Augmented reality improves myoelectric prosthesis training

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ABSTRACT

This paper presents the ARM Trainer, a new augmented reality-based system that can be used to train amputees in the use of myoelectric prostheses. The ARM Trainer provides users with a natural and intuitive method to develop the muscles used to control a myoelectric prosthetic. In addition to improving the training process, the new interface has the potential to mitigate psychological issues arising from amputation that are not addressed by existing approaches (e.g., self-image, phantom limb pain). We conducted an empirical study comparing our system to an existing commercial solution (Myoboy) and found the ARM Trainer to be superior along a number of subjective dimensions (enjoyment, perceived effort, competency, and pressure). We also found no significant difference in terms of muscle control development between the two systems. This study shows the potential of augmented reality-based training systems for myoelectric prostheses.

1. INTRODUCTION

Following the loss of a limb, amputees face a number of problems including adapting to a new body image, relearning how to perform simple tasks, and coping with psychological and physical pain. Prosthetics can alleviate many of these difficulties, but require a great deal of skill to operate efficiently. Myoelectric prostheses monitor muscle activity using surface electromyography (sEMG). As amputees contract specific muscles, the sEMG system detects the change in the electrical signal from the muscle and uses it to drive a set of motors within the prosthetic device. Amputees need to learn how to control the contraction of their muscles, in particular the level of activation of the muscle, and how to isolate independent muscles. A substantial training period is required before amputees can reliably use their myoelectric devices.

There is often a long delay between amputation and receipt of the custom prosthetic. While waiting for their prosthesis, therapists work with an amputee and encourage them to voluntarily activate target muscle sites (e.g., "Try to contract your biceps") (Dupont and Morin, 1994; Smurr et al., 2008). This is a challenging task, as there is little or no feedback provided to an amputee about their progress and the exercise is monotonous. When a prosthetic device arrives, the amputee can begin training with the actual device, but often experience irritation on their residual limb from the device. This prevents training for any extended periods of time. Amputees who do not receive a prosthetic limb soon after amputation are unlikely to ever use them in daily life. Instead, many amputees learn how to perform tasks unimanually. By the time their prosthetic limb arrives, they often feel that it is more troublesome to learn how to effectively use the prosthetic limb than to continue with their unimanual life (Burkhalter et al., 1976). Training administered prior to arrival of the prosthetic has been seen as an important component in the long-term success of amputees. Several software (Al-Jumaily and Olivares, 2009) and hardware (Dawson, 2012) training methods have been devised. One approach to training is to use a software system such as the Myoboy software suite (OttoBock, 2011), which records sEMG signals and processes them in real time. The Myoboy is a commercial product targeted towards prosthetics training and includes a simple video game controlled using biofeedback. In the game, users are asked to navigate two cars through a series of gates, with the height of each car being proportional to the activity at one of two muscle sites. The game is quite rudimentary, and as such there are many areas that its simple interface neglects (e.g., ease of use, interactivity, and the use of more than two channels). Other groups have developed similar game-based training systems that map muscle activity to on-screen actions. In one system, muscle activity was mapped to paddles in an adapted version of the classic Atari game, Pong (de la Rosa et al., 2008). In another system, users were able to play a modified version of Guitar Hero by activating their muscles (Armiger and Vogelstein, 2008). While these approaches provide engagement and motivation, they require actions that are unintuitive and do not map well to the final prosthetic. Others have chosen to map muscle activity directly to virtual prosthetics (Murray et al, 2006; Al-Jumaily and Olivares, 2009). These projects have shown that training using a virtual prosthetic may be effective, but there is still substantial room for improvement. Most systems employing a virtual prosthetic do not include engaging environments, instead focusing solely on the actuation of the joints, which can become monotonous. Additionally, the virtual representation is often a depiction of a prosthetic on-screen; there is no connection to the user's body. We point the reader towards Dawson's work for an extensive review of myoelectric training systems (Dawson, 2011).

The ARM Trainer has potential to improve an amputee's body image and decrease phantom limb pain, both of which are common afflictions in amputees (Hanley et al., 2004; Desmond, 2007). Self image issues arise when amputees reject their new body image or having trouble adjusting to the new way that they look. Phantom limb pain is a condition where a recent amputee seems to experience pain in the limb that was amputated. To treat this pain, amputees are often placed in front of a mirror-box that reflects their intact limb, so they perceive themselves as having two intact limbs (Ramachandran and Rogers-Ramachandran, 1996). This procedure is often successful, but in some cases the pain an amputee feels persists and virtual reality treatments may be administered (Murray et al., 2006). These problems may be treated by the ARM Trainer, as the amputees can see themselves with two intact arms or with a virtual prosthetic.

We have explored the use of augmented reality as a tool for training muscle control and developed a software interface, the Augmented Reality Myoelectric (ARM) Trainer (Figure 1), to provide a more natural and engaging interface to train for myoelectric prostheses. With this system, amputees are shown a real-time video of themselves with a virtual arm overlaid on their residual limb. The amputee controls this virtual arm by contracting the same muscles that will be used to control their prosthetic. This not only provides an intuitive interface for mapping the muscle activity to arm movement, but also provides a unique, personalized training interface.

2. THE ARM TRAINER

The ARM Trainer is a training system for myoelectric prosthetics that provides an intuitive and engaging way for users to learn to control their muscle activity. The system presents users with a real-time mirrored view of themselves with a virtual arm overlaid on their residual limb. Users are able to control this virtual arm with their muscles and use the virtual arm to play a game (Figure 1).

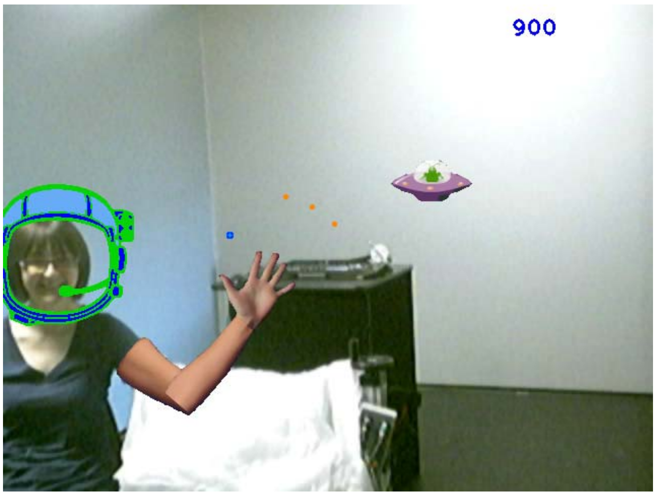

Figure 1. *The ARM Trainer system, as displayed to the user.*

The system is designed to be easy to use and is relatively portable. The custom software (written in the C programming language) combines signals from an EMG amplifier, a model of a virtual arm, and a live video feed. The system is run on a laptop running Windows 7 with a built-in webcam. The only additional hardware required is an EMG amplifier, which is required for all prosthetic trainers. This system is simple to configure and use, with minimal setup and an automated calibration procedure. As therapists have limited time with patients, ease of use is of the utmost importance. In addition, if users are to take the system home and practice outside the clinic, it must be robust and easy to use.

2.1 sEMG Signal Processing

During voluntary muscle contractions, the motor units of skeletal muscles generate electrical potentials that can be detected on the surface of the skin using sEMG. In our system, the sEMG signal is detected and amplified using a Bortec AMT8 system (Bortec, 2011). To digitize the signals from the AMT8 system, a USB National Instruments Data Acquisition System samples 4 channels at 2000 Hz. As the potentials generated by the motor unit result in a complex oscillating signal, the raw data need to be rectified and filtered to be viable for controlling the virtual prosthetic. An approximation of the signal envelope is computed for each channel by applying a root mean square (RMS) filter with a window size of 400 milliseconds to the raw data points.

2.2 sEMG Calibration

As the voltage detected by the electrodes varies widely between users, calibration of the sEMG signal was required. The voltage is dependent on muscle characteristics, the amount of tissue between the muscle site and the skin, and the electrode placement. For a user with weak muscles and high body fat, for instance, the potentials are quite low. If an electrode is not placed directly over a muscle site, there can also be a reduction in the detected signal. By performing the calibration procedure, the system becomes flexible enough to be quickly configured by a home user or a therapist with limited time.

To calibrate the system and determine appropriate gain values (k_i), users are asked to maximally activate each muscle site individually. The system monitored each channel and determines the maximum level of activation. For each of the four channels, the gain value for k_i was set to 1 / 70% of the maximum value of the filtered signal. The value of 70% was derived from pilot studies and represents a comfortable level for people to operate the arm without becoming quickly fatigued. Once the calibration is complete, the resulting k_i values are stored for later use. When the calibrated values are used later, a ceiling function is applied so all values fall within the range [0, 1].

2.3 Virtual ARM

The virtual arm is composed of three photo-realistic segments: a hand, forearm, and shoulder. The forearm and shoulder segments were taken from a still photo of an arm against a chroma key background. The shoulder of the arm was segmented from the background and overlaid at the determined location. The forearm was similarly segmented, aligned to the shoulder segment, and rotated to the calculated elbow angle. The position and orientation of the virtual shoulder can be adjusted using the mouse to manually align the virtual arm with the participant's natural arm. In a clinical deployment, one could place fiducial markers on the amputee's residual limb to locate it within the video stream and automatically align the virtual arm. The hand segment was taken from a 24 frame video sequence of a hand opening and closing against a chroma key background. After selecting the appropriate frame of the video based on the degree of hand closure, the hand is aligned to the distal end of the forearm. The resulting arm is composited with the input video sequence and displayed to the user.

As the user's muscle activity is used to control the movement of the virtual arm, the envelopes of the signals were used to drive the flexion and extension of the virtual elbow, as well as the degree of hand closure. The envelope for each signal (s_{it}) was first multiplied by the channel gain term (k_i) and the resulting value was used in conjunction with the opposing signal as proportional control for the parameters of the virtual arm (θ_{elbow_t} , θ_{hand_t}).

$$\theta_{elbow_t} \propto \theta_{elbow_{t-1}} + k_{biceps} \cdot s_{biceps_t} - k_{triceps} \cdot s_{triceps_t} \tag{1}$$

$$\theta_{hand_t} \propto \theta_{hand_{t-1}} + k_{flexor} \cdot s_{flexor_t} - k_{extensor} \cdot s_{extensor_t} \tag{2}$$

Extension of the virtual elbow joint is accomplished by maximizing the contraction of the triceps while minimizing the contraction of the biceps. Flexion of the virtual elbow is achieved through maximal contraction of the biceps and minimal contraction of the triceps. Similarly, the hand is opened by contracting the muscles on the forearm's flexor muscles and closed by contracting the forearm's extensor muscles. Use of these muscle groups provides a very natural interface for controlling the virtual arm, as there is a direct mapping from natural movement in the real world to movements of the virtual arm. Only one arm model was used in the empirical study. In clinical use, therapists could easily add a model of the amputees' intact limb, allowing them to have a more realistic experience.

2.4 Space ARMada

The gaming element of the system, Space ARMada, features the user as a space explorer who must defend themselves against aggressive, invading spaceships. A space helmet is overlaid on the users' head and spaceships appear sporadically on screen at different locations. The user's goal is to shoot the spaceships down (using the virtual arm as a canon) before being shot at by the spaceships. Points are awarded for successfully destroying a spaceship and deducted if the spaceship fires at the user. Users must alternate between fully open and closed hands to shoot bullets from the hand.

This game trains muscle control by requiring large, fast movements when the arm is pointing far away from the spaceship and finer movements as the arm approaches the correct position. The users can vary the spread and speed of bullets by controlling the speed of hand closure, thus encouraging them to vary their level of activation. As the control is proportional and co-contraction results in a slower movement, muscle independence is encouraged. In addition, the system encourages independence between the forearm and upper arm, as the elbow must remain stable while the hand is opening or closing to remain on target.

3. EMPIRICAL STUDY

An empirical study was conducted to evaluate the effectiveness of The ARM Trainer for muscle training as well as to gather users' subjective opinions of the system. The ARM Trainer was compared to a custom-written software game that mimics the functionality of the commercial Myoboy game. With the custom software (Myoclone, Figure 2), we could record complete data and have users operate both systems without exchanging electrodes. All participants used both the Myoclone system and the ARM Trainer, with the order randomized across participants. Twelve healthy volunteers (6 female, M = 26 years, SD = 3.4 years) participated in the study. While the results are not guaranteed to translate from the healthy population to amputees, this study can provide many insights into the design of training systems. The University of Alberta Arts, Science, and Law Research Ethics Board approved the study.

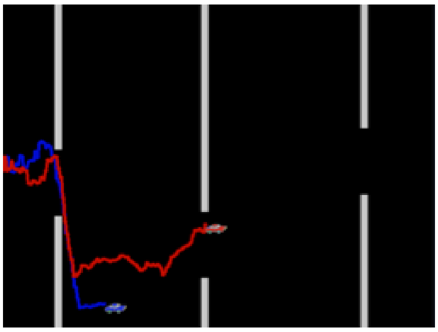

Figure 2. *In the Myo-boy clone, muscle activation controls the vertical position of the cars (e.g., red (top) car controlled by biceps, blue (bottom) car controlled by triceps). The cars move automatically from left to right. The user's goal is to steer the cars through the gaps in the walls.*

At the beginning of the experiment, four muscle sites (i.e., the biceps brachii, triceps brachii, and the muscles used for flexion and extension of the hand: palmaris longus, flexor carpi ulnaris, extensor carpi ulnaris, extensor digitorum) were located on the right arm of the participant. To increase the similarity between the normal population and the target amputee population, two additional steps were taken. First, the participant's arm was immobilized in the apparatus depicted in Figure 3a to prevent it from moving during the experiment. In addition, a white sheet was placed over the participant's arm to ensure that they focused on the virtual arm and not their own arm during the experiment.

Participants then performed the calibration procedure before beginning their baseline muscle control evaluation. The participants' ability to control their muscles was evaluated using a set of bar graphs representing their muscle activity in real time (Figure 3b). They were asked to match their muscle activity to three targets that were presented in sequence at 33%, 66% and 100% of calibrated muscle activity. Each target was active for 8 seconds followed by 8 seconds of rest. Each channel was evaluated in sequence, for a total of 12 targets. Participants were instructed to minimize co-contraction during this task.

As the original Myoboy software only process two signals simultaneously, the Myoclone phase of the experiment was split into two five-minute training segments. In the first segment, participants used their

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forearm muscles to control the height of two cars (by flexing and extending the hand) to navigate the onscreen cars through the gaps in the white gates. In the second segment, participants used their upper arm muscles to perform the same task. Before the training phase, participants were given a brief period to become accustomed to the interface. The ARM Trainer phase consisted of one five-minute session. In the ARM Trainer phase, users played Space ARMada, with the goal of eliminating as many spaceships as possible. Prior to the ARM Trainer phase, each participant had a brief period to become familiar with the interface. While the total time with each system differed, the time spent using each muscle group was the same.

To measure subjective opinions about the game, an adapted version of the Intrinsic Motivation Inventory (IMI) (McAuley, 1989) was used. The IMI is a validated questionnaire that assesses participants' subjective opinion towards an activity and evaluates the activity along four dimensions: enjoyment-interest, competency, effort-intensity, and tension-pressure. The questionnaire includes statements such as 'I enjoyed this game very much' and 'I am satisfied with my performance on this game'. Participants' responses were recorded on a 5-point Likert scale. The questionnaire was administered following each training system.

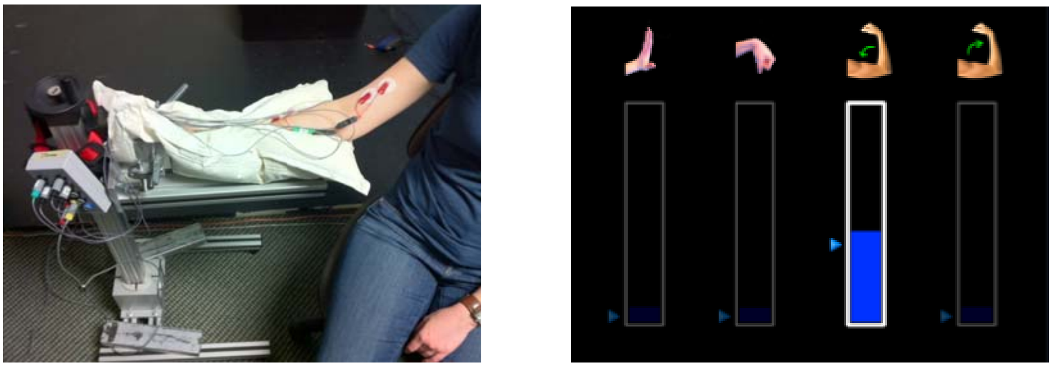

Figure 3. *a) sEMG electrodes placed on a participant in the immobilization apparatus. b) Task used for calibration, as well as the evaluation of muscle activation and isolation. Participants were asked to contract the specified muscle site to the level indicated by the highlighted triangle while minimizing the contraction of the other three muscle sites.*

4. RESULTS

Responses to the IMI were compared using a Wilcoxon signed rank test. For all dimensions, the responses related to the ARM Trainer were significantly better than those related to the Myoclone (Figure 4). Participants reported feeling more interest and enjoyment ($p < 0.01$) and felt more competent at playing the game ($p < 0.01$). Participants also reported that the ARM Trainer seemed to require less effort than the Myoclone ($p < 0.01$), and they felt less tension and pressure while playing ($p < 0.05$).

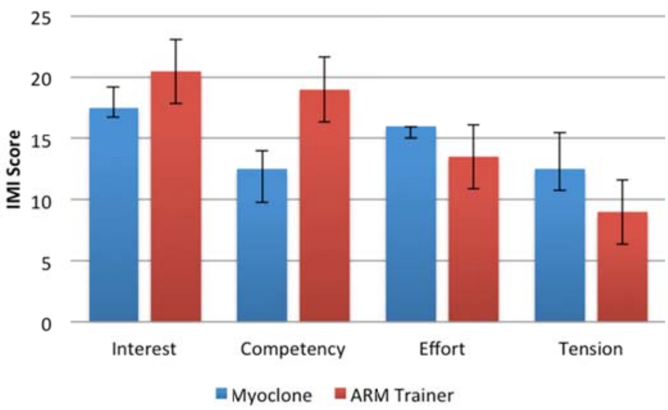

Figure 4. *Responses to IMI questionnaire, error bars show upper and lower quartile of participant responses.*

Muscle isolation was calculated by computing the Pearson correlation between the signals for each channel during the evaluation phase. High correlation between the signals from two muscle sites indicates a high degree of co-contraction of the underlying muscles. The improvement in muscle isolation for each system is the difference between the post-system correlation coefficient and the baseline correlation coefficient for each pair of muscles. This results in six values corresponding to the pairs of muscles (Table 1).

Table 1. *Improvement in isolation following each training system (Myoclone / ARM Trainer). Values represent the unitless change in correlation between each muscle site.*

Muscle Site	Flexor	Biceps	Triceps
Extensor	0.08 / 0.10	-0.01 / -0.05	-0.09 / 0.06
Flexor	-	-0.08 / -0.05	-0.06 / 0.00
Biceps	-	-	0.06 / 0.03

Muscle isolation was analyzed using a paired Z-test on the Fisher-transformed correlation coefficients of each pair of signals. No significant difference with respect to muscle isolation ($p > 0.05$) was found between the ARM Trainer and the Myoclone. Both systems showed small positive improvement in reducing the co-contraction of antagonistic muscles (e.g., biceps and triceps), but no improvement reducing the co-contraction of non-antagonistic muscles (e.g., forearm extensor and biceps).

The accuracy of muscle control was computed as the squared difference between the target (33%, 66%, 100%) and the filtered and scaled muscle activity. For each evaluation, this yields 12 accuracy values (3 for each of the 4 channels). The improvement in muscle control is the difference between the post-system accuracy and the baseline accuracy. Muscle control was analyzed using paired t-tests comparing the post-Myoclone improvements to the post-ARM Trainer improvements. As with the muscle isolation results, no significant differences were found between the two systems. The results show no pattern of improvement in the accuracy of activation with either the Myoclone or the ARM Trainer (Table 2). This is likely due to the short duration of the pilot study.

Table 2. *Improvement in muscle control accuracy following each training system (Myoclone / ARM Trainer). Values represent the unitless change in squared error from the target.*

Muscle Site	33%	66%	100%
Extensor	0.004 / 0.004	0.000 / 0.000	-0.006 / -0.005
Flexor	0.000 / 0.000	0.000 / 0.000	-0.021 / -0.005
Biceps	-0.005 / 0.000	0.001 / 0.000	-0.017 / -0.020
Triceps	-0.005 / 0.0000	0.002 / 0.000	0.056 / 0.068

5. DISCUSSION

Our study of the ARM Trainer shows that it provides an improved user experience over the current standard of care. Participants reported high levels of interest and enjoyment with the ARM Trainer, which could stem from several factors. The novelty of the augmented reality could play a large role as many participants were not familiar with the technology. Several participants laughed, or made positive statements such as 'That's cool!' upon seeing the video of themselves with the virtual arm and space helmet. The game design and visuals may be a factor in the increased enjoyment as well, as the ARM Trainer had more actions to perform, different subject matter and more detailed graphics. Some participants commented that they felt the arm was a natural extension of their body during the trials, even though the arm was clearly an overlay on the image. This is encouraging for the potential treatment of phantom limb pain and self-image issues. If effective, this would be the first EMG-driven treatment option for phantom limb pain, and a step forward for improving the well-being of recent amputees.

The increased competency and decreased effort reported by participants are likely related. The intuitive and natural mapping of the interface plays a role in this, as the actions required less cognitive resources to execute. The reports of decreased effort may stem from an increased engagement in the game and a reduced focus on generating the required muscle activities. It was also evident that several participants had become bored with the Myoclone game, as they began repeatedly making errors by contracting the wrong muscle and then quickly correcting it. The reduced tension and pressure is likely related to the increased enjoyment, as participants were having more fun, making it feel less like training. Feedback may also have played a small role, as a small explosion was immediately displayed in the Myoclone after an error, whereas participants could miss the spaceship a number of times before the spaceship fired back.

The muscle isolation results are encouraging, as the ARM Trainer performed no worse than the Myoclone, even though the Myoclone is targeted specifically at reducing the co-contraction of antagonistic pairs. The improvement in muscle isolation following the ARM Trainer can be attributed to the proportional control of the virtual arm that requires minimization of the antagonistic muscle to achieve movement of the virtual arm. While there was no improvement on non-antagonistic pair co-contraction in our study, we are optimistic that a long term study would show benefit, as the ARM Trainer requires participants to contract multiple muscle sites to perform optimally. Adding direct biofeedback may allow better development of muscle isolation with the ARM Trainer. Several participants struggled initially with the ARM Trainer due to co-contractions. For instance, while trying to extend the elbow, participants contracted the triceps (correct site), but also contracted the biceps (incorrect site), resulting in a net-zero movement for these actions. Participants responded by trying to increase contraction, which tended to only worsen the co-contraction and increase frustration. Direct visualization of the muscle activity for each channel would allow participants to see the co-contraction and respond appropriately.

Our approach has several limitations. Notably, we present a system specifically tailored for trans-humeral amputees. It is easy to imagine a similar system with two degrees of freedom, and only a virtual forearm and hand for below-elbow amputees, but it is more difficult to generalize to lower-limb amputees. An increased suite of games to keep amputees engaged longer, as well as providing additional measures and information on-screen to motivate amputees would improve the system. Additionally, the measures of muscle accuracy are likely not relevant for short task durations. In the initial baseline test, most participants were able to quickly match their muscle activity to each target without much difficulty. More reliable measures of muscle accuracy may be obtained by making this task more difficult by increasing the number of target levels. In addition, any small improvements in muscle activity may have been cancelled out due to fatigue.

6. CONCLUSIONS AND FUTURE WORK

We have shown the potential for augmented reality for myoelectric prostheses training. Our AR-based prosthetic training system allows natural control of a virtual arm using four sEMG channels. Our ARM Trainer performed at a level similar to existing methods in developing muscle control. More importantly, the use of augmented reality was shown to provide a better user experience than traditional game-based systems. This study paves the way for the use of augmented reality in amputee training. A long-term study is currently under development for amputees at a local rehabilitation clinic. This future study will allow self-image and phantom limb pain to be fully explored in the target population.

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