or graph was labeled with a title, and the screen displays were simple for ease in use by the trainees [2].

In a menu-driven program, it is important to make sure that the menu options are self-explanatory, have consistent wording, and allow for submenus or shortcuts (Fig. 17) to be used to accommodate differently skilled users [2]. The simple menu display in the software allowed users to easily select the area where they wanted to begin, or select a submenu to explore other options in the program. The menus also allowed for the user to return to the main menu and select other options, if needed.

Instructions and feedback

There were two types of feedback provided in the Myotrain program: graphical and written. Since Myotrain is a training program, instructions and feedback are imperative and must be direct, clearly, and meaningful. The instructions presented in the software showed the user how to control the myoelectric signals and what exercises to perform during certain tasks (Fig. 18). Walker and Hess explain that it is necessary for CAI to give learning outcomes, state clear objectives, and give teaching steps [2]. Before each instructional or practice procedure, the instruction window (Fig. 18) displayed learning outcome information, procedures that would be practiced, and steps needed to accomplish the task. This instruction allowed less human memory demands [2] and gave
the user the ability to control the learning by working alone to accomplish the given instructions.

These instructions were written in HyperText Mark-up Language (HTML), a standard used in Internet web design. The ease of navigation and linking in HTML coding allowed the instructions to be hyperlinked and provided easy access to any information that users wanted at any time. Users could access the Instruction window at any time by pressing the Instructions button at the bottom of the main screen (Fig. 19).

The other type of written feedback that was given to the users were the instructions in the Training Feedback window (Fig. 20) at the bottom of the screen. The written feedback showed the user what was happening with the arm and provided information on the user’s performance. The feedback in the program was specific to the training procedure and told the user what he or she was doing well or needed to improve [2].

**Figure 18.** Instructions window used to teach the user how to operate a myoelectric prosthesis. The window also gave specific exercises to perform when applicable.

**Figure 19.** The button bar at the bottom right corner of the main screen allowed users to choose options, such as Instructions and Arm Settings. It also allowed for the session recording to begin, pause, resume, or end.
<table>
<thead>
<tr>
<th>The elbow is locked</th>
<th>Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>The hand can now be controlled: Practice Un/lock</td>
<td>Elbow: 25</td>
</tr>
<tr>
<td></td>
<td>Hand: 20</td>
</tr>
<tr>
<td></td>
<td>Freeswing: 15</td>
</tr>
<tr>
<td></td>
<td>Co High: 45</td>
</tr>
<tr>
<td></td>
<td>Co Low: 30</td>
</tr>
</tbody>
</table>

**Figure 20.** The Training Feedback window gave users information on what was occurring with the arm model as they contracted their muscles. It also displayed the current arm settings for arm control. This sample feedback screen was taken while the user was practicing the locking and unlocking of the elbow. The user had just locked the elbow and was being instructed that the hand could now be controlled.

**Graphs and displays**

The other type of feedback given to the users was graphical feedback. The analog dials, histogram chart, and oscilloscope graph helped to give visual feedback to the users. These types of visual feedback are consistent with the feedback principles of reinforcement and helpfulness [2].

The dials (Fig. 21) showed what was happening with contractions. Similar to the dials on the Myolab II (Fig. 5), the analog dials showed the strength of the amplified muscle contraction as a relative percentage from 0 to 100%. This display helped show the user when he or she contracted a certain muscle (either the

**Figure 21.** Analog dials showed the user the magnitude of both channels as the muscles were contracted.
flexor or the extensor) and displayed a visual measurement of the amount of force or strength in the contraction. This meter also helped to show the user if he or she was successfully executing other arm coordination and controls, such as locking and co-contraction (unlocking).

Another display on the screen was the histogram graph (Fig. 22) that showed the user how many contractions had been performed within a certain strength range. Each time a user contracted a muscle, the histogram displayed a one-unit increase in the range of contraction. For example, the user in Figure 19 contracted the biceps brachii 3 times and triceps brachii 4 times in the 30% range. This graph informed the user of how frequently he or she was contracting in the correct range and where the majority of contractions was occurring. Feedback could be given to the user to modify strengths of contractions, if necessary.

The final graphical display was the oscilloscope display which gave a graph of strength-of-contraction vs. time (Fig. 23). The oscilloscope showed what was happening at the present time and also displayed past events. Users and

![Figure 22. Histogram displaying muscle contractions in certain ranges. This graph can be effective in showing users at the end of a training session how effectively they have been contracting their muscles.](image-url)
therapists could use this display to see how strength of contraction changed over time. Decreases in contraction strength, co-contraction and locking procedures, and general arm and hand movements can be identified with this display. The total displaying time of this graph was 400 seconds (6 minutes and 40 seconds).

**Signal processing**

The signals from the Handy Board were converted from analog to digital and the digital values that went into the PC serial port ranged from 1 to 225 bits. The software took the Root Mean Square (RMS) of as many values that it could obtain in 10 ms. This averaging allowed the signal to smooth out some of the noise from muscle contractions. The Dials and Oscilloscope Displays continued to display noise that affected the visual representation of the signal to the software user, so further signal processing was incorporated into the software. A seven-point moving average filter was added to the RMS data to eliminate more of the high-frequency noise. The moving average made the needles on the Dial Display (Fig. 21) more stable, and removed the noise from the oscilloscope signals.

The processed data values controlled the gauges in the software. During training, this data was recorded in the user database to be accessed and reviewed later by the therapist or prosthetist. The data was saved in a Comma
Separated Value (CSV) file format. The file also recorded information such as user's name, arm settings, date, time, and pertinent training feedback.

**Graphical display survey.** In order to determine which graphical displays to use in the software simulation program, an informal survey was conducted with 21 individuals. A copy of the survey questions is in Appendix A. A variety of controls were found on the Internet [6]. These were shown to these 21 individuals to choose which graphics they would prefer for displaying myoelectric information and which ones they would prefer for displaying timing information. Options were also given to show which displays were least appealing for the specified purposes.

Results from the pilot study (Table 2) show that the majority of the respondents preferred having the myoelectric signals displayed as an analog meter, histogram, and oscilloscope reading. The four that were least preferred for the myoelectric signal were the round dial, slider graph, mixture of line graphs, and progress bar with bitmap (Appendix A). It was unexpected to see that the progress bar with text was a least desirable graph to display myoelectric signal information because other researchers have used horizontal and vertical bar graph displays in their software programs to indicate the strength of myoelectric signals [16] [7].

Time displays would show users rates of co-contraction and length for locking arm. Those surveyed wanted to see a bar graph or slider graph to represent the timing and rates of contraction. The bar graph is consistent with what Sears uses to display threshold timing information in his software [13] [7]. Most (78%) preferred viewing the time in digital form (chronograph reading). Time displays were not integrated into the initial design of the Myotrain software because of time and resource constraints, but would be beneficial for future versions.
Table 2. Data showing results from the Gauge Survey given to 21 individuals. Each individual was asked to rate the three most and three least preferred meters for different software applications. The full survey can be found in Appendix A. Some answers were left blank on some of the surveys.

<table>
<thead>
<tr>
<th></th>
<th>Strength</th>
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<td>7</td>
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<tr>
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<td>2</td>
<td>11</td>
<td>3</td>
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<tr>
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<tr>
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<td>7</td>
<td>4</td>
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<td>3</td>
<td>5</td>
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<tr>
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<td>13</td>
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<td>18</td>
</tr>
</tbody>
</table>

Interaction with the program

Training involves more than observation and instruction. Users need to experiment and practice with the methods that are being taught in order to effectively learn a task [2]. After receiving instructions on how to do a certain procedure, trainees were allowed to practice and experiment in order to learn the procedure. The simple concepts were taught together and then used to teach more complex contractions that were needed to control the locking and unlocking of the elbow motor. The practice stage of the program was divided into three categories of similar functions: elbow movements, hand movements, and lock and unlock. These categories helped in sequencing the functions that users would have with an actual arm [2].
Software arm model

A simplified model of the Utah Arm 2 was programmed into the Myotrain software to give an effective representation of a real prosthesis. The Utah Arm 2 has three tasks: elbow movement, hand movement, and elbow locking and unlocking. The elbow will only operate if the elbow is unlocked, and the hand will only operate if the elbow is locked. Therefore, two states were used in our arm model: Unlocked (Arm or Elbow Mode) and Locked (Hand Mode). Certain settings can also be altered manually on the Utah Arm, therefore those settings were integrated into the design of the software model. Each of these tasks and the way the arm was modeled will be explained below.

Simplifications

The Utah Arm is a proportional control arm, which means that the speeds of the motors of the elbow and hand will move proportionally to the rate and amount of contraction in the muscles. For example, if the biceps is contracted slowly, the arm will move slowly. The Utah Arm also has integrated sensors for motion, motor torque, and motor temperature. The initial version of Myotrain simplified the arm and did not calculate these controls and sensors. The program did not display a graphic of an arm in motion during the training exercises so the users did not receive any visual feedback on proportional arm control or arm positioning. The feedback that they received from the various displays helped them understand the basics of movement and locking of the elbow without worrying about the fine-tuning of position and proportional control.

The simplification of some of these operations is currently done by therapists when users are trained using a myotester to learn basic movements of the arm and hand. The ability to modify the program code of a software trainer will allow for future improvements to take these parts into consideration during training.
Unlocked State

In order to control the elbow motor in the Utah Arm 2, the elbow must be unlocked, and a user needs to have at least a 10µV difference between the EMG signals from the two opposing muscle groups (i.e., biceps and triceps) (Fig. 8). The electronics and motor respond better when the difference between the signals is above 20µV [8]. This microvolt value was assigned a variable, called the Elbow Threshold in the program, and it could be modified in software much like it could be modified by gain dials on the actual arm.

The elbow motor moves up (flexes) when the user contracts the biceps enough to produce a difference in signal of 10µV more than the triceps. The triceps must be 10µV more than the biceps signal to move the elbow down (extend the arm). The Myotrain program modeled the elbow by taking the difference of the two signals and then verifying that the difference was above the Elbow Threshold value (Fig. 24). If it was above that level, then the program looked at the sign of the result to determine which way the motor would move. If the difference was positive (biceps > triceps), the feedback would tell the user that the arm was moving up. If the difference was negative (biceps < triceps), then the user would be told that the arm was extending.

In the Unlocked State, the elbow was extended also by simply relaxing the arm muscles and allowing the arm to drop into a Freeswing mode (Fig. 24). In this mode, the arm swings without any resistance, much like our own arms when we are walking. The Utah Arm takes the sum of the two signals (Channel A and Channel B) to determine if they are relaxed below a certain level (Freeswing Threshold) in order to relax the elbow motor [8]. Our software model took the sum of the two channels and then verified that the result was less than the Freeswing Threshold. If the value was below the threshold, then the user was informed in the Training Feedback window (Fig. 20) that the arm was at rest and in freeswing.
For the arm to switch from elbow control to hand control, the elbow had to lock. The Unlocked State also monitored locking to see when it needed to switch to the Locked state. In the Utah Arm, there are two conditions that must exist simultaneously for the elbow to lock: (1) the elbow has a load on it (elbow torque > 0) and (2) the elbow motor is stopped (motion = 0) for a certain amount of time. With an actual prosthesis, the arm has a range of motion (ROM) of 135° (Fig. 25). Since the forearm and TD have a certain weight, there is a

Figure 24. Elbow operations graph depicting the ranges that were needed to model the Utah Arm in software.

Figure 25. Range of motion of a prosthetic arm.
torque on the motor at almost every point in the ROM. For this reason, Myotrain's simplified model assumed that there was always torque on the motor, and that it was constant throughout the full ROM. In reality, the torque is not constant throughout the ROM because the forces on the elbow will change as the hand moves to different positions. It was not necessary to take this variable into account in this experiment because there was no active graphical representation of the arm present during the training exercise. Additionally, since proportional control was not integrated into the model, the variable effects of torque did not need to be taken into consideration.

Condition 2 for locking is met when the arm is in a position for a set amount of time, called the Lock Threshold. Since there is a load on the arm, there needs to be a contraction to hold the arm at a certain position—the user does not relax completely for the motion to be zero. In the software model, this range was determined by seeing if the arm was in the Locking Range (Fig. 26). The locking range is between the Freeswing and Elbow Thresholds. In this area, the arm will not move up (it is less than the Elbow threshold) and will not relax (it is above the Freeswing threshold), so its motion is essentially zero and the arm will lock if held in this range for about 1 second (Lock Timing).

The Myotrain software also checked to see if the difference of the contractions was in the lock range (Elbow Threshold < difference < Freeswing Threshold). If this condition was met for the amount of time set by the Lock Timing Threshold, then the elbow locked and the arm model moved into the Locked State for the hand to be controlled.

**Locked State**

In the Locked State, the hand is operational and the elbow cannot be moved. The hand is more sensitive in its operation than the elbow because only a 5µV difference in signal is necessary to make the hand move [8], but at least a 10µV difference is recommended. The hand is operated in the same manner as
the arm. If the difference of the EMG signals of the biceps and triceps is above the Hand Threshold (at least 5µV), then the hand will either open or close (Fig. 27). Normally, a stronger biceps signal will cause the hand to close, while a stronger triceps contraction will make the hand open [8] (Fig. 8). There is no special resting or Freeswing mode for the hand in the Locked State. The hand can manually be turned off to maintain a grip on an object, but when it is turned on, the hand is opening, closing, or stopped. Proportional control of the hand was not taken into account for the same reasons as explained above for the elbow.
To switch out of hand control and move the elbow again, users must unlock the elbow with a dual contraction of both muscles. The co-contraction is used by some myoelectric arms as a means to transfer control from one motor to the other [28]. The co-contraction has 4 parts to it (Fig. 28): (1) both muscles are contracted together at a certain rate (Rate Threshold), (2) the sum of both muscles goes above a high threshold, (3) the sum of both muscles goes below a low threshold, (4) steps 1-3 occurs in a certain time interval (Time to Complete Co-contract). A co-contraction is a quick contraction and relaxation of both muscles. Some therapists describe the co-contraction as a quick clenching of the fist or snapping of the fingers [9]. Upon a successful co-contraction, the hand
motor is deactivated, and the elbow motor is turned on. The user must raise the arm a small amount to disengage the metal locking pin to complete the unlocking procedure.

In the software, while in the Locked State, Myotrain looked for a co-contraction where each signal was above the Co-contract High Threshold and the rate of contraction was above the Rate Threshold. If these conditions were met, then it checked to see if the user relaxed below the Co-contraction Low Threshold within the specified amount of time (Co-contraction Time). When a co-contraction was successful, the user was notified in the Training Feedback window (Fig. 20), and instructed to relax and then raise the arm to get the arm
out of Locked State. Upon relaxing and raising the arm, the arm model moved back into the Unlocked State where the elbow could be manipulated.

**Arm settings**

The Utah Arm 2 can be manipulated by turning different potentiometer dials inside the arm and hand (Fig. 29). The elbow dials do not affect the hand operations, and vice versa. These adjustment dials allow the prosthetist to modify the arm settings so that the arm will function optimally for each user. Settings that can be changed in the arm and hand include biceps and triceps gains and thresholds, lock timing, EMG filtering, freeswing thresholds, co-contraction rates, and muscle differencing gains. Each of these settings will customize the arm to the user.

In the software model, users were able to make some changes to the arm, similar to the actual Utah Arm. Arm settings could be accessed from the button bar at the bottom of the screen (Fig. 19) or from the Edit Menu at the top of the main screen. When settings were accessed, a window appeared, allowing the user to make modifications to elbow and hand settings (Fig. 30). The Movement Settings modified the thresholds for the Elbow, Hand, and Freeswing. The time needed
Arm settings could be manipulated in software to customize the arm model to the user. Settings could change both elbow and hand operations. Co-contract settings for unlocking the arm included modifications to the high and low thresholds, rates for each muscle channel, and timing needed to complete the co-contraction. If users wanted to revert to the programmed defaults, then they could push the Defaults button to apply the defaults.

Settings were saved in a text file in the user’s folder for easy access by a therapist or evaluator. They were also saved in the CSV file when each training session was completed. Some of the arm settings were also displayed in the Training Feedback window for easy reference (Fig. 20). If a user made changes to settings during a training session, they were recorded in the data file. Evaluators would be able to determine if the modifications to the arm were successful at helping the user succeed at a certain task.

Training Procedure

No documented procedural standards for myoelectric prosthesis training were found. Through correspondence with eight prosthetists and professionals in the Orthotic and Prosthetic (O&P) field, only one said he used a standard written training procedure to train a user to control myoelectric devices. The other respondents stated that there was no set training procedure, but they gave comparable answers that showed an informal training standard existed to
successfully teach individuals to use myoelectric prostheses and become independent users. A training procedure that was common among some of the prosthetists surveyed was Motion Control’s training program for the Utah Arm. This program is documented in Motion Control’s *Utah Arm 2 Handbook* and in a video called *Training the Client with an Electric Arm Prosthesis*. Most of the training procedures used in this study for the Myotrain program are from the Motion Control training procedure. Other training elements came from suggestions received through correspondence with prosthetists and therapists around the world.

**Training setup and procedures**

The primary goal of prosthetic training is to maximize the potential use of the prosthesis in the client’s daily life [9]. In training a user to successfully use a myoelectric prosthesis, there are three main teaching procedures: signals training, control training, and use training [9]. Practice is another important part of training that needs to be used and emphasized during each stage to ensure quick and successful use of the prosthesis. The user must practice the procedures as much as possible for additional reinforcement and ultimate success [9] [14].

**Signals training**

The first step in training an individual to use a myoelectric prosthesis is to find optimal placement of the electrodes for muscle contractions. This is important because finding the location of the most consistent and best antagonist muscle groups will ensure a user can control the prosthesis effectively. The prosthetist will make sure that the electrode sites are not located in areas of hypersensitivity or where there is scabbing or open wounds [9]. The EMG site testing is done by placing the electrode bar over a muscle group and having the user first flex his or her non-amputated arm, then both
arms together, and then only the amputated arm. This helps the user learn how to contract the muscles that are needed and observe the signal on a monitor. Traditionally the signals are observed on a myotester such as the Myolab II, but this software trainer program allowed users to see their signals on the computer monitor.

In the Myotrain software, users chose the Test EMG Sites menu button (Fig. 17) and then were presented with three options for testing their muscle sites: Channel A, Channel B, or Both Channels (Fig. 31). They were tested on each channel separately to learn how to contract the biceps and triceps separately and then tested on both channels to make sure that there was a good difference of signal between the two.

As good locations are found for muscle contractions, the user or therapist marks the areas in pen and then slightly moves the electrode bar (about 1 cm) until the best location is found [8]. Once one muscle group is located and marked, the antagonist muscle group is then located. The therapist is looking for the best difference between the two muscle groups, not necessarily the strongest signal from each [8]. The user will be more successful if there is about 20µV of voltage difference that can be controlled between the electrodes—but 10µV will suffice. When the optimal sites are located for the electrodes, then controls training can begin.

**Controls training**

With the electrodes in place on the antagonist muscles, the user can begin training to control and use the myoelectric prosthesis. Initially, this training is
done using the Myotester to display the signals as users contract their muscles in the appropriate control processes. Once the user is comfortable and able to perform the simple operations of elbow and hand movement, the user is taught use of the arm [9]. It is important to go from simple to complex and reinforce each step with practice [9]. During controls training, the user will learn how to move the elbow motor up and down, how to open and close the hand, and then how to lock and unlock the elbow.

In the training software, users were able to learn how to use the arm, the hand, or lock and unlock the elbow (Fig. 32). Instruction usually began with the elbow motor, teaching the user to move it up and down. During the Arm Up and Down exercises, the arm would not lock. This is similar to pushing the lock override button on the Utah Arm to prevent locking during initial training. This feature was added to allow users to concentrate on the simple task of moving the arm before worrying about locking and unlocking the elbow. Appropriate feedback was given to the user in the Training Feedback window (Fig. 20) when correct and incorrect arm movements were made during the learning process.

Once satisfied with the arm procedure, the user was taught to open and close the hand. This motion is similar to the bending of the elbow because it entails contracting the same muscles as the elbow requires. Just like the arm procedure, the Hand Open and Close exercise would not allow the elbow to unlock if the user accidentally co-contracted. An inadvertent co-contraction would trigger feedback in the Training window telling the user that he or she co-
contracted. Other appropriate training was also given while opening, closing and resting the hand.

After learning the hand operations, users were instructed how to lock the elbow by stopping the arm in one location for a certain length of time (about 1 second). After learning the locking control, users learned how to unlock the elbow with a co-contraction.

When all of these control procedures have been taught to the user and the user feels comfortable with them, at-elbow trainees normally don a myoelectric prosthesis and begin use training with the arm. Trainees using the Myotrain software were allowed to practice (Fig. 33) their skills after completing the Learn Procedures part.

During the practice options in the Myotrain software, users were able to practice the same exact procedures that they learned during the Learn Procedures portion of the program. In addition, users could practice full control of an arm. This portion of the program allowed them to see what happened if they accidentally locked or unlocked their arm. The full control gave them a real-life example of the arm model and allowed them to practice as if they were wearing a prosthesis. The feedback given during the Complete Control exercise was positive and negative feedback related to the way the user controlled the arm and hand. Some of the exercises included in the Complete Control portion helped the user imagine scenarios for controlling a real prosthesis. Using these scenarios, users could practice use training even without having a prosthesis.

**Figure 33.** Practice options for the user to choose from after having completed the learning procedures of the Myotrain program.
Use training

To accomplish the goal of prosthetic training, users need to be taught how to use their arms in different situations so that it can ultimately be used in normal daily routines [14]. During use training, the therapist or prosthettist teaches the user how to use the arm and hand together for different tasks or operations. An important part of this training includes showing the user how to pre-position the arm to pick up or hold an object with the artificial hand. Pre-positioning means to place the arm in an appropriate position so that a certain task can be performed well with both hands or arms [9].

Use training usually entails starting with basic use of the arm to do tasks such as picking up and placing objects for pre-positioning and integrated hand and elbow use. After learning basic integrated functions, the user is instructed to work on other, more complex, everyday tasks like cracking an egg, hammering a nail, getting bills out of a wallet, etc. This final part of use training leads the individual into practicing activities of daily living (ADL) that are functional activities specific to each individual. Practicing ADL procedures will help give the individual a sense of accomplishment and realization of how to succeed at doing normal daily tasks with a myoelectric prosthesis [9].

A user will normally work on use training once he or she is fitted with a myoelectric prosthesis. The advantages of use training with a fitted myoelectric arm are many. Users can get a true feel for how to run the arm and perform tasks. They will have a chance to see how to use both arms and hands at the same time. A computer simulation cannot replace the real experience of practicing using a myoelectric prosthesis.

The Myotrain software program does not have use training integrated into the training procedures because the best use training is done with the prosthetic limb in place. Part of the program training touched on use training during the practice and testing phase. In these parts of the program, users were instructed to accomplish certain tasks that simulated what would be done with a
myoelectric arm. For example, the program would instruct a user to perform the appropriate contractions in order to pick up a cup. The user did not physically see these actions on an arm, but could operate his or her muscles so that they mimicked the actions that would normally be performed with a real myoelectric prosthesis.

**Practice and testing**

Because reinforcement is important in any type of learning [2], there are three areas in the software simulation where users practiced the skills they had learned. First, the main area for practicing was in the Practice area of the program (Fig. 33). Here, users chose what control procedure they wanted to practice. For example, a user might want to practice locking and unlocking the elbow. This was the main area where users practiced the procedures for myoelectric control to become successful at using a myoelectric arm. The other area where users practiced was in the Learn Procedures area (Fig. 32). The Learn Procedures area allows users to practice procedures after they have been taught how to control the arm. Practicing in this area allowed the user to immediately test the control sequence and learn how to accomplish it.

Feedback was provided to the user during each part of the program, especially during Practice. This ensured that there was a “cyber” therapist that gave written feedback to the user during the training stage. The computer recorded each training stage during the program, allowing the therapist or prosthetist to assess the training that was done by the individual.

**Experimental Setup**

The setup of the experiment received approval from the Human Subjects Review Committee to use humans as subjects for the experimental protocol (Appendix B). The ten subjects selected for the study were not amputees because this study was to show that the software could train adults to use a
myoelectric prosthesis. Users do not need to be amputees to learn how to use a prosthesis. In fact, sometimes amputees may have a motivational factor which may affect their performance if they are not willing or psychologically prepared to learn how to use a myoelectric prosthesis [14].

Ten individuals were randomly selected and equally divided to participate in the two groups—control and experimental. All subjects were considered above-elbow amputees and electrodes were placed on the biceps and triceps muscles. For the first two days, the control group was taught how to use myoelectric prosthesis by the traditional at-elbow training while the experimental group was trained by the Myotrain software program. On the third day, all 10 subjects were tested on the arm and then on the software to ascertain proficiency. A summary of the experimental procedure can be found in Table 3. Details for each part of the experiment will be explained below.

On Day 1, both groups were asked to read and sign papers related to the experiment as set forth by the Human Subjects Review Committee (Appendix B). All subjects were then given an introduction to the study and explanation of the goal of the research. A brief introduction on Utah Arm 2 functions was then presented to each subject. Explanations on arm movement up and down, the hand opening and closing, and the locking and unlock mechanisms were shown to the subjects. Following the introduction of material, subjects were allowed to ask questions. Once questions were answered, training began for each group in the experiment.

A Utah Arm 2 (Fig. 2) was borrowed from Motion Control in Salt Lake City, Utah for training and testing purposes in the experiment. The hand operated opposite what had been written in the literature. Contraction of the biceps (Channel A) was supposed to close the hand, and contraction of the triceps should open it [8]. The loaner hand opened with biceps contraction and closed with triceps contraction. The hand could not be modified for the experiment so
Table 3. Experimental setup showing the three days of learning, practice and testing for the control and experimental groups.

<table>
<thead>
<tr>
<th>Control Group</th>
<th>Experimental Group</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day 1</strong></td>
<td></td>
</tr>
<tr>
<td>Read and sign papers</td>
<td>Read and sign papers</td>
</tr>
<tr>
<td>Introduction to study</td>
<td>Introduction to study</td>
</tr>
<tr>
<td>Introduction to the arm controls</td>
<td>Introduction to the arm controls</td>
</tr>
<tr>
<td>Questions and Answers</td>
<td>Questions and Answers</td>
</tr>
<tr>
<td>Test EMG sites</td>
<td>Learn about Myotrain software</td>
</tr>
<tr>
<td>Learn procedures with arm</td>
<td>Test EMG sites</td>
</tr>
<tr>
<td>Finish</td>
<td>Learn Procedures</td>
</tr>
<tr>
<td></td>
<td>Finish</td>
</tr>
<tr>
<td><strong>Day 2</strong></td>
<td></td>
</tr>
<tr>
<td>Finish Learn Procedures if not completed</td>
<td>Finish Learn Procedures if not completed</td>
</tr>
<tr>
<td>Practice arm control</td>
<td>Practice arm control</td>
</tr>
<tr>
<td>Elbow</td>
<td>Elbow</td>
</tr>
<tr>
<td>Hand</td>
<td>Hand</td>
</tr>
<tr>
<td>Lock/Unlock</td>
<td>Lock/Unlock</td>
</tr>
<tr>
<td>Full control</td>
<td>Full control</td>
</tr>
<tr>
<td>Finish</td>
<td>Finish</td>
</tr>
<tr>
<td><strong>Day 3</strong></td>
<td></td>
</tr>
<tr>
<td>Practice arm use for 5 minutes</td>
<td>Practice arm use for 5 minutes</td>
</tr>
<tr>
<td>Test on arm control</td>
<td>Test on arm control</td>
</tr>
<tr>
<td>Test on software</td>
<td>Test on software</td>
</tr>
<tr>
<td>Post testing evaluation</td>
<td>Post testing evaluation</td>
</tr>
<tr>
<td>Finish</td>
<td>Finish</td>
</tr>
</tbody>
</table>

that the operations matched the literature, so changes were made to the Myotrain program to make sure that the feedback was accurate with the actual hand movements. This way, experimental subjects would be learning the same way that the control subjects were learning to control the hand.

Motion Control also lent a Myolab II (Fig. 5) and electrodes (Fig. 6) for obtaining EMG signals and interfacing them with the PC. A Handy Board (Fig. 11) was borrowed from the Toying With Technology Center at Iowa State
University and programmed with the code to convert the analog signal to digital and send it over the serial port to the PC (Fig. 4, Fig. 14). A Pentium II-266 MHz computer ran the Myotrain software and was used to by the experimental subjects during training and by both groups during the software testing.

**Control procedure**

Five control subjects were randomly chosen to be trained at-elbow by the experimenter on how to use the Utah Arm 2. Below is an explanation of the three days of experimentation.

**Day 1**

The control subjects were first tested with a myotester to determine optimal sites for the biceps and triceps muscles. Once locations were found for the best difference between signals, locations were marked on a sheet of paper for future reference and electrodes were fastened to the respective muscles with elastic Velcro strips.

Following EMG testing, subjects were taught the motions to move the arm up and down. Subjects were instructed to contract the biceps to move the arm up and then relax. Subjects were told that relaxing allowed the arm to go into freeswing mode. They performed this exercise five times. Next, they were taught that they could force the arm down by contracting the triceps muscles. They practiced moving the arm up and then forcing it down five times. Adjustments were made and training was given if some individuals had a hard time differentiating the biceps and triceps signals. Subjects were explained that the hand operated with the same contractions; Channel A opened the hand, and Channel B closed the hand. Subjects then practiced the motions of opening and closing the hand.

The final step of learning about the signals was to have subjects practice locking and unlocking. Subjects held a contraction in a certain range on the
myotester and then relaxed to simulate a lock (Fig. 26). Next, they practiced co-contracting their muscles to unlock the elbow (Fig. 28). Subjects practiced the co-contraction until they felt comfortable with the quick contraction and relaxation. Additional instruction and training was given to subjects who did not co-contract both muscles, contracted at a slow rate, or relaxed too slowly.

After learning how to control EMG signals, subjects' electrodes were plugged into the Utah Arm 2 and the subjects were instructed on each of the control procedures: elbow, hand, lock and unlock. Time was spent looking at proportional control, locking at different angles along the arm's ROM (Fig. 25), and relaxation. The majority of the learning was allocated to understanding the co-contraction and unlocking the elbow with a co-contraction and then contracting the arm up to manually unlock the mechanical pin.

When subjects accomplished the tasks and commands at about 80-100%, the exercises for Day 1 were complete. Myoelectric training is complete and fitting of a prosthesis normally occurs when, "the client can tolerate a one-hour training session, and is consistently generating sufficient signals to operate the prosthesis in at least basic functions, for example opening and closing of the hand and bending and extending the elbow" [9].

**Day 2**

On Day 2, subjects completed any training that was not completed on Day 1 before beginning their practice session. Next, subjects practiced controlling the elbow, the hand, and the locking and unlocking mechanism of the elbow. Users had to succeed 80-100% of the time at carrying out commands from the trainer before moving on to the next task. After accomplishing these tasks, the subjects practiced nine practical uses with the arm:

1. **Picking up and dropping a cup** (move arm to ~90°, lock, pick up cup, unlock, move arm down, lock, drop cup)
2. **Picking up and dropping a ball** (lock arm ~0°, pick up ball, unlock, move arm up and lock ~90°, drop ball)

3. **Picking up a ball and placing it on a cup** (lock arm ~0°, pick up ball, unlock, move arm up and lock ~90°, drop ball on cup)

4. **Taking a ball off of a cup** (preposition hand, lock arm ~90°, grab ball, unlock, move arm down to ~0°, lock, drop ball)

5. **Picking up a soft foam brain off of a cup or table** (preposition hand, lock arm at appropriate angle, lightly grab brain, unlock, move arm up and down, lock, drop brain)

6. **Picking up and placing a stapler on a table** (preposition hand, lock arm at appropriate angle, grab stapler, unlock, move arm up, move arm down to place stapler on table, release stapler)

7. **Picking up and placing a notebook on a table** (preposition hand, preposition notebook at edge of table, lock arm at appropriate angle, grab notebook, move arm up, move arm down to place notebook on table, release notebook)

8. **Grabbing an electrical or telephone cord** (preposition hand, put cord between hand's fingers, move arm up and down, release cord)

9. **Locking and unlocking arm at five points in the arm's full ROM** (lock arm at ~0°, unlock, move arm up to ~45°, lock, unlock, move arm up to ~90°, lock, unlock, move arm up to ~110°, lock, unlock, move arm up to ~135°, lock, unlock, take arm down to ~0°)

These nine exercises helped the subjects learn the integration that is involved with using a myoelectric prosthesis. Subjects were trained in combining elbow and hand movements and minimizing the errors of executing commands.

When subjects completed these practice exercises with at least 80% accuracy, they were finished with Day 2.
Day 3

The last day of the experiment involved testing the subjects on their ability to control the arm upon command from the trainer. Subjects were allowed to practice for five minutes if they desired. Following the practice time, users were then given seven tests on arm control:

1. **Move arm up, relax down** (move arm up, relax into Freeswing, repeat 5 times)
2. **Move arm up, force down** (move arm up, force arm down with Channel B, repeat 5 times)
3. **Open hand, close hand** (open hand, then close hand, repeat 5 times)
4. **Close hand, open hand** (close hand, then open hand, repeat 5 times)
5. **Lock arm at any angle, then unlock elbow and relax** (move arm up, lock, unlock, move arm down, repeat 5 times)
6. **Lock and unlock arm at five points in the arm’s ROM, move arm down** (move arm up, lock, grab cup, unlock, move arm up, move arm down, lock, drop cup)
7. **Pick up a cup on a table, bring arm up, take arm down, drop cup** (move arm up, lock, pick up cup, unlock, move arm up, move arm down, lock, drop cup)

Data was collected on correct and incorrect actions performed, relative speed of execution, confidence level, and general observations.

Following the at-elbow testing, control subjects were tested on the software to compare their performance with the arm to their performance on the computer. Subjects were introduced to the software screen and meters with a brief explanation and then were asked to perform Tests 1-5 on the computer. Raw data of signal strength and Myotrain feedback were collected in CSV files, and observations were written on paper during the tests.

Once the subjects finished the arm and computer tests, each was interviewed for feedback and observations dealing with the computer software
and overall training. The questions asked in the interview are found in Appendix C.

**Experimental procedure**

Five subjects were randomly selected to use the Myotrain software program to learn how to use the Utah Arm 2. Below is an explanation of the three days of experimentation.

**Day 1**

After completing the paperwork and questions and answers portion of the first day (Table 3), experimental subjects began the Myotrain program, signed on as a user (Fig. 34) and began the learning process by pressing the Training button (Fig. 15). Myotrain subjects had to learn about the program’s details before they could learn how to use the arm. The primary method of learning about the program and the arm was reading the instructions in the Instructions window (Fig. 18) since no trainer was present during the experiment. Because reading was essential, subjects were reminded to read the instructions and follow the directions.

After learning about the software’s windows and instruction navigation, subjects began testing for correct EMG sites in the same manner as the control group (Fig. 31). Channel A (biceps) was tested first, then Channel B (triceps), and finally both muscles were tested together to ensure that there was a good difference of signal between the two.
In the next step, experimental subjects learned how to use the arm (Fig. 17). Subjects learned about the elbow movements, hand movements, and then the locking and unlocking mechanisms. After reading about the control mechanisms, subjects were able to practice what they had learned. The practice helped to reinforce the instruction received through reading. For the elbow movements, subjects practiced moving the arm up and down and relaxing to Freeswing. Feedback was given in the windows throughout the learning time to help the user make necessary adjustments. Learning hand movements included opening, closing and stopping the hand. To learn the lock and unlock mechanism, subjects were asked to lock the elbow and then unlock it during the practice time. Once the users were comfortable with having learned and practiced their procedures, they were finished with the first day.

**Day 2**

Subjects were asked to complete the Learn Procedures portion of the software if they did not complete it the day before. Once they were done with the Learn Procedures part, they went on to practice how to use the arm (Fig. 33). Subjects practiced arm movements, hand movements, and locking and unlocking. Additionally, subjects had the ability to control the full arm and were asked to imagine and try the following practice scenarios in arm control:

1. **Practice locking and unlocking** (move arm up, lock arm, move hand, unlock arm, relax)
2. **Imagine picking up a ball on a table** (move arm up, lock, grab ball, unlock, move arm down)
3. **Imagine holding a cup** (move arm up, lock, grab cup, unlock, move arm, lock)
4. **Imagine other examples** such as holding a fork, hammering a nail, cutting tomatoes, picking up a briefcase
After practicing the procedures and obtaining 80-100% accuracy in carrying out exercises, as defined by Doolan [9] and Sears [3], this training session was complete.

**Day 3**

Myotrain subjects were given five minutes to learn how to use the Utah Arm 2 before they were tested on the arm operations. The experimenter was not allowed to answer any questions or provide any feedback. Following the conditioning with the arm, testing was performed. Testing for the experimental subjects was exactly the same as explained above for the control group. Subjects using the software were also tested on the computer and given the post evaluation interview before finishing the testing session (Appendix C).
RESULTS

Ten subjects were randomly selected to be evenly divided into two groups: control and experimental. Table 4 shows the breakdown of the ages and gender of each group that participated in this experiment. There were a total of 7 males and 3 females. The overall average age of all participants was 26.5 years.

Table 4. Summary of the age and gender of the 10 participants in the study.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Age</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>29</td>
<td>M</td>
</tr>
<tr>
<td>3</td>
<td>28</td>
<td>M</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>M</td>
</tr>
<tr>
<td>8</td>
<td>21</td>
<td>M</td>
</tr>
<tr>
<td>9</td>
<td>27</td>
<td>F</td>
</tr>
<tr>
<td><strong>Average Age</strong></td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td><strong>Experimental</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>31</td>
<td>M</td>
</tr>
<tr>
<td>5</td>
<td>27</td>
<td>M</td>
</tr>
<tr>
<td>7</td>
<td>21</td>
<td>F</td>
</tr>
<tr>
<td>10</td>
<td>27</td>
<td>F</td>
</tr>
<tr>
<td><strong>Average Age</strong></td>
<td>27.2</td>
<td></td>
</tr>
</tbody>
</table>

Data collected from the experimental procedure included both numerical and subjective observations. During the learning and practice stages of training, both the control and experimental subjects improved at their skills of controlling the Utah Arm. On the third day when subjects were tested, the experimental group was able to correctly control the Utah Arm. The following information will present the data that was collected over the three days of the experimental procedure.
Learning Procedures Results

The control group received at-elbow training for the Learn Procedures portion of the experiment. Individuals were taught how to control the Utah Arm 2 and then were allowed to briefly practice what they had learned. Subjects performed the tasks of elbow and hand movement at a performance level of at least 80% before being taught the next procedures. Elbow locking and unlocking took the longest time to learn. Co-contraction training occupied the bulk of the training time over the first two days. The majority of the subjects did not spend much time on the hand controls because they felt that they had learned how to run them by knowing how to run the elbow motor.

The experimental group spent more time on average training the first two days than the control group. Table 5 shows the time spent by each subject by day and session. The average amount of time spent by both groups for all three days was 59 minutes. The control group spent an average of 54 minutes in training and testing, while the experimental group took 10 more minutes.

Table 5. Total amount of time spent each day by each subject. Average overall time spent by each subject is also listed. A normal therapy session should last 1-2 hours, depending on the patient.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Avg Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1:00</td>
<td>0:40</td>
<td>0:52</td>
<td>0:50</td>
</tr>
<tr>
<td>2</td>
<td>1:25</td>
<td>1:15</td>
<td>1:00</td>
<td>1:13</td>
</tr>
<tr>
<td>3</td>
<td>0:50</td>
<td>1:20</td>
<td>1:20</td>
<td>1:10</td>
</tr>
<tr>
<td>4</td>
<td>1:00</td>
<td>0:45</td>
<td>0:50</td>
<td>0:51</td>
</tr>
<tr>
<td>5</td>
<td>1:10</td>
<td>1:15</td>
<td>1:05</td>
<td>1:10</td>
</tr>
<tr>
<td>6</td>
<td>0:40</td>
<td>0:55</td>
<td>1:00</td>
<td>0:51</td>
</tr>
<tr>
<td>7</td>
<td>1:01</td>
<td>0:45</td>
<td>1:00</td>
<td>0:55</td>
</tr>
<tr>
<td>8</td>
<td>0:55</td>
<td>0:55</td>
<td>0:45</td>
<td>0:51</td>
</tr>
<tr>
<td>9</td>
<td>0:40</td>
<td>0:50</td>
<td>0:50</td>
<td>0:46</td>
</tr>
<tr>
<td>10</td>
<td>1:15</td>
<td>1:30</td>
<td>0:50</td>
<td>1:11</td>
</tr>
<tr>
<td>Avg</td>
<td>0:59</td>
<td>1:01</td>
<td>0:57</td>
<td>0:59</td>
</tr>
<tr>
<td>Con Avg</td>
<td>0:49</td>
<td>0:56</td>
<td>0:57</td>
<td>0:54</td>
</tr>
<tr>
<td>Exp Avg</td>
<td>1:10</td>
<td>1:06</td>
<td>0:57</td>
<td>1:04</td>
</tr>
</tbody>
</table>
Upon finishing their training on the computer on Day 1, all of the experimental subjects commented on how difficult it was to learn how to unlock the elbow. Some subjects felt like they were unable to perform it, while others felt that it was just a challenge that could be overcome. All subjects in the control group finished the unlocking learning exercises with 80% or more accuracy when attempting to co-contract. Not all of the experimental subjects had achieved that accuracy by the end of Day 1. The experimental subjects also had high contraction strengths in order to successfully co-contract (Fig. 35). The EMG signals on the computer were near 75% of contraction strength when contractions were successful (Table 1).

Figure 35. Subject 5 learning how to lock and unlock the arm on Day 1. During this interval, he was able to successfully co-contract the arm at 619 s, having tried a total of 13 times. Contraction strengths are in bits (1 bit = 19.6 mV).
Overall the subjects in the control group felt confident about controlling the myoelectric prosthesis after the first day of instruction. Everyone in the experimental group was not as confident with his or her abilities at the unlocking function.

**Practice Procedures Results**

On Day 2, both groups practiced the procedures that they had learned the day prior. Subject 2 had not completed the exercises as required on Day 1, so he spent time completing the learning exercises before continuing with the rest of the training of Day 2. Control subjects commented that it was easier to move the arm the second day. Not as much contraction strength appeared to be necessary as was the day before for the subjects. Some subjects had to retrain on the opening and closing of the hand to make sure that they closed the hand when they wanted to close it. After 5-10 practices, they felt comfortable with it. Experimental subjects were able to practice the procedures on the computer and even practice full control of the arm. Subjects 2 and 5 mentioned that it was hard to imagine the arm moving to pick up an object when there was no arm. The difficulty in visualizing the task that was requested by the software made it hard to perform the operation.

Control subjects felt more confident in using the arm by the end of the second day of training. Most users were performing around 90% accuracy on all commands. Many of the users practiced proportional control with the myoelectric arm during the practice exercises. Experimental subjects were more confident in co-contracting their muscles to unlock the elbow. They expressed their pleasure at being able to control the unlocking mechanism in software.

**Testing Results**

Seven tests were given to all subjects on the third day of training. Each was given five minutes to practice on the arm before testing. The experimental
subjects used this time to fine-tune their ability to operate the Utah Arm, since it was the first time they had used the actual arm. These subjects were happy that they could control the arm with general ease. Some adjustments had to be made for relaxing and co-contracting, but the experimental subjects started to use the visual and audio feedback from the arm to help make their adjustments and refine their understanding of how the arm was controlled. None of the control subjects used the full five minutes for practicing before the test.

Results were recorded both numerically and subjectively (observations). Numerical results looked at the total attempts at an action and the total successes. Mistakes were also taken as numerical data, such as how many times the subject opened the hand when it needed to be closed. Observational data recorded information such as relative speed of execution and the confidence level of the user. Both parts of this data are presented in the following section.

Test 1: Arm up, relax down to freeswing

Both groups had 100% accuracy in bringing the arm up from the down position (0°). Members of both groups struggled to relax completely after bringing the arm up to 135°, and the arm locked at least once on 7 of the 10 subjects (Table 6). After successfully unlocking the elbow, they were all able to relax the arm to freeswing and continue with the next trial run of Test 1. Subject 1 had trouble relaxing, which was an abnormal behavior from his previous 2 days of training.

Test 2: Arm up, force down with triceps

Both groups made no mistakes in this test, bringing the arm up and then forcing it down with a triceps contraction. The arm did not inadvertently lock for any of the subjects during this exercise.
Table 6. Data from Test 1 showing relaxing successes and errors for all subjects. Averages (Avg) and standard deviations (SD) are shown for all (Tot), control (Con), and experimental (Exp) subjects.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Attempts to Relax</th>
<th>Success At Relax</th>
<th>% Success</th>
<th>Lock Arm Mistake</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>5</td>
<td>55.6</td>
<td>2</td>
<td>22.2</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
<td>1</td>
<td>16.7</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
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<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
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<td>16.7</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
<td>1</td>
<td>16.7</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
<td>1</td>
<td>16.7</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
<td>1</td>
<td>16.7</td>
</tr>
<tr>
<td>Tot Avg</td>
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<td>5.0</td>
<td>85.6</td>
<td>0.8</td>
<td>12.6</td>
</tr>
<tr>
<td>Con Avg</td>
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<td>5.0</td>
<td>84.4</td>
<td>0.8</td>
<td>11.8</td>
</tr>
<tr>
<td>Exp Avg</td>
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<td>0.8</td>
<td>13.3</td>
</tr>
<tr>
<td>Tot SD</td>
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<td>0.0</td>
<td>6.8</td>
<td>0.4</td>
<td>7.0</td>
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<tr>
<td>Con SD</td>
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<td>0.0</td>
<td>18.2</td>
<td>0.9</td>
<td>10.8</td>
</tr>
<tr>
<td>Exp SD</td>
<td>0.4</td>
<td>0.0</td>
<td>7.5</td>
<td>0.4</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Test 3: Open hand, close hand

All subjects were able to open and close the hand during this exercise (Table 7). Subjects 3 and 9 confused the muscles groups that controlled the opening and closing operations of the hand on their first attempt. Subjects 4, 7, 8, and 9 caused the arm to unlock with a co-contraction due to the dual contraction of their muscles when switching from open to close. These subjects allowed the arm to lock and then continued on with their exercise of hand movement.
Table 7. Data showing attempts and successes at opening and closing the hand. Inadvertent co-contractions that occurred during Test 3 are also in the table.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Att Open</th>
<th>Succ Open</th>
<th>% Success</th>
<th>Att Close</th>
<th>Succ Close</th>
<th>% Success</th>
<th>Inadv Co-con</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
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<td>5</td>
<td>100.0</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
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<td>5</td>
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<tr>
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</table>

Test 4: Close hand, open hand

Subjects 7 and 8 co-contracted during the hand movement test and caused the arm to unlock. They waited for the motor to relock and then continued on with their test. Subject 8 was not concentrating and made 4 errors by confusing the muscle groups that controlled the hand. He opened the hand two times when he meant to close it, and closed it two times when he meant to open it. Subject 8 also had 3 inadvertent co-contractions during this exercise. All other subjects performed the test perfectly and were able to move the hand appropriately (Table 8).
Table 8. Data for Test 4, showing the attempts and successes at closing and opening the hand. There were a total of 4 inadvertent co-contractions during this test.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Att Close</th>
<th>Succ Close</th>
<th>% Success</th>
<th>Att Open</th>
<th>Succ Open</th>
<th>% Success</th>
<th>Inadv Co-con</th>
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<td>0.0</td>
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<td>0.0</td>
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</table>

Test 5: Lock arm at any angle, unlock arm, relax to freeswing

All subjects performed the arm up and lock operation without any difficulty, but most had problems with the co-contraction to unlock the elbow. All but subject 5, from the experimental group, performed below 80% in the co-contraction portion of this test. On average, both groups performed equally, but the experimental group’s standard deviation was greater than the control’s (Table 9).

During this exercise, many inadvertent hand movements were made while individuals attempted to co-contract and unlock the elbow. When the co-contraction failed, the size of the contraction caused the hand to either open or close. All but subject 3 had inadvertent hand movements. Others had a hard
Table 9. Data showing unlocking success and mistakes during co-contractions exercises in Test 5. The % Error column gives the percentage of inadvertent arm locks to attempts at relaxing the arm to freeswing. The Mstk Total gives the total mistakes with hand operations and accidental locking.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Att Co-con</th>
<th>Succ Co-con</th>
<th>% Success</th>
<th>Mstk Open</th>
<th>Mstk Close</th>
<th>Arm Lock</th>
<th>Att Relax</th>
<th>Mstk Total</th>
<th>% Error</th>
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<td>1.3</td>
<td>2.0</td>
<td>16.8</td>
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</tbody>
</table>

Subjects 2 and 4, both from the experimental group, had the most mistakes of the 10 subjects with 6 mistakes each. There were a total of 28 mistakes during Test 5, and the experimental group made 21 of them.

**Test 6: Lock and unlock 5 times in the full range of motion (ROM)**

In Test 6, the experimental group was able to perform better at the co-contraction than the control group. This time, 66.2% percent of the time the experimental group was able to unlock the elbow. The control group was able to
co-contract successfully only 55.5% of the time. The deviation with both groups is large, with 14.0 for the experimental and 12.9 for the control (Table 10).

All but subject 1 caused their hand to move during the co-contraction. The majority of the hand mistakes were opening the hand, so subjects were favoring their biceps while they were co-contracting. A total of 84 mistakes occurred during this test, with 61 of them being made by members of the control group. Subject 2 had a high number of errors (26) again. Subjects 7 and 10 were next with 12 and 11 respectively.

Other errors in this exercise came from inadvertent locking when the arm was brought to the down position after reaching the top of the ROM. Four of the subjects made the eight locking mistakes.

**Table 10.** Test 6 data showing success rates and mistakes of all subjects while trying to lock and unlock the Utah Arm 2. Total number of mistakes was tallied from hand operation and locking mistakes.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Att Co-con</th>
<th>Succ Co-con</th>
<th>% Success</th>
<th>Mstk Open</th>
<th>Mstk Close</th>
<th>Mstk Hand</th>
<th>Mstk Lock</th>
<th>Att Lock</th>
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<td>4.0</td>
<td>9.4</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>
Test 7: Pick up cup, raise arm, drop arm and cup

Subject 9 overshot the target where the cup was and had to relock the arm to get it in the right position in Test 7. All other subjects were able to move the arm up and lock it without incident. Some subjects confused the hand operations and closed the hand before opening it to grab the cup. Unlocking was below the 80% standard for six of the individuals, and a large deviation existed for both groups (Table 11). The control group had a higher average percentage for successful co-contractions with 79.7% and a deviation of 19.6, and the experimental subjects had an average of 65.9% with a deviation of 28.5. These results were not significant in showing that the control group performed better than the experimental because of the large deviation in each group.

Subjects 2 and 4 had the poorest percentages for co-contraction with 29.4% and 45.5%. Subject 9 also had a low percentage of 55.6% success at co-

<table>
<thead>
<tr>
<th>Subject</th>
<th>Att Open</th>
<th>Succ Open</th>
<th>% Success</th>
<th>Att Co-con</th>
<th>Succ Co-con</th>
<th>% Success</th>
</tr>
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<td>100.0</td>
<td>7</td>
<td>5</td>
<td>71.4</td>
</tr>
</tbody>
</table>

| Tot Avg | 6.4 | 5.0 | 83.2 | 7.9 | 5.0 | 72.8 |
| Con Avg | 6.4 | 5.0 | 82.1 | 6.6 | 5.0 | 79.7 |
| Exp Avg | 6.4 | 5.0 | 84.3 | 9.2 | 5.0 | 65.9 |
| Tot SD  | 1.5 | 0.0 | 15.8 | 2.1 | 0.0 | 19.0 |
| Con SD  | 1.7 | 0.0 | 19.1 | 1.7 | 0.0 | 19.6 |
| Exp SD  | 2.2 | 0.0 | 22.8 | 4.9 | 0.0 | 28.5 |

Table 11. Data for Test 7 showing attempts and successes at opening and unlocking the Utah Arm to pick up and move a cup that was on a desk.
contracting. Three subjects had perfect co-contractions. Two of these subjects (subjects 6 and 8) were from the control group and one was from the experimental group (subject 5).

There were some inadvertent hand movements during co-contraction, but not as many as in Test 6. Subject 2 again had the most mistakes with 5 out of 19. More subjects had a problem of closing the hand instead of opening it at the end of the procedure to let the cup drop. Table 12 shows the data recorded for these two measurements.

Subjects were able to lock and control the arm fairly well. There was no inadvertent locking of the elbow during the descent of the arm with the cup.

Table 12. Information on inadvertent hand movements during unlocking of the elbow and success rate of dropping a cup at the end of Test 7. Total mistakes are determined by adding Mstk Hand and the unsuccessful drop attempts (Att Drop – Succ Drop).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Mstk Open</th>
<th>Mstk Close</th>
<th>Mstk Hand</th>
<th>Att Drop</th>
<th>Succ Drop</th>
<th>% Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1.0</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4.0</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4.0</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>8</td>
<td>5</td>
<td>62.5</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
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<td>0.0</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>0</td>
<td>1.0</td>
<td>8</td>
<td>5</td>
<td>62.5</td>
</tr>
<tr>
<td>Tot Avg</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>5.9</td>
<td>5.0</td>
<td>87.5</td>
</tr>
<tr>
<td>Con Avg</td>
<td>0.0</td>
<td>0.2</td>
<td>0.2</td>
<td>5.4</td>
<td>5.0</td>
<td>93.3</td>
</tr>
<tr>
<td>Exp Avg</td>
<td>1.0</td>
<td>0.8</td>
<td>1.8</td>
<td>6.4</td>
<td>5.0</td>
<td>81.7</td>
</tr>
<tr>
<td>Tot SD</td>
<td>0.7</td>
<td>0.6</td>
<td>1.3</td>
<td>1.2</td>
<td>0.0</td>
<td>14.8</td>
</tr>
<tr>
<td>Con SD</td>
<td>0.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.0</td>
<td>9.1</td>
</tr>
<tr>
<td>Exp SD</td>
<td>1.0</td>
<td>1.1</td>
<td>2.0</td>
<td>1.5</td>
<td>0.0</td>
<td>18.8</td>
</tr>
</tbody>
</table>
Computer Testing

After completing the at-elbow testing, all subjects were tested on the Myotrain software to compare results and abilities between the subjects. A problem that subjects encountered in these exercises was the locking of the elbow. Subjects would be resting and their elbow would lock before or during their test exercise. Since there was no manual override for the lock in the procedure used during testing (Practice Complete Control), subjects were told to act as if they were in the arm mode to mimic the arm up and then relaxation of the muscles. If a subject inadvertently locked the arm and the model moved into the Locked State (Hand Mode) during Computer Tests 1 and 2, information was recorded as if they were in the Unlocked State (Arm Mode), moving the arm up and down. The contractions to control the raising and lowering of the elbow and the closing and opening of the hand are essentially identical (Fig. 36, Fig. 37).

Figure 36. Computer Tests 1 and 2 for subject 3 with the arm in Unlocked State. Channel A signal caused the arm to move up, then the biceps was relaxed to freeswing (10-60 s). For Test 2, Channel A signal caused the arm to move up, then the Channel B signal moved the arm down (85-125 s).
Computer Tests 1 and 2 from subject 6, showing the EMG signals when the arm was in Locked Mode. The contractions are essentially identical to Fig. 36. Arm locked at 7 s. Test 1 (10-60 s) and Test 2 (70-105 s).

Because of this close similarity, users were not asked to get out of the Locked State before completing the particular tests.

**Computer Test 1: Arm up, relax to freeswing**

All subjects were able to perform the task of contracting their biceps to mimic the arm moving up, and then relaxing to cause the arm to go into freeswing mode. Six of the subjects (2, 4, 5, 6, 7, 8) caused the arm to go into Locked State during this exercise. All but subject 8 were able to contract the biceps and then relax. Subject 8 was not able to contract his biceps because when he did, his triceps also contracted. He did not get any signal strong enough from the biceps to make the arm move up or hand open.

**Computer Test 2: Arm up, force down with triceps**

All subjects were able to perform the correct muscle contractions of biceps and triceps except for subject 8 (Fig. 38). His muscles were still favoring the triceps and thus the arm was not moving up and the hand was not opening.
Subject 8 favored the triceps (Channel B) during most of the computer tests. At all times except about 115 s, the triceps are stronger than the biceps. The arm never went up during this exercise because the triceps were favored.

During this trial, some subjects were in the Hand Mode but were able to perform appropriate contractions that would cause the correct actions for Test 2 if the arm were in the Unlocked State.

**Computer Test 3: Open hand, close hand**

All subjects performed well on this exercise except subject 8 for the same reasons as in Tests 1 and 2. Subject 10 closed the hand before opening it the first time, but then made the correction and completed the test.

**Computer Test 4: Close hand, open hand**

Subject 8 was still favoring the triceps and therefore was not able to cause the hand to open. Subjects 4, 5, 7, and 10 opened their hand first before they
closed the hand but they were able to correct themselves and finish the rest of the test by closing and then opening the hand.

**Computer Test 5: Lock and unlock 5 times**

There were many co-contraction attempts, but few successes at unlocking. The average co-contraction percentage in this part of testing was 33.4% with a deviation of 34.3. Experimental subjects did as well as the control subjects on the computer at co-contracting (Table 13).

**Table 13.** Data for Computer Test 5 showing success of individuals at co-contracting. Subjects were asked to lock and unlock their elbow five times during the recording of the data session. Only 4 subjects were able to complete the exercise in the time allotted.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Att Co-con</th>
<th>Succ Co-con</th>
<th>% Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>1</td>
<td>3.3</td>
</tr>
<tr>
<td>2</td>
<td>37</td>
<td>1</td>
<td>2.7</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>2</td>
<td>12.5</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>5</td>
<td>22.7</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>5</td>
<td>100.0</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>5</td>
<td>83.3</td>
</tr>
<tr>
<td>7</td>
<td>14</td>
<td>5</td>
<td>35.7</td>
</tr>
<tr>
<td>8</td>
<td>41</td>
<td>3</td>
<td>7.3</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>2</td>
<td>50.0</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>1</td>
<td>16.7</td>
</tr>
</tbody>
</table>

| Tot Avg | 18.1 | 3.0 | 33.4 |
| Con Avg | 19.4 | 2.6 | 31.3 |
| Exp Avg | 16.8 | 3.4 | 35.6 |
| Tot SD  | 13.8 | 1.8 | 34.3 |
| Con SD  | 15.9 | 1.5 | 34.5 |
| Exp SD  | 13.2 | 2.2 | 37.9 |

The locking of the arm was performed well by all the subjects. After subjects successfully co-contracted, some forgot to move the arm up to unlock, and the computer did not give them any additional feedback until they moved the arm up. Many of the subjects were favoring their triceps during Test 5, and
the graphs showed the triceps graph above the biceps (Fig. 39). It appeared that this favoring of the triceps caused the software to not respond as quickly to the co-contraction attempt, and feedback was not given by the computer to show what was actually happening. The algorithms were checked for bugs, but none were found. It is not known why the software reacted this way.

Figure 39. Subject 3 received feedback at 200 and 205 s, but no feedback until 295 s because he was favoring his triceps. At 295 s he had a successful co-contract. The unlock did not occur until 330 s when the arm went up (Channel A flexed).

In calculating the results for the co-contraction successes in this portion of the program, only the spikes where a co-contraction occurred and the software gave feedback were counted as co-contraction attempts. The other spikes where no feedback was given (220 to 295 s in Fig. 39) were ignored. Results would probably have been different if the computer was able to pick up the signals correctly when the subjects favored the triceps.
DISCUSSION

The results presented indicate that the Myotrain program was successful as a trainer because subjects were able to control the Utah Arm immediately after their electrodes were connected to it. None of the differences in the testing results were significant (p > 0.05) when compared on a mixed procedure F-test. The lack of significant differences between the control and experimental subjects is an indication that the software trainer was able to train subjects just as well as the at-elbow training. Discussing the results can help draw conclusions on the effectiveness of the trainer and find the strengths and weaknesses of the software.

Learning Procedures Results

Both groups were able to learn how to use the Utah Arm 2. Progress was made throughout the time that the users were training to use the arm, both with the software and at-elbow with the trainer. The training for the control group was tailored to each individual’s needs and abilities. More time was spent with subjects who had a hard time distinguishing between their biceps and triceps, and less time was spent on portions where individuals already did well, such as the hand movements. This allowed for training to be adjusted to the needs of the individual [9] [14]. The subjects using the computer were able to pace themselves too by spending time on the areas where they needed the most help (co-contraction) and less on the areas they did well with (arm up and down, hand open and close).

Much like actual myoelectric training, elbow locking and unlocking took the longest amount of time to learn and practice [9]. The subjects in both groups took their time to learn this procedure so that they could get used to the dual contraction and control the unlocking mechanism.
The experimental group on average did spend more time training the first two days than the control group. Day 1 was 6 minutes longer than Day 2’s average, probably suggesting that the subjects took more time to read about the software program on the first day and then were able to train more on the second day. The extra time was probably dedicated to learning about the program. Even though they did take longer to train, it was only about 10 minutes longer on average. A potential myoelectric user learning through the software could take as long as desired because there would not be any man hours of a prosthetist or therapist occupied in the training. As the software is improved and more effective training algorithms are added to the program, this time could be shortened if necessary.

The lack of confidence in performing the co-contraction on the software on Day 1 was a major concern. CAI should be edifying and allow individuals to feel good about their performance so that their self-esteem is built rather than making them feel they have failed and causing them to lose interest [18]. After the subjects were done on Day 1, the software was evaluated for any bugs in the co-contraction algorithm. It was found that there was a conflict of information in creating the algorithm. Two sources of literature stated that the co-contraction was a sum of the biceps and triceps [3] [8]. This sum would allow the computer to check the thresholds (Fig. 27) by adding Channels A and B. Using the sum, a smaller contraction strength on each muscle would be needed to reach the threshold. The algorithm that was used during the experiment was based on a telephone conversation with a Utah Arm technician from Motion Control who had stated that the co-contraction threshold looked at each signal strength separately. This would make the users contract harder since each channel is compared separately to the thresholds. The sum was originally programmed into the software algorithm, but then changed to look at the channels separately after the phone conversation. Although there was a mistake, users were still able to successfully co-contract, but not as easily. The software was not updated
for Day 2 or Day 3 of training so that additional variables were not added into
the procedure, but it was noted that a bug needed to be fixed.

The mistake in the algorithm may also explain why the Myotrain users
had to contract much harder to successfully co-contract the arm. With the
computer looking for each signal to go above a certain threshold, rather than the
sum of the two signals, users had to contract almost twice as hard to get the
unlock to function.

Another reason for the lack of confidence in performing the co-contraction
could also have been the lack of additional feedback for the software user. The
at-elbow subjects were not all successful at the co-contraction from the start and
took some time to coach and train. They had feedback from the trainer, audio
feedback from the motor, and visual feedback from the arm itself. Software
users did not have any audio feedback or visual feedback of an arm. The
Myotrain users only had visual feedback from the meters, the Training Feedback
window, and the written instructions. The lack of audio and visual feedback
from an arm may make a difference in the effectiveness of the trainer. Adding
audio files and a visual graphic of an arm to the software may make the subjects
more confident and able to control the unlocking mechanism in the Utah Arm.

It may be important to note that the experimental subjects did feel that
the difficulty of the co-contraction actually gave them a challenge to overcome.
Subject 2 mentioned that having the software harder to operate than the actual
arm was actually beneficial because he trained harder to learn it and do well at
it.

Practice Procedures Results

Practice on Day 2 helped both groups of subjects improve on their control
skills and really learn how to use the arm with practice. Control subjects did
comment that it was easier to move the arm the second day because they felt
that they did not have to contract as hard. The practice time gave them the
chance to experiment and test their ability to fine-tune the control procedures that they had learned the day before. The increase in confidence levels and performance accuracy was an indication that the practice had given them an opportunity to improve and gain self-esteem through success [18].

The experimental subjects were also more confident at their control of the arm, especially with the unlocking mechanism. The extra training time and practice to adapt to what the computer wanted them to do allowed them to be conditioned to co-contract. The co-contraction algorithm had not been changed, so the subjects trained themselves to do what the software expected them to do.

**Testing Results**

The five minutes that subjects were given to get accustomed to the arm on Day 3 was beneficial since the experimental group was able to make some adjustments to control the Utah Arm. Every subject in the experimental group said that they were amazed and happy that they could control the arm when they were connected to it. By observation, experimental subjects began to focus on the visual and especially audio feedback provided by the arm. The sounds of the motors turning, the clicking of the lock engaging and disengaging, and the whirl of the elbow motor when a co-contraction was successful were all used by the experimental subjects during these five minutes. Subjects used these sounds to give them feedback so that they could adjust to the sensitivity of the arm.

Experimental subjects also mentioned that it was easier to control the actual prosthetic arm than the computer model. The contractions did not have to be as strong for moving the arm, the hand, or for co-contracting. One explanation for the higher contractions in the software simulation has been discussed already with the co-contraction algorithm mistake. Another reason for the difference in contraction strengths may be that there was no visual feedback of proportional control on the Myotrain screen. Users were only able to see information telling them that the arm was moving up or down, but there was no
feedback about speed of movement or position. The absence of this feedback may have caused them to not worry so much about the size of the contraction and be concerned more that they were successful at carrying out the instructions.

**Test 1: Arm up, relax down to freeswing**

The first test measured the subjects' abilities to move the arm up and relax the arm into freeswing mode. Moving the arm up was accomplished by both groups, but relaxing was more difficult. During training, some users were not as successful at relaxing and had inadvertent locks when they tried to relax to freeswing. Each group had an equal number of locking occurrences, so there is no difference in the training from at-elbow or the computer to make subjects better at relaxing. Most of the locking of the elbow occurred when individuals would not relax quick enough when the arm was at 135°, and the arm would stay stationary and thus lock.

**Test 2: Arm up, force down with triceps**

Test 2 determined if users were able to move their arm down after they had moved the arm up. There was no emphasis on proportional control, so users could move the arm as fast or as slow as they wanted up and down. Since both groups were able to control the arm, this test indicated that the control and experimental subjects could control the arm up and down.

**Test 3: Open hand, close hand**

Subjects were able to operate the hand properly in Test 3. There was still some confusion for subjects 3 and 9 on which hand operation the biceps controlled when contracted. This could have been more of a problem of concentration rather than a lack of understanding. The main error that was committed during Test 3 was the unlocking of the elbow when switching between the biceps and triceps muscles. Three of the four users who did co-
contract held their arm at 90° and rotated their wrist to get the arm to switch between muscle groups. This position was best for proportional control of the Utah Arm, but also was more prone to the electrodes picking up a co-contraction because it was easier to co-contract in this position when switching between muscle groups. During the two previous days, the at-elbow subjects who preferred this method trained to distinguish between the two signals, but still made errors during the test. The two experimental subjects who co-contracted did so because his arm was being flexed while at 90° (subject 4) and she was switching between the two muscles too quickly causing both to be contracted at the same time (subject 7). Since the mistakes by the individuals were few and even between the two groups, the software trainer can be considered a reasonable trainer for myoelectric use in hand motion.

**Test 4: Close hand, open hand**

During Test 4, subject 8 appeared to be distracted and was not concentrating on accomplishing the tasks of closing and opening the hand. He made 7 of the 8 errors during this session because he mixed the hand operations and contractions, and accidentally co-contracted 3 times. The other subjects showed that they were able to control the myoelectric prosthetic hand by closing and opening it.

**Test 5: Lock arm at any angle, unlock arm, relax to freeswing**

Test 5 was the first test to measure the subjects’ ability to unlock the elbow after locking it in place. Both groups performed essentially the same in the exercise of unlocking. There was less of a variation in the control group’s accuracy but there was no significant difference between the two groups ($p = 0.7495$). The fact that there was not a significant difference between the two groups can show that the Myotrain software could train the users as well as the at-elbow trainer.
Subjects 2 and 10 had the lowest averages of unlocking accuracy of the experimental group with 50.0% and 45.5%. Subject 5 from the experimental group had the best co-contraction accuracy of all subjects with 83.3%. One reason for the low percentage in subject 2 is that he was co-contracting by throwing his arm in an outward motion and “popping” his elbow. This procedure was his interpretation of how to co-contract the biceps and triceps. His method, although functional at times, was not consistent and tended to favor movements in the hand when attempting to co-contract (Fig. 40). This is the main reason why subject 2 had 6 of the 21 errors for inadvertent hand movements (Mstk Hand) during unlocking.

Figure 40. Subject 2 made many mistakes during co-contraction because he threw his elbow to cause both muscles to contract. Sometimes one muscle was favored above another and the hand moved inadvertently. This is what happened from 30-70 s. A successful co-contract occurred at 93 s, and the arm went up to unlock at 108 s.
The experimental group did have 75% of the total errors (21 of 28) in Test 5. This test was the first time that the experimental group was performing an organized set of commands with the actual arm. Because it is a real-life, mechanical object, it has different forces acting on it, actual electrical wiring and battery source that may not run ideally. Individuals who trained on the arm itself were able to adapt to these normal glitches during training, but the experimental group only experienced an ideal arm modeled in software. The mistakes and inability to unlock the arm may have been part of running the actual Utah Arm rather than an ideal or virtual model. These subjects had not trained on an arm that dictated a need for fine-tuning.

Some subjects (4, 5, and 7) from the experimental group locked on the relaxation after successfully unlocking the arm because they did not relax quickly enough. The control group only made one mistake in locking during relaxation, compared to 4 errors committed by the three experimental subjects. The lesser number of errors in the control group could be attributed to their experience with an actual arm and being able to know how the arm locks if relaxation is not done quickly. Creating a more complex model of the arm in software could help to make the transition to the real Utah Arm better and decrease the number of errors committed by experimental subjects.

Test 6: Lock and unlock 5 times in the full range of motion (ROM)

The next measurement for success at locking and unlocking was Test 6. The control group had practiced some of this exercise the previous day and everyone had scored greater than 80% during the practice. The experimental group was performing on average below 80% during Day 2. Both groups were successful at bringing the arm up and locking it in place along five points in the ROM. Observing unlocking success averages, the experimental group actually performed better at the co-contraction than the control group but statistical analysis showed that the difference was not significant (p = 0.4022). Subject 5
again had the highest accuracy of all 10 subjects with 86.2%, the only one above 80%. The lowest percentage was 44.6% held by subject 9 of the control group. The experimental subjects were just as able to run the Utah Arm in this exercise as the control subjects.

Mistakes were again prevalent in this test. Because there were many contractions that occurred—at least 25 locks and unlocks in total for each subject, there were also a number of errors. The control group made 28.8% of the errors, most of them happening with inadvertent hand movements. Since most of the hand mistakes were opening the hand during co-contraction, subjects who made those errors were favoring their biceps over their triceps during the contractions. Subject 2 had a large number of errors again. He had as many errors as all of the control subjects combined. His errors were again due to his co-contraction movement of popping his elbow. Additional feedback could be integrated into the software to watch for users whom might not be as successful at co-contracting and giving them different options and ideas on how to perform the unlocking of the arm.

The inadvertent locking while relaxing the arm was caused again by subjects not completely relaxing when they were at the top of the ROM. Three of the 4 subjects who made locking mistakes were in the experimental group, totaling 7 of the 9 errors. A visual model and more sophisticated computer model of the Utah Arm in software may help reduce the number of errors so that users are aware of the need to relax quicker and not hold the arm stationary for too long.

Test 7: Pick up cup, raise arm, drop arm and cup

The final test with the Utah Arm measured subjects' abilities to integrate all of the operations of the arm into accomplishing a task. Users had already shown that they could move the arm up and down (Tests 1, 2, 5, 6) and cause the hand to open and close (Test 3, 4). Subjects also were able to demonstrate that
they could lock and unlock the elbow (Tests 5, 6). Test 7 put all of these elements together and looked at combining them to pick up and drop a cup.

All subjects were able to bring the arm up and lock it into position to prepare to grab the cup. After locking the elbow, four users mixed up the hand operations and closed their hand before trying to open it. Once subjects had the cup in hand, they tried to contract to get the elbow unlocked. Subjects 5, 6, and 8 were 100% accurate in unlocking their arm. The two lowest scores came from subjects 2 and 4. Subject 4 had a hard time co-contracting because his electrodes were not placed over the triceps completely. This is the location that he decided was the best when he began training on Day 1, and he kept the same location through the experiment. The triceps electrode was too lateral, and therefore received more residual and weaker EMG signals than direct and stronger EMG signals that would come from better placed electrodes. Subject 2 continued to co-contract by throwing his elbow, which brought the experimental average down and increased the number of errors in hand movements (Table 11, Table 12).

The last trial of Test 7 looked at hand operations to see if subjects could open the hand to drop the cup after locking the elbow in place. Half of the subjects made errors closing the hand before opening it to drop the cup. Seven of the nine errors in final hand movement came from three members of the experimental group. The lack of concentration during the trial and the lack of a visual representation throughout training with the software may be the causes of these mistakes. Subjects 5 and 10 were two of the three who made these errors in this exercise. Both of them expressed in the post interview that they were visual learners and would have benefited from having a graphic of an arm on the screen.

**Computer Testing**

The subjects were tested on the computer software to see how each subject performed the tests on the computer software in comparison to the real arm.
This data was taken to hopefully enhance or better explain the reasons for performance in using the Utah Arm. Control subjects were given a brief explanation of the screens for feedback information and then were tested on the software. It was thought that control subjects would be able to use the software effectively since it was supposed to model the Utah Arm on which they had been trained.

**Computer Test 1: Arm up, relax to freeswing**

During the first computer test, it was observed that the arm was easily locked if users did not relax below the freeswing level (Fig. 26), and the arm model went into the Hand Mode. Because the co-contraction was more difficult to perform on the software than on the actual arm, subjects were allowed to stay in the Hand Mode for Test 1 and Test 2. The subjects were not required to unlock the elbow to get back in Hand Mode, but they were required to perform the task as if they were using the arm. The subjects who performed all of Test 1 and Test 2 in Arm Mode were subjects 1, 3, 9, 10. All others either locked their elbow before or during the test exercises.

Subjects did not have a hard time performing the arm up task. The difficult part for some was the relaxation. Subjects 1, 4 and 5 forgot to relax after their first trial and forced the arm down with a contraction. Subject 8 had a difficult time on the computer getting a good biceps signal to separate from the triceps signal. He favored his triceps whether he was flexing his arm or extending it. In all of Test 1, he was able to relax his triceps once.

Despite the glitches with the locking mechanism in the computer software, both groups were able to control the computer model by moving their muscles. Typical graphs depicting correct movement in Test 1 are found in Figures 36 and 37.
Computer Test 2: Arm up, force down with triceps

In Test 2 on the computer, subjects controlled the arm up and down by contracting the biceps and triceps. Subject 8 still did not differentiate the signal between his two muscles, so the arm never went up in his trials (Fig. 38). All other subjects were successful in this test.

Computer Test 3: Open hand, close hand

This test was successful in showing that subjects were able to move the hand. Subject 8 was able to open the hand the first time (115 s), but then failed at other attempts because he was still favoring the triceps (Fig. 38). Subject 10 was the only one to close the hand before opening it the first time. She expressed in her post interview that the hand operations were unnatural because flexing the biceps should close the hand and the triceps should open the hand. As mentioned before in the Methods and Materials, the operations were reversed in the hand that was sent from Motion Control, so users were taught on the computer and at-elbow to run the hand in the atypical mode.

Computer Test 4: Close hand, open hand

During Test 4, subject 8 was still favoring the triceps and therefore was not able to cause the hand to open. He did contract the biceps, but the triceps was still a stronger contraction and the difference caused the hand to close when it was supposed to open. Subjects 4, 5, 7, and 10 opened their hand first before they closed the hand. Subject 6 was actually in the Arm Mode during this exercise because he had co-contracted about 10 seconds before the trial began. He continued in the arm mode and performed the contractions as would have been done in the Hand Mode.
Computer Test 5: Lock and unlock 5 times

The last computer test was a challenging test for many of the participants because they had to co-contract their muscles and cause the elbow to lock and unlock. All did well with the locking, but there were problems with the unlocking. First, the algorithm for co-contraction was inaccurate because it did not take the sum of the biceps and triceps signal to calculate the high and low co-contraction thresholds, but rather looked at each signal separately. Despite the mistake in the algorithm, software users were still able to train themselves to co-contract on the computer, and accomplished the unlock successfully on the arm. Because experimental subjects could control the arm's unlocking mechanism, the software was successful in training users to unlock the Utah Arm 2.

The second problem encountered with the software during this test was that the feedback would hang up in two instances. First, when users favored their triceps during a co-contraction the software was not able to determine if it was a correct or incorrect co-contraction (Fig. 39). All subjects except subject 7 had this occur to them at least one time during their trials. No feedback was given in the Training Window when the triceps were favored to tell them if they had performed any action (correct or incorrect). The other problem that occurred in this test was the feedback that was given when subjects successfully co-contracted their muscles to unlock. To complete the unlock, the arm needed to be lifted up a small amount to release a pin from the locking position. In the software, after the successful co-contraction, there was a quick flash of feedback telling the users to relax their muscles and then move the arm up. For most subjects, this message flashed too quickly and many missed it, thinking they were still in the Locked State. The feedback would not respond to any actions done by the EMG signals until the user relaxed and then raised the arm (Fig. 41).
Figure 41. The Training Feedback Window did not give any information to the user after a successful co-contract until the user relaxed and contracted the biceps (Channel A). Subject 6 successfully co-contracted at 120 s, but did not see any feedback until 197 s.

The bugs that were encountered in the software will be fixed. These may have been the reasons why the Myotrain users were not able to co-contract as well from the beginning because the feedback was insufficient and too fast for them. In the post interviews, all but one subject recommended that there be larger text and/or scrolling text in the feedback window to help view past messages.

The inaccuracy of co-contractions during the computer Test 5 could be explained by the reasons above. It is interesting to note that the best and worst scores for the computer test came from experimental subjects (100.0% and 2.7%). Subject 2 had the lowest score mostly due to his manner of co-contracting, while subject 5 was perfect at co-contracting in Computer Test 5. Their low amounts are most likely due to co-contraction style and electrode placement. Subjects 6 and 9 were the most successful of the control group to co-contract on the computer, with 83.3% and 50.0% respectively.
Only the contractions where computer feedback was displayed in the Training Window and in the subject database were counted as co-contraction attempts. If all of the attempts had been detected and counted, the results might be different for each subject. If the attempts were failed co-contractions, the co-contract success percentages would be lower. If they were successful co-contractions attempts, then the numbers would bring better results. No significant differences can be drawn from the co-contraction portion of Test 5 because the numbers were so widely distributed and almost random. The lack of difference shows that both groups were able to make the software arm model co-contract at about the same success rate. Figure 42 is a graph showing the co-contraction successes of all subjects in Tests 5, 6, 7, and Computer Test 7. It can

**Figure 42.** Subjects were compared looking at their success in unlocking the elbow in each of the unlocking tests. Subject 5 was the only individual who was always above 80%. Subjects 2 and 4 were the poorest performers at this exercise.
be observed that subjects 2 and 4 had the lowest co-contraction accuracy of all
the subjects. The two top performers were subjects 5 and 6, with the former
always performing above 80%.

**Other Discussion**

An interesting observation was that certain individuals had less errors
than others (Fig. 43). There were far fewer errors committed by the control
group during testing of the Utah Arm. The reason for the disparity has been
explained in the previous paragraphs, but basically could be due to switching
from a simple, ideal model on the computer to the realistic model of a
myoelectric prosthesis. Individually, subjects 2 and 4 had the most errors with
38 and 24, while subjects 1 and 9 had the least with 7 each.

![Figure 43](#)

**Figure 43.** Total mistakes made by subjects varied. Experimental subjects
had more mistakes than the control subjects. Subject 2 had the most
mistakes, while subjects 1 and 9 had the least.
Despite the large number of errors, subjects trained on the Myotrain software were able to pick up a Utah Arm and operate it just as well as the control group that was trained at-elbow. This is important because the Myotrain software was a simple, uncomplicated model of a Utah Arm that was successful at teaching adults to operate a myoelectric prosthesis. Making the computer model more complex and realistic may help make the computer significantly more effective as a trainer. The complex model may also help to decrease the errors committed by the software trainees.

During the post interviews, experimental subjects felt that they were well prepared to operate the myoelectric prosthesis. They mentioned that there was some fine-tuning and adjustments that had to be made to get accustomed to the Utah Arm, but they were pleasantly surprised that they could operate the arm.
FUTURE CONSIDERATIONS

In today's technological world, there are advantages in moving toward software training programs for individuals learning to use a myoelectric prosthesis. Software training can save time and money for the potential prosthetic user. The user can test out the use of a prosthesis in his or her home before deciding if purchase is warranted. The individual can also pace the training while the computer gives feedback. While the user is not at-elbow with the prosthetist or therapist, the computer software can also help to reinforce training that was done before being fitted for the prosthesis. Using this software for children would be a creative way to help them learn the control of myoelectric devices, as Lovely showed with his myotrainer in 1990 [16].

The software trainer can also help prosthetists and therapists so that they can have an additional resource to train the users when they are not present. The extra repetition of tasks should help to accelerate the control efficiency and success of the user. This will ultimately allow the user to start wearing the prosthesis sooner and start living a normal life more quickly.

Software Enhancements

There are many improvements that can be made to the software prototype, and additional experiments that can be performed to investigate other questions proposed through this research.

Some additions or changes that can be done to the software package include software features, training features and integration features.

Software features

There can be an additional graphical interface with videos or graphics of an arm that moves as the user is controlling the arm with the electrodes. This would provide the user with additional visual feedback and a reality of what is
being done. Audio feedback and instructions could also be added to the program to allow the user to have oral feedback from the computer on his or her performance during control procedures. Listening to the sounds of the motors and locking mechanism would also help to give the computer trainees additional feedback that will help them when they transition from the model to the actual arm.

Future research could look at which graphs are actually better for feedback purposes. In the post interviews, most users relied on the dials, the oscilloscope, or the training feedback, but no one used the histogram chart. The histogram chart was chosen from the beginning of the study as a result of a preliminary survey given before the software was created. Adding a bar graph as Lovely [16] and Sears [7] [13] have done in their simulations could be useful to users. Giving the subjects an option to pick and choose what feedback screens they want to use may be a good option to add.

Additionally, timing clocks or mechanisms showing the rate of contraction and locking time would also be effective to give more detailed feedback on locking and unlocking procedures. Sears has included a bar graph for this timing mechanism in the ProControl 2 software package [7].

In a future edition of the software, an improved database system will help to give better and more accessible feedback to therapists and users on demand or once training is done [2].

Improving navigation and menu options and links will help to ensure that users are able to get to a part of the program that they want quickly and efficiently [2]. This will keep users from having to go to the Main Menu in order to get back to the training menu when they end their session.

Training features

The training feedback features used were simple but useful. More complex algorithms could be incorporated into the design of the software to allow
the program to adapt to each user and train in the areas that are deficient. This would allow the training to be more personal. Games and fantasy exercises could be added to the software to increase the motivational content of the program [16] [18]. This would allow users to become intrinsically motivated to do well in performing control of the myoelectric prosthesis because they are being challenged and trying to attain a goal [18]. Lovely’s training program for children started this idea of gaming, but it needed more elaboration and creativity to be added [16].

Additional training improvements for the software would include a hard copy printing of the performance after a practice session or after the complete training session. Either the user or the therapist could use this print out to assess performance and to provide a documented copy of achievement and effort. In the testing and practice areas, additional ADL examples could be incorporated into the training routine to help the user see the end-goal of the training and a practical use of the arm in real-life applications.

Integration with myoelectric devices

Motion Control has started to market a software package that will control a ProControl 2 (below elbow) myoelectric arm [13]. The software allows the user to change settings in the arm through software, rather than opening up the arm and altering the settings with a screwdriver. The Myotrain software package created with this thesis research could be adapted so that it would be able to communicate with any prosthetic device and provide feedback from the device to the computer trainer once the individual is fitted with the arm.

Additionally, this computer program could be set up to adapt to different arms, so that Motion Control, Liberty Mutual, Otto Bock, and other myoelectric arm manufacturers could have their settings read and controlled by the software package. This would allow a user to select his or her myoelectric arm at the beginning of training and the software trainer would adapt to the different
features and functions of the device for instruction and training. A software package of this type would allow users to test arms and find the ones that would suit them best.

An educational section on different myoelectric arms and their advantages could also be included in the software to help educate the users or potential users on myoelectric prostheses.

**Additional Investigations**

There are further questions that can be researched as a result of the research done on this adult myoelectrical software trainer. First, audio feedback has been used with some myotesters to teach individuals to use the EMG signals. No documentation could be found showing that audio feedback is helpful in training users to identify and train to use EMG signals. Jacobsen and others reported the need for more research in this area in their initial presentation of the Utah Arm [4]. Preliminary observations from this experiment show that those who trained on the Myotrain software used audio feedback from the Utah Arm when they operated the arm for the first time. Further investigation could prove if this is actually true and give beneficial information to prosthetists and therapists.

The gauges that were used in this software program were chosen because of a survey that was conducted informally with 21 individuals. A more in-depth survey could be done to see what the best gauges would be to use to display information to the user. An experiment could also be done that allows users to train on different gauges to monitor their success rates relative to the types of displays they chose to use in the software.

Additional investigations could look at studying the efficiency of the EMG signals and control of the arm over time as the individual begins to fatigue. This could look at an adaptive signal like the ProControl software has created [7], and how the signal sensitivity will change with fatigue.
Other experiments could research ways to control more than one motor at a time, alternative ways to switch control of motors, and also investigate the ability to control individual myoelectric fingers with muscle contractions.

The field of biomedical engineering is a growing and expanding field. Unfortunately there is not much funding going into research in the upper-limb myoelectric industry [4] [13], but advances will be made over time as questions are answered and new ideas are put to reality. This research has helped to show that software simulation programs can be used to teach adults control sequences operating the Utah Arm 2. Further explorations and advances can help to improve the lives of amputees who use myoelectric prostheses.
APPENDIX A: GAUGE PILOT STUDY

Some of the following graphs are to be used for a software program that will measure myoelectric signals when an individual contracts different arm muscles. (Myoelectric: voltage signals that occur in muscles when they are contracted).

![Graph example]

Figure 1. Example of a how myoelectric signals are normally graphed or displayed.

Normally, a signal is graphed according to time (x-axis=time, y-axis=myoelectric signal in volts)

If you were to use the software program, which graph or graphs would you like to see to display the strength of a myoelectric signal? (circle three) (Figures 1, A-J used by permission from each author written in italics next to their respective meter)

A. Analog Meter (Mark C. Malburg)
B. Mixture of Line Graphs (Yuheng Zhao)
C. Histogram (Ken C. Len)
D. Progress bar with text (Chris Maunder)
E. Progress bar with a color gradient from low to high (Matt Weagle)
F. Progress bar with a bitmap (picture, graphic, or standard color) (Davide Calabro)
G. Pie Chart (Yuheng Zhao)
H. Oscilloscope reading (like the normal graph in Fig. 1) (Mark C. Malburg)
I. Round dial (Daniel Frey)
J. Slider graph (Pedro Pombeiro)

Which three would you not want to see displayed? _____ _____ _____

On some myoelectric prostheses, a certain amount of time is needed to hold a contraction to activate a control feature (such as locking the elbow motor in place).

If one of the graphs were used to display the time, which three would you choose to see?

_____ _____ _____

Which are the least desirable? _____ _____ _____

Would you rather see the time on a clock or a digital stopwatch-type display? (circle one)
Figure A1. Examples of meters and gauges used in a survey which helped determine which feedback displays were used in the Myotrain program.
APPENDIX B: AGREEMENT AND SURVEY

Below is the information and survey given to subjects prior to the experiment.

Dear Participant:

Thank you for your interest in participating in this research that looks at training individuals to use myoelectrically controlled motors with a software program. This research will help to determine the effectiveness of software training in the prosthetic industry. This training may help to save time for patients as it can supplement or replace signal training done by a prosthetist. Individuals can train themselves to control prosthetic devices before being fitted for a myoelectric device and without having a prosthetist sitting at elbow.

If you decide to participate in this research, you will be identified by a number (i.e. Subject #4). This number will be used to analyze the data that will be collected by the software program you will be using. Only the researcher, Scott Openshaw, and Dr. Patrick Patterson, his Major Professor, will have access to the documents that link your personal information with your subject number. After the research is completed, all references to individual names will be destroyed and only subject numbers will be kept on record. The data to be collected during training will include such items as: strength of myoelectric signal produced, success at carrying out commands, and motor control information.

You will be carrying out the training program for 3 days (1-2 hours the first two days, and about 1 hour the third day). You will be trained to learn how to control the myoelectric signals for 2 days and then will be tested on the 3rd day for proficiency. You will be randomly selected to be in either the control group or the experimental group. The individuals in the control group will receive at-elbow training using an actual myoelectric arm. Individuals in the experimental group will be trained through the Myotrain software. Both groups will be tested using the myoelectric prosthesis.

In this experiment, you will have electrodes connected to your upper arm muscles to measure their electromyographic (EMG) signals. Velcro will be used to keep the electrodes in place. You may have a mild discomfort if the hooks of the Velcro are against your skin or if the strap is too tight. If you are in the control group, your arm will have to be wet with water during the EMG testing portion of the training. Precautions have been taken to ensure that there are no dangers of electrical shock in this experiment when your electrodes are connected to a PC.

During the software training procedure, you will be instructed to flex your arm muscles in different sequences and for repeated amounts of times. Occasionally, but not often, this may cause your muscles to become fatigued and sore.

You will not receive any monetary compensation from participating in this research.

Your participation in this experiment is voluntary and you may terminate your participation at any time by contacting the researcher, Scott Openshaw: 294-1197 or opee@iastate.edu.

If you have any questions or concerns before or during the training experiment, please contact Scott Openshaw.
Survey given to individuals on the first day of experiment:

Name ____________________________ Gender ______

Age ______

Address ____________________________
______________________________
______________________________

Phone ____________________________ Email ____________________________

Please circle one of the following answers in each question below:

YES NO Do you have a pacemaker or other internal electronic device?

YES NO Are you pregnant?

YES NO Have you ever used a myoelectric prosthesis?

YES NO Have you ever seen electromyographic (EMG) signals before?

YES NO Are you comfortable using computers?

What is your expertise of computer use?

NO EXPERTISE BEGINNER INTERMEDIATE ADVANCED

How often do you use a computer?

NEVER SELDOM OFTEN DAILY (monthly) (weekly)

How often do you play computer games?

NEVER SELDOM OFTEN DAILY (monthly) (weekly)

How often do you use computer simulation or training programs?

NEVER SELDOM OFTEN DAILY (monthly) (weekly)
APPENDIX C: POST-EXPERIMENTAL INTERVIEW

Subjects were asked the following questions after being tested to run the Utah Arm and the Myotrain software.

1. Was the screen layout appropriate for this application?
2. Were the screen colors appropriate?
3. Were the dial meters helpful in training?
4. Was the histogram helpful in training?
5. Was the oscilloscope helpful in training?
6. Was the training feedback sufficient?
7. Which windows did you rely on most for training?
8. What windows would you like added?
9. Were the color-coded channels helpful?
10. Were the instruction windows helpful in teaching you about the arm's/software's function?
11. Was it easy to navigate in the instruction window
12. What improvements would you suggest with the displays?
13. Was the trainer successful in teaching you how to use an arm?
14. In what ways was it successful?
15. In what ways was it not successful?
16. Any other comments?
REFERENCES


http://www.libertymutual.com/corporate/technology/utaharm.html
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