Game-Based Myoelectric Muscle Training

by

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ABSTRACT

For new myoelectric prosthesis users, muscle training is a critical step that promotes effective use and long-term adoption of the prosthesis. Training, however, currently has several problems: 1) existing approaches require expensive tools and clinical expertise, restricting their use to the clinical environment, 2) exercises are boring, repetitive, and uninformative, making it difficult for patients to stay motivated, 3) assessment tools focus exclusively on improvements in functional, real-world prosthesis tasks, which conflicts with other therapeutic goals in early training, and 4) little is known about the effects of longer-term training because existing studies have subjected participants to a very short series of training sessions. While myoelectric training games have been proposed to create a more motivating training environment, commercially available games still exhibit many of these issues. Furthermore, current research presents inconsistent findings and conflicting results, making it unclear whether games hold therapeutic value.

This research demonstrates that training games can be designed to address these issues by developing a low-cost, easy-to-use training game that targets the therapeutic goals of myoelectric training. Guidelines for promoting a fun, engaging, and informative training experience were identified by engaging prosthesis users and clinical experts throughout the design of a myoelectric training game. Furthermore, a newly developed set of metrics was used to demonstrate improvement in participants' underlying muscle control throughout a series of game-based training sessions, further suggesting that games can be designed to provide therapeutic value. This work introduces an open-source training game, demonstrates the therapeutic value of games for myoelectric training, and presents insight that will be applicable to both future research on myoelectric training as well as aspects of training in clinical practice.

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1 Introduction and Background

1.1 Introduction

Upper-limb amputee and congenitally limb-different patients (i.e., those born without a limb) who still possess control over their residual musculature may choose to make use of a myoelectric controlled prosthesis (i.e., a prosthetic limb controlled by the user's muscle contractions). Patients first learning to use such a device often undergo muscle training activities to strengthen their musculature, promoting correct and reliable control of the device. However, existing myoelectric training practices exhibit several problems:

1. Current training tools ***require expensive medical-grade hardware and expert supervision*** which limits the access that patients have to training. Many clinics do not even offer training programs.
2. Existing ***training is monotonous, uninformative, and discouraging***, and has the potential to cause more harm than good. This makes it difficult for patients to stay engaged and motivated during training, possibly even deterring them from further use of myoelectric prosthetics.
3. When evaluating progress during training, many ***assessment tools focus exclusively on improvements in functional, real-world prosthesis tasks***, which conflicts with the therapeutic goals identified by clinical experts during early training.
4. While training is critical for new prosthesis users, ***little is known about the effects of longer-term myoelectric training***. Many previous studies exploring the effects

of myoelectric training have subjected participants to only four or fewer short training sessions.

This research has addresses these issues and contributes to the field of research in myoelectric muscle-training games by:

1. ***Introducing a low-cost, easy-to-use training game*** that makes use of a commercially available input device and requires no expert supervision. The game focuses specifically on targeting therapeutic goals that promote success with myoelectric control.
2. ***Uncovering design insight for promoting a fun, informative, and positive myoelectric training experience*** through a series of user-centered design sessions with experienced prosthesis users and clinical experts. This design insight was incorporated into the game through an iterative development process, and will help inform the design of other therapeutic games in the future.
3. ***Identifying new muscle-control metrics*** that quantify the foundational characteristics of muscle control needed to achieve proficient use of a myoelectric prosthesis. These metrics allow patient progress to be assessed in a way that more accurately represents the therapeutic goals identified by clinical experts during early training.
4. ***Demonstrating that improvement in myoelectric control develops gradually and continually*** by conducting a 300-session user study. This finding has implications for both research and clinical aspects of myoelectric training.

Each of these contributions is further elaborated upon in the following sections.

1.1.1.1 Introducing a low-cost, easy-to-use training game

Based on conversations with an expert from a local prosthetics clinic and observations of a training session with one of her patients, an open-source myoelectric training game was designed. Through this initial experience with the myoelectric training process, the therapeutic goals that therapists focus on during training were identified and incorporated into the training game. A low-cost solution and easy-to-use experience were ensured by making use of a consumer-grade input device and designing the game with intuitive features and game-mechanics. The game is currently being used as a training tool at a local prosthetics clinic.

1.1.1.2 Uncovering Design Insight

A series of user-centered design sessions with experienced prosthesis users and clinical experts was conducted to observe how the training game was used by the intended target audience and to collect feedback and suggestions for further improvements. The game was incrementally improved throughout the series of design sessions based on these suggestions. A thematic analysis was also conducted using transcribed logs of the design sessions to further reflect on user feedback. This information was formalized into a set of design guidelines for promoting a fun, informative, and positive training experience. These guidelines will help guide the future design of myoelectric training games as well as therapeutic games more generally.

1.1.1.3 Identifying New Muscle-Control Metrics

There are currently no validated outcome measures for assessing levels of muscle control and underlying control signal quality, so a set of metrics was identified to fill this gap. The metrics were designed based on knowledge gained through experiences with myoelectric muscle training and conversations with clinical experts. These metrics quantify many of the therapeutic goals that therapists aim to achieve during muscle-training exercises and, in doing so, provide further evidence and support for therapist intuition and clinical experience. By using these metrics during early training, therapists can provide patients with targeted, personalized feedback on their progress.

1.1.1.4 Demonstrating that Improvement in Myoelectric Control Develops Gradually

The newly identified metrics were used to follow the progress of 30 participants as they completed a series of ten 30-minute training sessions. The results of this study indicate that – much like many other complex motor-tasks – improvements in myoelectric control develop gradually and continually throughout training. This suggests that the findings of previous research studies that conducted only a short series of training sessions may not necessarily be representative of myoelectric training in general. It also suggests that assessing a patient’s capacity for myoelectric control early in the clinical training process may not be appropriate, since the patient is likely to continue improving throughout the course of training.

1.2 Background

1.2.1 What is Myoelectric Control?

Myoelectric control operates by sensing the electric signals that emanate from muscle tissue during a muscle contraction. These electric signals are subjected to a series of post-processing steps (discussed in detail below) and then used as input to control a mechanical, electrical, or computer system. Myoelectric control is used in various fields including sports, electrodiagnoses, rehabilitation, and – specifically of interest in this research – as input to control a powered prosthesis. For example, an upper-limb prosthesis user can open, close, rotate, and switch between a variety of finger grips with their prosthetic hand using myoelectric control. Myoelectric control has been used in prosthetics since the 1950's [7], and while the techniques for acquiring and interpreting the raw EMG signals have evolved since then, the main principles of myoelectric control have remained unchanged. The following sections explain how raw EMG signals are read from the muscle contractions, and how these raw signals are then processed before being used as input to control a prosthesis.

1.2.1.1 Reading EMG from Muscle Contractions

Myoelectric signals as a control input are typically acquired using EMG sensors positioned on the skin's surface, directly over muscle sites of interest. Accurate positioning of the sensors is critical, as even a small misalignment or shift can have a significant impact on the signal acquired from the sensor [23]. Surface electrodes are also sensitive to the relative temperature and humidity of the skin, making it difficult to accurately calibrate a myoelectric limb for prolonged use since these qualities often change over the course of daily prosthesis use. Techniques such as implantable electrodes (which mitigate the risk of electrode shift and temperature/humidity changes) [13] and targeted muscle reinnervation[1] (to essentially amplify the muscle signal beneath the skin surface) [26] have been explored to help address these issues. While these advanced techniques show promise for improving the reliability and consistency of signal quality, surface EMG is non-invasive and is, by a large margin, the most prominent approach used in clinical practice.

1.2.1.2 Processing Raw EMG to Remove Signal Variability

The amplitude of an EMG signal is also subject to random variability because the muscle contraction detected by each electrode is actually an aggregate of hundreds of individually firing muscle fibers. To effectively use this signal for myoelectric control of a prosthesis, the raw EMG must be processed in real time. Typically, this involves rectifying the signal and then smoothing the variability of the signal amplitude by computing its mean value over some sliding window of time or computing the square root of the mean of the squared signal. Since most of the power of the EMG signal is known to be bound below 400Hz, with most of the power appearing around 100 Hz,

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[1] Targeted muscle reinnervation (TMR) is a medical procedure that allows nerves that have been damaged or "disconnected" during amputation to be "re-assigned" to control another muscle within the body. This technique can be used to provide patients with more natural and intuitive control over their myoelectric prosthesis.

In one example of TMR [26], the nerves that were originally used for control of the amputated hand were re-routed to instead control the patient's pectoral muscles. By positioning the EMG sensors on the patient's chest, the patient could now "think" about moving their amputated hand to control their prosthesis.

high- and low-pass filters can be used to eliminate other potential sources of noise. A notch filter is also often used to remove the 60 Hz interference from electronics and other electric appliances. To ensure maximum consistency between a real-world prosthesis and the controls in the training game developed in this research, these same processing steps were performed on the raw EMG signal before being used as control input for the game (full details available in **Appendix A**).

1.2.2 The Use of Myoelectric Control in Prosthetics

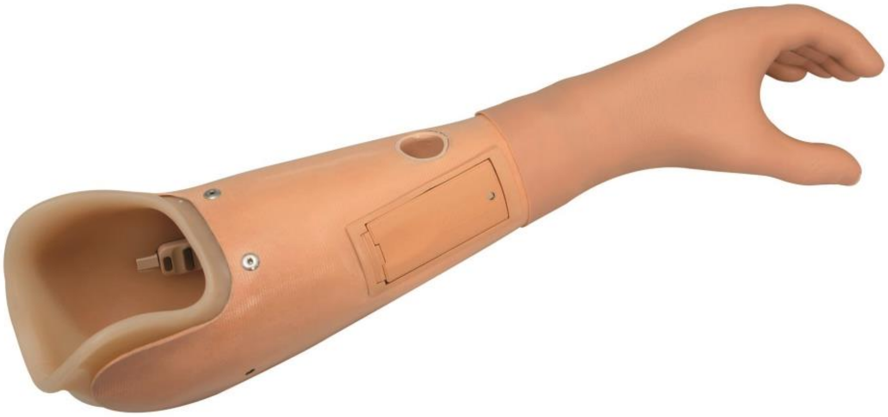

Figure 1-1: Two-Site Proportional Control, Trans-Radial Myoelectric Prosthesis. This device operates by detecting the user's forearm muscle contractions with 2 EMG sensors positioned within the prosthetic socket (just visible inside the device). The user performs a *flexion* (i.e., inner-forearm muscle contraction) to make the hand close, and an *extension* (i.e., outer-forearm muscle contraction) to make the hand open.

Muscle contractions can be used to control a myoelectric prosthesis in many different ways. In this section, one particular method that was explored in this research, known as two-site proportional control, will be discussed in detail. An explanation of how this method of control can be adapted to suit the needs of individuals with widely varying levels of skill will be provided, and alternatives to two-site proportional control will be introduced. Finally, the reasons why two-site proportional control was of specific interest in this research will be discussed.

1.2.2.1 Two-Site Proportional Control

EMG signals have been used in a variety of ways as inputs for controlling assistive devices such as prostheses (i.e., artificial limbs). This research focused on both a specific type of myoelectric control, known as two-site proportional control, as well as a specific assistive device, known as a trans-radial prosthesis (Figure 1-1), which is used by individuals with a mid- to upper-forearm amputation (*trans-radial*) who possess independent control over their inner- and outer-forearm muscles (*two-site*). The user of such a device can *proportionally* control the speed of hand aperture and wrist rotation by varying the strength of their muscle contractions – stronger contractions result in faster movement. For simplicity, this type of myoelectric prosthesis is referred to as a “myo” in the remainder of this dissertation.

In its standard form, two-site proportional control allows the user to contract their outer-forearm muscles (known as an *extension*) to open the prosthetic hand, and contract their inner-forearm muscles (known as a *flexion*) to make it close again. More sophisticated prostheses also support different modes of operation that overload the 2 inputs to allow independent control of another degree of freedom, such as pronation/supination of the prosthetic wrist. Users switch between modes of control with a *mode-switching trigger*, the details of which depend on the exact prosthesis being used. One common example of such a trigger (and the one explored in most detail in this research) is a quick, simultaneous co-contraction of both the inner- and outer-forearm muscles. However, other triggers, such as holding a prolonged inner- or outer-forearm contraction or even flipping a physical switch on the device are also commonly used in practice [46].

1.2.2.2 Adapting Control to Accommodate User Needs

As a result of a traumatic or surgical amputation, or of different developmental limb formation, some prosthesis users have trouble isolating contractions between the flexion and extension muscle sites and experience unintentional co-contraction. This can be detrimental to the standard method of control described so far [45], so the two-site proportional control strategy has been adapted in several ways to make prosthetic use feasible for these individuals. One option is to reduce the method of control to a single input muscle site. The prosthesis will open or close automatically in the absence of muscle contraction (as appropriate, depending on the muscle site used), with the user controlling motion in the opposing direction by contracting their muscle. This approach is known as “auto-open” or “auto-close”. Another option is to algorithmically disambiguate between intentional and unintentional contractions. Some examples of this approach are to ignore all muscle contractions below a particular threshold (i.e., a *minimum activation threshold*), consider only the stronger of the 2 muscle signals as intentional input at any given time (i.e., a *maximum* control policy), or to consider the first of the 2 signals to exceed a threshold as intentional, ignoring the other signal until the first drops below the threshold again (a *first-over* control policy). These and many other adaptation strategies are described in a review of control for upper limb prosthetics [20], in which a taxonomy of existing myoelectric control strategies is introduced and a consistent set of terminology is proposed to be used in future research on the control of upper limb prosthetics.

1.2.2.3 Alternatives Beyond Two-Site Proportional Control

There are different methods for controlling a myoelectric prosthesis beyond the two-site proportional control described so far. On-off control (e.g., simple on/off movements, no variability of speed), three-state (e.g., soft contraction for “open”, strong contraction for “close”), and rate-based (e.g., fast onset contraction for “open”, gradual onset contraction for “close”) are all approaches that can be used instead of two-site proportional control [20], although they are often considered to be less intuitive. Another method of myoelectric control, known as pattern recognition-based control, infers the user’s intended movements from signal characteristics or “features” measured at a number of muscle sites [41]. Unlike conventional control strategies, pattern recognition-based controls are not restricted by a one-to-one mapping between muscle site and motion class (e.g., hand-open, hand-close). This allows pattern recognition-based control strategies to offer a greater number of motion classes without the use of the mode-switching triggers required in conventional control. Pattern recognition is another popular topic of research [15,20,23,26,41,27,29] and has only recently been commercialized in prosthetics after many decades of research.

Some patients alternatively choose to use a non-powered prosthesis. Both passive limbs (i.e., no movement, largely intended for their aesthetics) and body-powered hooks (i.e., a cable-driven mechanism that allows the user to open/close hook by shrugging their shoulder) are popular alternatives to myoelectric control. Myoelectrically controlled devices, however, tend to provide the greatest benefit when performing activities of daily life.

1.2.2.4 Focus on Two-Site Proportional Control

The reason two-site, proportional control was specifically chosen as a focus of this work was because of its immediate clinical relevance. Prosthetic devices that employ two-site proportional control are one of the most popular choices among patients, so many of the existing clinical training tools are designed specifically for this type of control. Proportional control is almost always treated as the first option when introducing a new patient to myoelectric control, and typically only abandoned if proven to be unsuccessful or inappropriate based on the patient's abilities. By improving training for two-site proportional control, this research provides immediate real-world benefit to amputees and new prosthesis users.

1.2.3 Learning to Use a Myoelectric Prosthesis

The training regime[2] for new myo users can be divided into 2 main phases. The first phase, known as the *pre-prosthetic* phase, occurs before the patient even receives

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[2] It is important to note that, in my work, I refer to *user training* (i.e., the act of coaching/encouraging an individual to improve their muscle control and functional prosthesis use) as opposed to *system training* (i.e., the act of priming a pattern-recognition based system to accurately classify input data), a term that is currently also relevant to the field of myoelectric controlled prosthetics.

their prosthesis. Because of changes to the residual forearm musculature that may occur following the amputation surgery (or because of congenital limb-differences[3]), patients may train to identify, isolate, and strengthen their muscle contractions during this early phase of training. Once a patient receives their prosthesis, they begin the *prosthetic* phase of training during which they practice basic prosthetic control in tasks such as picking-up, holding onto, moving, and releasing various objects. In this way, they learn to incorporate myo use into their everyday lives, adapting tasks to increase the utility and overall embodiment of their artificial limb.

Even though pre-prosthetic training is critical for promoting success, it is often overlooked or neglected completely. This section further introduces the pre-prosthetic phase of training, discusses the limitations of commonly used training tools, and explains how inadequate training approaches are at least partially to blame for the current abandonment issues related to myoelectric prosthetics.

1.2.3.1 Pre-Prosthetic Training is Critical, but often Overlooked

While the prosthetic phase of training focuses on practical aspects of myo use, it is often delayed because of factors like post-surgical recovery, prosthesis fitting and fabrication, and insurance processing times. This delay places a heavy importance on the pre-prosthetic phase of training which should begin as early as possible following the amputation to take advantage of neural plasticity and prevent the development and

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[3] "Limb-different" is the general term used to refer to individuals missing one or more of their limbs, whether caused by accident, disease/infection, or congenital birth defect.

habituation of one-handedness – a mindset that can lead to problems with prosthesis use and embodiment later in training [45]. Even though research suggests that training for prosthesis use should begin within the first 30 days following amputation [31], in many clinics patients receive minimal guidance or support during this critical period. This is one reason that the training game developed in this research was designed specifically for use in the pre-prosthetic phase of training.

1.2.3.2 Existing Training Tools – and their Limitations

In clinics that employ specialized therapists to help coach new patients through muscle identification and strengthening exercises, tools like the Ottobock PAULA suite[4] are used [35]. The PAULA suite contains a muscle signal visualization tool, a virtual myo hand, and a "car" game. These tools can help new patients identify and understand their musculature, but – as is detailed in *Article #2: Designing Game-Based Myoelectric Prosthesis Training* – they have several limitations. First, the training exercises are repetitive and quickly become monotonous, making it hard for patients to stay motivated with training. Furthermore, the PAULA suite makes use of expensive, medical-grade

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[4] In addition to the Ottobock PAULA suite, several other training tools are commonly used in clinics. Bebionic [9], a competing prosthetics manufacturer also produces a suite of training software and a stand-alone robotic hand that patients can use to practice with before the fitting of their personalized socket is complete. Tools such as these exhibit similar issues as the PAULA suite, but were not explored further in this research. Additional information can be found in Dawson's extensive survey of existing myoelectric training tools [15].

sensors that require therapist oversight for positioning and calibration, making it unsuitable for use outside of the clinical environment – patients receive no training or support between their clinical visits. Finally, the tools provided in the PAULA suite do not provide patients with the right type of feedback, which can result in a negative training experience and ultimately deter patients from further pursuing myoelectric prostheses.

In many cases, the situation is even worse because most clinics do not employ specialized training staff, such as occupational therapists, to help new patients. In these cases, patients may receive no coaching whatsoever in preparation for their new myo and are essentially sent home to "figure it out by themselves" after fitting and fabrication is complete.

1.2.3.3 Many Myo Users Ultimately Abandon Their Prosthesis

Many myo users ultimately end up abandoning their prosthesis altogether (research suggests that as many as 75% of users ultimately abandon their device [10]), with a common complaint being that the benefits of the myo arm were not sufficient to continue use. This is a huge problem, because, in addition to the numerous hours dedicated by clinicians, technicians, and the myo users themselves, a myoelectric prosthesis can easily cost in excess of 100,000 USD – a massive investment of time and money if it is to ultimately be abandoned.

Again, as is detailed in *Article #2: Designing Game-Based Myoelectric Prosthesis Training*, conversations with experienced users and clinical experts made it clear that this high level of abandonment was at least partially due to insufficient training for patients when first learning to use their prosthesis. The results of a previous survey [47] conducted with 11 experienced myo users further suggests that the reason patients do not find value in their prosthesis could be related to an initial lack of training. In this study, even experienced users reported that the mode-switching triggers used to control their prosthesis were a pain-point and a common source of error and frustration [47]. Since the ability to create quick, accurate, and repeatable triggers can be strengthened and developed through muscle training, this suggests that even these users (and therefore myo users in general) could benefit from further training exercises.

1.2.4 Muscle Training Games

Games have been proposed to address the issues of maintaining motivation and patient engagement that are prevalent in existing training approaches. Games promise to create a fun, engaging, and motivating environment for patients to train their muscles. However, commercially available muscle training games share many issues with other training tools. Furthermore, research on muscle training games presents inconsistent and even contradictory findings, as discussed below.

In this section, a discussion of how existing training games share many of the same issues as other types of training is presented. Then, the currently inconsistent state of research exploring game-based training tools is discussed. Finally, a plan to improve the state of myoelectric training games is introduced.

1.2.4.1 Limitations of Commercially Available Games

Muscle training games have been proposed to address the repetitive and monotonous aspects of traditional pre-prosthetic muscle training approaches, with a handful of commercial games currently being used within clinics (e.g., Ottobock "car game"[5] [35], Bebionic software suite [9]). These games, unfortunately, are not generally well-received by patients, and are even considered as being potentially detrimental to the training experience by some clinical experts [44].

Existing commercial games share many problems with other clinical training tools. First, they still make use of medical grade equipment that is expensive and requires expert guidance to configure and calibrate properly. This restricts the use of games to within a clinical setting, and patients miss out on training between their clinical visits. Second, commercial games do not provide patients with the right type of feedback and require expert coaching and intervention for patients to successfully learn from training exercises and improve their muscle control. Finally – and perhaps most salient to this research – existing games focus solely on therapeutic goals at the expense of patient engagement and quickly become repetitive, mundane, and ultimately discouraging for new patients.

1.2.4.2 Inconsistent Findings on Game-Based Training

There is currently little consensus on myoelectric muscle training games in the literature. Some work, which focuses on the technological challenges of designing myoelectric controlled software, presents examples of games and suggests their

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[5] An in-depth description of the "car game" can be found in *Article #2: Designing Game-Based Myoelectric Training*.

applicability to pre-prosthetic training [3,5]. However, other research suggests that certain games may be no more effective than any other type of training [16,45] or even a total lack of training altogether [17]. It is also currently unclear whether the game activity must be “task-similar” to real-world prosthetic use (e.g., a virtual hand “grabbing” game) in order for training to be effective [17], or instead, whether it is simply beneficial to have patients actively using and improving control in their forearm muscles [14,38].

The inconsistencies in myoelectric games research may be attributed to how previous studies have chosen to evaluate their training games. Previous studies take an “all or nothing” approach when validating training games [16,17]. These studies aim to show direct and full transfer from in-game learning, expecting immediate improvements in real-world prosthetic control. However, in doing so, the improvement and mastery of foundational skills needed to later achieve effective myoelectric control may be discounted or overlooked. In fact, clinical therapists often state that their main objective in the pre-prosthetic phase of training – the phase targeted by these training games – is to help patients build these foundational skills and their fundamental understanding of myoelectric control, and that they have no expectation of achieving real-world skill transfer in these early stages of training [43,45].

1.2.4.3 How Game-Based Training can be Improved

This work proposes that effective training games lie somewhere in the middle of the 2 extremes described above; games do not necessarily need to consist solely of task-similar *game activities* to be effective, but instead – in addition to providing players with a fun, engaging experience – the underlying *game mechanics*[6] must be designed to encourage and stimulate the development of the foundational muscle control skills identified by therapists and clinical experts. In this research, these foundational skills are formally quantified by introducing a set of muscle-control metrics and demonstrate improvement in these skills throughout a series of game-based training sessions. Furthermore, a fun, engaging experience is developed by following guidelines that have previously been identified as best-practices for the design of therapeutic games.

1.2.5 Best-Practices for Designing Therapeutic Games

The applicability of therapeutic and training games is certainly not limited to myoelectric muscle training. Game-based therapy/training has been used with patients of cerebral palsy [50], stroke [6,27,28] and paralysis [21,42], as well as those with cognitive [24], visual [48], and auditory [2] deficit. This work was informed by existing research on therapeutic games and, in this section, a survey of this previous research is provided. Specific care has been taken to highlight how the design insights identified by these authors are relevant to both the training game developed in this research as well as myoelectric training games in general.

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[6] A task-similar *game activity* enforces the restriction that the game's background and story must mirror real-world training outcomes (e.g., the game must involve aspects of "hand grabbing"). A task-similar *game mechanic*, conversely, requires that the underlying techniques used during game play align with training goals (e.g., the game must encourage the development of muscle isolation), but does not enforce a similar restriction on the game's story.

1.2.5.1 Direct and Indirect Training Goals

Therapeutic games can be divided into 2 main categories: *direct* and *indirect* [30]. *Direct* therapeutic games focus on physical, quantifiable improvements and are typically designed around an existing training protocol. Games intended to help improve strength, stability, and range-of-motion in stroke patients are examples of a direct therapeutic approach. In contrast, *indirect* therapeutic games focus on aspects that, while not directly tied to physical or quantifiable improvement, play a critical role in the rehabilitation process as a whole. For a recent amputee, indirect therapeutic goals could include reaching an acceptance of their new reality, increasing perceived embodiment and acceptance of their prosthesis, and integrating prosthetic use into their daily tasks. It is worth noting that current research in myoelectric training games has focused only on direct therapeutic goals (typically focusing solely on functional transfer to real-world prosthetic use). In this work, the importance of these indirect therapeutic goals has been reflected in the design which has led to a training experience that effectively helps patients develop muscle strength and control in addition to maintaining motivation and positive morale.

1.2.5.2 Balancing Gameplay to Accommodate Patient Needs

An important quality that should be present in therapeutic games is the ability to scale and adapt the game experience to a widely ranging audience. Therapy is a unique experience for each patient, and well-designed games should cater to each patient's unique needs. Appropriate levels of difficulty are especially important because patients can often be vulnerable during times of rehabilitation (e.g., following a traumatic event, stroke), and games that are too hard could further expose patient vulnerabilities and be detrimental to the patient’s overall recovery. When designing therapeutic games, it is especially important to be aware of the delicate balance between a challenging game that is conducive to rehabilitation, and one that is too hard and may discourage or deter patients from further pursuing therapy [21]. During the design sessions in this research, several therapists specifically commented on the excessively difficult and discouraging environment that many existing myoelectric training games create, and care has been taken to ensure that the game developed in this research promotes both fun and success throughout training.

1.2.5.2.1 Balancing in a Multiplayer Environment

In multiplayer or other competitive scenarios (even a friendly competition), small differences in skill level can be magnified during game play, resulting in largely varying levels of success between players [21]. This can be positive (as it allows individual patients to easily see improvement over time) and negative (as it can highlight differences in abilities between players), but either way it exemplifies the importance of creating an easy way for the player/therapist to balance varying levels of skill within therapeutic games.

1.2.5.2.2 Balancing through User-Specific Calibration Settings

One approach for balancing the game experience for a wide range of skill levels is to provide a calibration tool that allows the user input to be adjusted and scaled to account for differences in range of motion or muscle strength between players. Previous researchers exploring adaptable and accessible games consider a thorough, but quick, calibration procedure to be an indispensable tool within a therapeutic game [22]. Calibration is especially important in myoelectric training games (myoelectric control is inherently sensitive to changes in skin temperature, humidity, and sensor placement), and the calibration tools in the game developed in this research were continually improved and throughout the design process (full details available in Appendix B).

1.2.5.2.3 Balancing Success and Challenge

Another technique to balance the overall game experience between players of widely varying levels of skill is to incorporate purely aesthetic, non-game altering means of rewarding correct input or movement within the game. This means keeping the main game experience as simple (and accessible) as possible, but including optional elements above and beyond the main game mechanic. This approach allows “beginners” (i.e., players just starting therapy or learning the game details) to succeed and progress through the main game experience, while still allowing “expert” players to feel a sense of depth and accomplishment as they “gain full control” over the game by unlocking extras or uncovering in-game secrets. Designing games according to this principle creates an engaging experience for players at all levels of skill without hindering success for novice users [22]. The training game developed in this research was designed for players of widely varying levels of skill by including different methods of control, levels of difficulty, and optional in-game elements such as obstacles and barriers.

1.2.5.2.4 Balancing Player Engagement with Therapeutic Goals

When designing therapeutic games, it is also important to remember that it is just as much about a patient’s abilities as their disabilities [21]. Therapeutic games do not need to sacrifice from the overall game experience in order to be accessible and comply with therapeutic goals. This point is especially relevant in a series of studies related to the use of time-pressure[7] as a game mechanic in a therapeutic situation. In agreement with several standard guidelines for therapeutic game design [8,18], one study suggested that the use of time-pressure should be avoided in therapeutic games for children with multiple-sclerosis because these elements could trigger muscle spasms which are detrimental to the underlying therapeutic exercise [1]. However, a follow-up study found that these fast-paced, time-pressure elements are exactly what many of the patients enjoy about video games in general, and that they could safely (i.e., without the increased risk of creating muscle spasms) be incorporated into therapeutic games for children with multiple-sclerosis to create an engaging experience as long as they were designed in a way that was appropriate for the players (e.g., by ensuring a simple control strategy and enforcing a low penalty for errors during these periods of play) [24]. These results are a reminder that designing accessible and adaptable therapeutic games doesn't mean sacrificing engagement or in-game experience. The training game developed in this research both incorporates mechanics like time-pressure to ensure a fun and engaging experience, as well as many other mechanics that were designed to specifically target underlying therapeutic goals.

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[7] Time-Pressure is a game mechanic intended to create a sense of suspense or excitement by intentionally rushing the player beyond a speed of play that is comfortable, often requiring quick reaction time or reflexes.

1.2.5.3 Importance of Autonomy and Player Experience

Therapeutic games – and exercises in general – are typically intended for use over a prolonged series of sessions. Patients are often expected to complete the same tasks, day after day, as they gradually improve. For many patients, this can quickly become monotonous. One approach to increase engagement and investment in the therapeutic activity is to incorporate game elements that players can relate with, instilling a deep connection with the game. For example, researchers focusing on therapeutic games for children who use wheelchairs [21] chose to make the antagonist in a downhill skiing game also a wheelchair user. Players enjoyed a game that was "designed specifically for them" and felt that it helped to create a positive, empowering training experience. To encourage a sense of autonomy, players can customize the appearance of the game by using the coins collected during gameplay to purchase a variety of characters, backgrounds, and other collectables – many of which were suggested by patients during design sessions.

The design insights discussed so far suggest that the design of therapeutic games – while often overlooked – holds a great importance in the overall quality and effectiveness of therapy. One study demonstrated an extreme example of this importance with a therapy game designed to help children with auditory deficit [2]. The results of this study showed that players reported detecting smaller tone-differences when playing a well-designed game than they did when completing the original therapeutic exercise. This is exciting because the ability to detect tone-differences was previously thought to be a genetic trait that remained constant and could not be trained or learned[8]. Furthermore, it highlights the important role that game design may play in helping motivate new prosthesis users to strengthen and improve their muscle control.

1.2.5.4 Designing Games to Facilitate Therapy

In addition to being designed according to patient needs, therapeutic games should cater to the needs of the therapists and clinicians administering or guiding the patient through therapy. For these clinical experts, therapeutic games are one of many tools used to get their job done, so they should be designed to be as convenient and useful as possible. Designing features into a game such as quick start-up and configuration (as well as the ability to load a patient's personal settings from their previous visit), the ability to quickly tweak settings while causing minimal disruption to game play, and the ability to log and report each patient's history and progress make therapeutic games an indispensable tool for clinical experts [4]. The game developed in this research was designed according to these principles to ensure its utility as a clinical training tool.

1.2.5.5 General Principles of Game Design Still Apply

Finally, many principles of design for games in general are also applicable in therapeutic situations. Challenge (i.e., clearly defined tasks that challenge players and

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[8] While the therapeutic game probably did not impact players' innate genetic abilities, this example demonstrates how a motivating environment can increase levels of engagement, willingness to succeed, and consequently, overall performance.

stimulate engagement), theme (i.e., cohesive background, story, and character design that creates an immersive experience), reward (i.e., elements of gameplay that create incentive for players to complete required tasks), and progress (i.e., markers that demonstrate improvement, game-completion, or the development of skills) are 4 general characteristics of fun, engaging games that encourage strong player investment [19]. The Player Evaluation and Needs Satisfaction (PENS) guideline also suggests that a sense of competence (i.e., the player feels in control of their avatar), autonomy (i.e., the game world feels “real”, the player can interact with the game world in meaningful ways), and relatedness (i.e., player connects with characters and narrative) are essential for fun and successful games in general [39]. The first article in this dissertation, *The Falling of Momo: A Myoelectric Controlled Game to Support Research in Prosthesis Training*, explains in detail how these best-practices of game design were incorporated into the game designed in this research.

1.2.6 Myo Armband

Myoelectric prostheses make use of medical-grade EMG sensors to detect the user’s muscle contractions. Existing training tools also employ these sensors, making them extremely expensive (see Table 1-1 for more details). However, a number of less expensive, consumer-grade EMG sensing devices have recently entered the commercial market and may be suitable for use as a myoelectric training input device.

The Thalmic Labs Myo Armband[9] (referred to as the *myoband* in this thesis) is one such consumer-grade EMG sensing armband that was explored in detail in this research. The armband communicates through a Bluetooth interface, and is intended to be used by able-bodied individuals as a gesture-based input device, allowing the user to control their music playlist, YouTube video, or slideshow presentation with a number of gestures derived from muscle contractions and overall arm movement (via inertial sensors). Several "connectors" have also been developed that allow the myoband to be used as an alternate input device for existing popular video games[10].

In this section, the motivating factors for using the myoband as the input device in this research will be discussed. Furthermore, a comparison between the armband and a medical-grade solution currently used in training clinics will be presented to demonstrate that the technical capabilities of the armband are sufficient to provide patients with an accurate training experience.

1.2.6.1 A Low-Cost, Easy-to-Use Training Device

The motivation for using the myoband as a training device in this work is because it is low-cost, accessible, and easy to use. First, the myoband retails for under 200 USD, a fraction of the price of existing medical-grade training equipment. Furthermore, the myoband can easily be purchased from a number of box chain technology vendors, unlike the existing tools that are only sold by a single vendor. Finally, the myoband can easily

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[9] Thalmic Labs: www.myo.com

[10] Myo Market: market.myo.com/category/games

be slipped over the wrist and slid into place making it easy for a single person to set up. Existing training tools require expert identification of muscle sites and are tricky to secure in place without aid from another individual.

1.2.6.2 The Myoband Provides an Accurate Training Experience

To ensure that the myoband was sufficient for capturing accurate and meaningful input, the device's technical specifications were compared against existing medical-grade technology (details in Table 1-1). While the myoband may have technical capabilities inferior to medical-grade alternatives, it is still suitable for training purposes. The lower sampling rate of the myoband is adequate to accurately reflect the frequency content of the EMG signal [40] and the reduced digital signal resolution has been shown to have a minimal negative impact on pattern recognition based classification performance (even outperforming a higher resolution signal in certain scenarios) [49]. Furthermore, use of the myoband streamlines many of the sensor-positioning and calibration processes that required expert guidance and supervision when using medical-grade equipment.

While the manufacturer's armband development libraries are capable of streaming EMG as well as the on-board classification of several generic hand gestures, several of the stock armband interactions (e.g., perform a particular gesture to "unlock" the armband, a mandatory "vibrate" on gesture-recognition) have made these tools inadequate for use with amputees. To address this problem and to facilitate further research and development, open source libraries[11] for working with the armband that

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[11] github.com/hcilab/MyoStream, github.com/hcilab/MyoBuffer, github.com/hcilab/MyoProportional

bypass these consumer-focused functions were developed in this research (see **Appendix A**). This ensured the most realistic in-game control by processing EMG signals as done in a typical myoelectric prosthesis [29] and enabled working with the armband in a Java/Linux environment (the manufacturers of the armband have not yet officially supported Linux development).

	Myo Armband	**Medical-Grade (E.g., Ottobock MyoBoy)**
Cost	~ 200 USD	> 5000 USD
Sampling Rate	200 Hz	~ 1000 Hz
ADC Resolution	8-bit	~ 16-bit
Sensor Positioning (Initial Setup)	1. Armband is slid onto residual forearm, held in place by band's elasticity.	1. Clinician palpates forearm to identify ideal muscle belly sites. 2. Patient then holds medical-grade sensors in place while clinician secures them with a tourniquet (requiring two individuals to be present)
Sensor Positioning (Adjustment)	1. Patient rotates band such that each muscle belly is situated directly beneath one of eight available sensors.	1. Patient must remove tourniquet, releasing sensors and allowing them to move freely. 2. Repeat **Sensor Positioning (Initial Setup)**
Calibration	1. Patient uses mouse to adjust slider within game's settings menu. 2. Patient receives feedback about their adjustments in real-time through signal visualization bars.	1. Patient must remove tourniquet, releasing sensors and allowing them to move freely. 2. Clinician uses a small screw-driver to adjust hardware potentiometer on sensor. 3. Repeat **Sensor Positioning (Initial Setup)** 4. Patient does not receive feedback about adjustments until sensors are repositioned and secured with tourniquet. 5. Calibration adjustments may be insufficient – repeat until satisfactory calibration achieved.

Table 1-1: Comparison of the Myoband with other Medical-Grade Devices.

1.2.7 Research Setting and Methods

Both myoelectric prosthesis users and clinical experts were engaged throughout the course of this research. In this section, the prosthetics clinic where this end-user interaction occurred is introduced, and the methods that were used when engaging these individuals are discussed.

1.2.7.1 Setting: Atlantic Clinic for Upper Limb Prosthetics

The patients and staff of one prosthetics clinic in particular were engaged throughout the course of this research. The *Atlantic Clinic for Upper Limb Prosthetics* is located within the UNB campus and is affiliated with UNB's Institute of Biomedical Engineering. The clinic is a world leader in upper limb prosthetics, and serves patients from across Eastern Canada. The clinic is unique because it focuses solely on upper limb prosthetics and employs both clinical and research staff, including an occupational therapist who specializes in upper limb myoelectric control and myoelectric muscle training.

1.2.7.2 Methods

A participatory, iterative approach was used when designing the training game developed in this research. The information collected through this process was then formalized into a set of design guidelines using a deductive thematic analysis. In this section, these techniques will be introduced and an explanation of how they were used in this research will be provided.

1.2.7.2.1 Participatory, Iterative Design

Learning myoelectric control is a unique experience for amputees and congenitally limb different patients. To design an effective training game for these users, a *participatory, iterative* design approach[12] [32] was used. Amputee and congenitally limb different patients (the target audience of the game) were engaged throughout the design process and encouraged to *participate* by playing a demo of the training game, comparing and reflecting it with their myo training experiences in the past. The game was *iteratively* improved and refined between each session, building upon the current prototype based on the feedback, suggestions, and criticisms collected.

At the time of publication of *Article 2: Designing Game-Based Myoelectric Prosthesis Training*, a total of nine design sessions with six patients and three clinical experts had been conducted. However, the design of the game was continually improved as patients became available and, to date, a total of 14 design sessions (nine patients, five clinical experts) have been completed. A detailed timeline of new features, improvements, and refinements can be found in Appendix B.

1.2.7.2.2 Deductive Thematic Analysis

A deductive thematic analysis [12] was also performed, during which a set of *themes* or *design guidelines* was identified using the information collected through design

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[12] Participatory design is an approach that directly involves the end-user throughout the design process. Problems and ideas are identified and developed through interviews, workshops, and interactive sessions. Participatory design encourages strong engagement between the designer and end-user, which can lead to a better understanding of the problem domain for designers, a greater sense of ownership for end-users, and ultimately, a better design.

sessions with patients and clinical experts. Patient sessions – which consisted of a semi-structured interview focused on previous myoelectric experience and training, followed by game demos and feedback collection – were audio recorded, then transcribed offline. The transcribed sessions were coded, then grouped into predetermined themes to provide evidence for the experiences and opinions of local clinical staff. Coding was first performed independently by two researchers who subsequently met to discuss and combine their independent findings. However, no formal inter-rater reliability tests were conducted. Expert sessions (which were also audio recorded and transcribed) consisted of more direct, targeted questions and were used to provide further support for the research findings.

1.3 Articles contained in this Thesis

This research demonstrates that myoelectric training games can be designed to provide patients with a fun, positive, and effective training experience. Through this work, a number of issues that are found in existing training games and other forms of conventional muscle training have been addressed:

1. Current ***training tools require expensive medical-grade hardware and expert supervision,*** which limits the access that patients have to training. Many clinics do not even offer training programs.
2. Existing ***training is monotonous, uninformative, and discouraging***, and has the potential to cause more harm than good. This makes it difficult for patients to stay engaged and motivated during training, possibly even deterring them from further use of myoelectric prosthetics.

3. When evaluating progress during training, many ***assessment tools focus exclusively on improvements in functional, real-world prosthesis tasks***, which conflicts with the therapeutic goals identified by clinical experts during early training.
4. While training is critical for new prosthesis users, ***little is known about the effects of longer-term myoelectric training***. Many previous studies exploring the effects of myoelectric training have subjected participants to only four or fewer short training sessions.

In each of the four articles contained in this dissertation, work is presented that specifically addresses these issues. The articles are presented in chronological order and reflect the research approach taken, which resembles the process taken by Hernandez and Knights in their previous research on exergames[13] for children with multiple sclerosis [24,25]. The research initially focused on the process of designing training games (*articles #1 and #2*), then shifted focus to assessing their therapeutic value (*articles #3 and #4*).

In the following sections, a short description of each article is provided along with an explanation of how the work addresses one of the four issues with existing training

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[13] Exergames are a category of games specifically intended to encourage physical activity and exercise.

introduced above. Table 1-2 provides a further breakdown of the research focus and contributions presented in each article.

1.3.1.1 Article #1: The Falling of Momo: A Myoelectric Controlled Game to Support Research in Prosthesis Training

Aaron Tabor, Alex Kienzle, Carly Smith, Alex Watson, Jason Wuertz, and David Hanna. 2016. The Falling of Momo: A Myo-Electric Controlled Game to Support Research in Prosthesis Training. In Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts (2016): 71-77.

Training tools require expensive medical-grade hardware and expert supervision. The training game developed in this research was designed to specifically address this issue by a) making use of a low-cost, commercially-available input device, and b) creating an intuitive gameplay and calibration procedure. This article discusses the motivations for creating an accessible muscle training game, provides an overview of the underlying therapeutic goals that were identified and incorporated into the game mechanics, and describes the initial version of the game.

1.3.1.2 Article #2: Designing Game Based Myoelectric Prosthesis Training

Aaron Tabor, Scott Bateman, Erik Scheme, David R Flatla, Kathrin Gerling, "Designing Game-Based Myoelectric Prosthesis Training," Proceedings of the ACM Conference on Human Factors in Computing Systems, May 2017, Denver, USA. p1352-1363.

Training is monotonous, uninformative, and discouraging. The reason for conducting user-centered design sessions with experienced prosthesis users and clinical experts was to iteratively improve the training game by incorporating users’ ideas to create a fun, engaging, and motivating experience that provides players with meaningful and intuitive feedback to help them achieve success. The information gathered through this study was formalized into a set of design guidelines for creating fun, informative, and positive training games. This article presents these design guidelines and discusses how they are important for both future work in myoelectric training games as well as in therapeutic games in general.

1.3.1.3 Article #3: Quantifying Muscle Control in Myoelectric Training Games

Tabor, Aaron, Wendy Hill, Scott Bateman, and Erik Scheme. 2017. Quantifying Muscle Control in Myoelectric Training Games. *In Proceedings of Myoelectric Control Symposium (MEC) 2017.* Fredericton, New Brunswick. 4.

Assessment tools focus exclusively on improvements in functional, real-world prosthesis tasks. The muscle control metrics proposed in this article were developed to specifically address this issue and fill a gap in clinical outcome measures. These metrics directly relate to the therapeutic goals identified by therapists during early muscle training and quantify the intuition and expertise of the clinical therapists who helped identify these goals during earlier design sessions. This article introduces the metrics, describes how they can be captured and computed through the training game, and discusses how they can be used to follow patient progress and improvement throughout training.

1.3.1.4 Article #4: Improvements in Myoelectric Control over Multiple Game-Based Training Sessions

Tabor, Aaron, Scott Bateman, and Erik Scheme. "Improvements in Myoelectric Control over Multiple Game-Based Training Sessions." *In Preparation for submission to Transactions in Neuroscience and Rehabilitation Engineering (TNSRE).* 2017.

Little is known about the effects of longer-term myoelectric training. This article presents the results of a 300-session user study, in which the progress of 30 participants was followed as they each completed a series of ten 30-minute training sessions. The results of this study suggest that – much like many other complex motor-tasks – improvement with myoelectric control develops gradually and continually throughout training. Since many previous studies have used a much shorter series of training sessions, this finding introduces new knowledge about the longer-term effects of myoelectric training, and suggests implications for both research on myoelectric training and aspects of clinical therapy in practice.

Paper	Venue	Research Focus	Contributions
1. The Falling of Momo: A Myoelectric Controlled Game to Support Research in Prosthesis Training	CHI Play 2016 – Companion Extended Abstracts (Published) *Awarded:* *Best Game – Panel Judged*	What are the characteristics of "ideal" muscle control? What aspects of muscle control do new prosthesis users focus on during training? How do new prosthesis users train their muscles in the current clinical environment?	Identified characteristics of "ideal" muscle control Identified "state of the art" in clinical myoelectric muscle training programs.
2. Designing Game Based Myoelectric Prosthesis Training	CHI 2017 (Published)[14]	Are there special considerations to be taken when designing games for myoelectric muscle training? (and if so) How do we integrate these design considerations into a positive and engaging game experience?	An open source myoelectric muscle training game Guidelines for future designers of muscle training games and therapeutic games in general An adapted UCD process for working with small, geographically disparate populations Identify the value of consumer-grade tools for therapeutic purposes.
3. Quantifying Muscle Control in Myoelectric Training Games	MEC 2017 (Published)	How can we better assess the learning and improvement that occurs during myoelectric muscle training?	Metrics for quantifying and assessing characteristics of muscle control
4. Improvements in Myoelectric Control over Multiple Game-Based Training Sessions	TNSRE (In Preparation)	Does myoelectric muscle training lead to improvements in foundational aspects of muscle control? (and if so) How does muscle control develop and improve over the course of training?	Muscle control does improve through training, but develops gradually and continually over time.

Table 1-2: Articles Contained in this Dissertation.

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[14] An extended-abstract paper that presents the initial findings of this study was also published throughout the course of this research: Tabor, Aaron, Scott Bateman, and Erik Scheme. "Game-Based Myoelectric Training." In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*, pp. 299-306. ACM, 2016.

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2 Article 1 – The Falling of Momo: A Myoelectric Controlled Game to Support Research in Prosthesis Training

Aaron Tabor, Alex Kienzle, Carly Smith, Alex Watson, Jason Wuertz, and David Hanna. 2016. The Falling of Momo: A Myo-Electric Controlled Game to Support Research in Prosthesis Training. In Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts (2016): 71-77.

2.1 Abstract

Myoelectric control makes use of the electrical signals created by the body's muscles as an input to control a device, such as a prosthetic limb or powered orthosis. While myoelectric prostheses have been in use and under constant R&D for almost 50 years, they are not without problems. For myoelectric control to be effective the user has to learn how to activate and control muscles in isolation and in ways that are unintuitive but easily interpreted by the system. Learning how to control muscles in this way can be a frustrating and time-consuming process. In this paper, we outline our work to develop a training game that aims to setup prosthesis wearers for success by mapping typical controls used for prostheses to game input. Furthermore, our game provides a wide range of options that allow the input controls and game difficulty to be scaled appropriately to the skill of the player. Above all, our game aims to be fun and, unlike previous myoelectric training games, it focuses on providing a fully featured casual game.

2.2 Author Keywords

Prosthesis training; myoelectric control; games.

2.3 ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

2.4 Introduction

Learning to use a myoelectric controlled device can be a frustrating experience, as users must completely retrain the function of their muscles. There are many different technical challenges to the successful adoption of a myoelectric prosthetic limb. However, one important challenge for the user of a prosthesis is learning how to contract the muscles in a consistent way. While prostheses and their controllers are in constant research and development, these technologies remain very expensive and far from a perfect replication of a real limb. Long term adoption of myoelectric control prostheses is low [3], but research shows that a key ingredient for successful adoption is early access to training [3]. Using a low-cost, consumer-grade device like the Myo armband (shown in Figure 2-1) to capture input could make training exercises accessible to users outside of the clinic. By providing a training game that uses a consumer grade input device, we hope to make the training process accessible at home.

The recent release of the Myo Armband by Thalmic Labs [8], shown in Figure 2-1, has opened new opportunities for software developers to create and explore myoelectric input driven applications. Using this device, games for prosthesis wearers can now be designed and developed without the need for expensive, specialized equipment. We targeted the Myo as the controller for “The Falling of Momo” because it is based upon the same technology that is used in myoelectric controlled prostheses. As a consumer-grade device, the technical capabilities (ex: sampling rate, analog-to-digital conversion resolution) are inferior to medical-grade equipment, but recent research suggests that the capabilities of the armband are sufficient for effective training to occur [9,14].

“The Falling of Momo” is a survival, casual game developed with the Processing language. Using the Myo Armband as input to replicate the controls of a prosthetic limb, players guide their character through gaps in rising platforms in order to progress, score points, collect coins, and unlock new content. The longer a player survives, the faster the platforms will rise. “The Falling of Momo” aims to provide users with an engaging game that provides a fun experience and motivating training environment. It also scales in difficulty to be suitable for both novices and experienced prosthesis users.

Figure 2-1 The Myo Armband. This device is worn around the upper forearm and detects electrical activity emanating from muscle tissue using EMG sensors.

2.5 Background

2.5.1 Myoelectric Control of Prosthetic Limbs

Often, an upper limb amputee will still have control of residual muscle tissue that remains at the site of amputation. For these amputees, the use of a myoelectric controlled prosthesis is an attractive option. Unlike traditional prostheses, a myoelectric device can be controlled using the electrical signals produced by the user’s muscles to create movements that can aid day-to-day tasks, for example, by closing a prosthetic hand to grasp and hold an object. Typically, surface EMG (electromyogram) sensors are installed in the sleeve of the device, and make contact with the user’s residual muscle tissue when slid into place. Depending on the device and method of control, muscle contractions can control a range of movements or gestures including the opening/closing of a robotic hand, the rotation of the wrist, or the flexion/extension of an elbow joint.

While the best case for myoelectric control is to read input signals from functionally equivalent muscle groups [11] (e.g., closing a prosthetic hand should involve stimulating those muscles that would otherwise be used to close a physical hand), the severe restriction of input data (often two, and as little as a single functional muscle) results in a control scheme that is counter-intuitive for many people. In devices with more actuated degrees of freedom (e.g., a limb that both rotates and opens/closes), a mode switching strategy is often employed, which can be confusing. To complicate matters further, the control of the device is extremely sensitive to environmental conditions, such as humidity and sensor placement. Even the presence of nearby under-ground or over-head power lines, or other electrical equipment, can corrupt the input control signals in myoelectric devices.

For the reasons mentioned above, it is of the utmost importance that a prosthesis user trains their muscles so that they are able to produce strong, separable, and reliable control signals. Typically, during training, a user focuses on 4 aspects of their muscle stimulation:

- ***Amplitude*** – The amplitude of a signal is a measure of the ‘strength’ of a muscle contraction. Strong and reliable muscle contractions are easy to identify by a myoelectric control system and are less likely to be corrupted by external noise.

- ***Rate*** – The rate of contraction is defined by how quickly a muscle is contracted. In more complicated devices, a mode-switch between limb movement sets is often initiated by issuing a quick ‘impulse’ of muscle contraction.
- ***Isolation*** – Muscle isolation is necessary to produce reliable, identifiable input. A user must learn how to contract a particular muscle target, while leaving the others at rest.
- ***Control*** – The level of control a user demonstrates defines how accurately one can attain and sustain a particular amplitude of muscle stimulation. Many devices with proportional control (i.e., the ability to open/close with varying speeds) are controlled by the amplitude of the input signal.

2.5.2 Typical Control Mapping

For a typical trans-radial (i.e., an amputation which occurs between the wrist and elbow) amputee, EMG sensors are positioned along the residual inner- and outer-forearm muscles (typically the flexor and extensor carpi radialis). For an amputee with control of both of these muscles, a typical control strategy consists of contracting the outer-forearm muscle (known as an “extension”, see Figure 2-2) to open the grip of the prosthetic hand, while contracting the inner-forearm muscle (known as a “flexion”, see Figure 2-3) results in a closing of the grip of the hand. More complicated devices also interpret a quick co-contraction impulse (see Figure 2-4) as a mode-switch, so that the same flexion and extension signals now control the rotation of the prosthetic wrist. For an amputee with control of only a single forearm muscle, motion of the robotic hand is often automated in one direction, with the opposing movement initiated through muscle contraction. For example, the prosthetic hand of an amputee with control of only a single forearm muscle may close automatically, opening only in the presence of muscle stimulation. This control policy is known in practice as an “Auto Close” policy. Typically, amputees with only a single input site do not use more complex prosthetic devices.

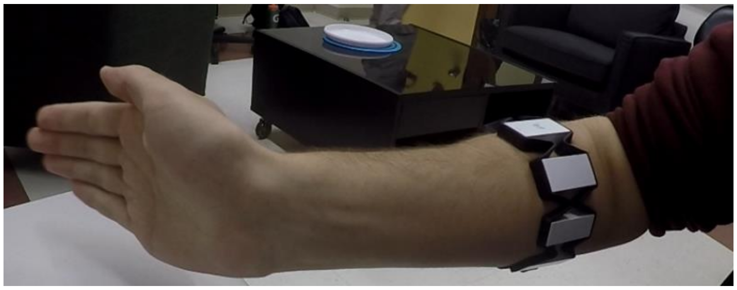

Figure 2-2: Extension motion (contracting the outer-forearm muscles)

Figure 2-3: Flexion Motion (contracting the inner-forearm muscles)

Figure 2-4: Co-contraction impulse (quick, simultaneous contraction of both the inner- and outer-forearm muscles)

2.5.3 Myo Controller

The Myo armband is a Thalmic Labs [8] product that allows the user to control technology through movements and contractions of their forearm. Using gestures and motions, one can browse the web, control presentations, and control your favorite music software to play, pause and skip tracks. It is a commercially available and affordable system for developers and app users alike. Using a Bluetooth connection, the Myo can wirelessly sync to your Mac or Windows PC to enable its controls. The gestures are detected by the eight EMG sensors on the Myo armband, which is the same technology used in myoelectric prostheses. While the Myo armband can perform on-board gesture recognition, in "The Falling of Momo" we use the raw EMG data collected by the armband as input. This allows us to ensure that the EMG signal processing and control policies are as close as possible to those employed in medical-grade prostheses.

2.5.4 Games for Prosthesis Training

While games that use myoelectric control exist, we have yet to find an example that meets certain niche requirements; existing games were either not designed from the ground up with user training in mind [1] or lack game elements or mechanics that provide good gaming that players find fun or engaging [5]. Game-based training is not unique to myoelectric control and therapeutic and training games have been created and used successfully with a wide variety of audiences, including those suffering from visual impairment [13], cerebral palsy [15], and those recovering from stroke [2,7,10,12]. However, current research in myoelectric training games presents conflicting results about the effectiveness of game-based training. While studies suggest that game-based training is just as effective as other training techniques (and can therefore be used interchangeably) [4], other work has found that certain training games are no more effective than a total lack of training [5].

2.5.5 Observation of Myoelectric Training Games

During our research, we have been working with a practicing occupational therapist who works with upper-limb amputees on a daily basis. We sat in on a session with one of her clients to observe the current training strategies that are used in practice. Currently, the prosthesis wearer (referred to here as Jill) trains her muscle control in a very direct way. Jill is directed to issue a series of contractions, which are read by EMG sensors and displayed on a computer monitor. While training "games" exist, these are often simply virtualizations of the real world control strategy. One "game" allows the user to control the motion of a virtual limb, but without any other visual stimulation or interaction with objects, it became evident that Jill very quickly grew tired of this exercise. Another "game", intended for training muscle isolation, involved rolling a red ball up a hill while keeping a blue ball stationary. While Jill was clearly quite skilled with her muscle control, the objectives of the game were very vague, and she was immediately greeted with error messages and negative feedback. It was evident that she did not find the second game to be an enjoyable experience, and commented, "I am bad at this", even though her therapist continually reassured that despite the error messages, she was indeed performing the correct actions. Clearly, this game did not provide a positive training environment.

Existing training games lack both intuitive game mechanics, which makes it easy for the player to understand what they need to do, and gameplay depth, which motivates the player to continue training. Our goal in this research is to create a game that is clear, fun and engaging, and helps the player train their muscles for improved myoelectric control.

2.6 Design of The Falling of Momo

We have developed a casual game in the style of Falldown[15]. The player must navigate through gaps (as shown in Figure 2-5) in continually rising platforms and jump over obstacles (visible in Figure 2-6) to avoid being squished by a series of spikes at the top of the screen. Additionally, the player collects coins during their descent to accumulate a higher score. Our goal was to create a game with ranging levels of difficulty that would be fun and rewarding for those new to myoelectric control, while still providing a challenge to those with a lot of experience. Many aspects of the game (discussed in *Game Play*) also incorporate training exercises that would normally be conducted by an amputee training their muscles for use with a myoelectric controlled prosthetic limb in a very natural way.

While the Myo armband has the capability to collect a large amount of input data, we intentionally limited our design to use only the input that is available on a typical prosthetic device. Controls are derived from signals captured during flexion (Figure 2-3),

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[15] Falldown on Apple’s App Store: https://itunes.apple.com/ca/app/falldown/id323493586

extension (Figure 2-2), and co-contraction ‘impulses’ (Figure 2-4) to replicate the controls of a prostheses as closely as possible.

2.6.1 Game Play

The user controls Momo’s movement using flexion and extension contractions detected through the Myo armband (flexion corresponds to either the left or right movement of Momo, depending upon which arm the Myo is worn). Momo’s speed is controlled proportionally according to the amplitude of the input signal (corresponding to the intensity of the contraction). At higher levels of difficulty, the player must exert strong contractions to descend through quickly rising platforms, encouraging players to train their muscles to produce accurate, high-amplitude contractions.

Contraction thresholds are configurable within the game, so that the player is always training against realistic, personal targets. Additionally, we have implemented two separate user-selectable control policies: maximum and differential modes. In maximum mode, only the strongest contraction at any given time is considered for game input, while in differential mode, the difference between the two contractions is treated as the amplitude of the input signal. While maximum mode is suitable for beginners, differential mode encourages the user to train their muscles in isolation. Both maximum and differential modes are common strategies used for controlling myoelectric prosthetics and were suggested by the experts at our local prosthetics clinic.

Figure 2-5: Momo making his way through gaps in the rising platforms. For an efficient descent, the player must keep muscle stimulation quiet while falling to avoid catching against the edge of a gap.

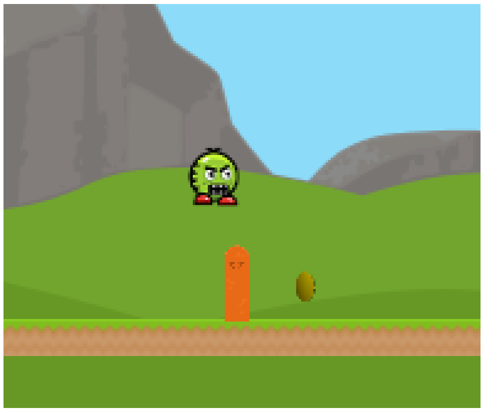

Figure 2-6: Momo is jumping over an obstacle to get a coin. Jumping helps the player train their co-contraction impulse, which is used in many prosthetic devices as a mode-switching signal.

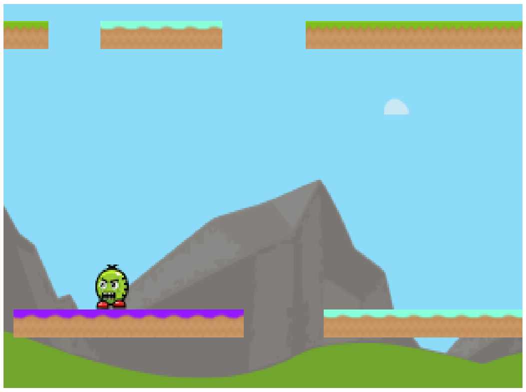

Figure 2-7: Icy (shown on the right) and Sticky (shown on the left) platforms allow the user to master a wide range of muscle contraction intensities.

Coins Collected: xx

Customize screen is a work in progress, in the future you will be able to unlock different players, platforms etc.., with the coins you have collected during the game!

Figure 2-8: The Customization menu allows the user to purchase additional character costumes, collectables, and game themes using the points they accumulate during gameplay. This feature adds replay value, and keeps our users excited about training.

The game also features icy (low-friction) and sticky (high-friction) platforms to provide depth-of-play and to further encourage muscle control (shown in Figure 2-7). Players must exert gentle muscle stimulation to avoid slipping past gaps while on icy platforms, and similarly, exert strong muscle contractions when passing over sticky platforms. We summarize how our game mechanics cater to the standard myoelectric training objectives in Table 2-1.

Often, for those completely new to myoelectric control, achieving any detectable muscle stimulation at all is considered a training success. We have implemented an optional “Direction Assistance” control mechanism that allows players at this early stage of training to still enjoy and benefit from our game. Instead of using flexion/extension to control the direction of Momo’s movement, “Direction Assistance” control causes any elicited muscle contraction to direct Momo towards a nearby gap. To cater to those patients with only a single functional muscle site (or similarly, patients who cannot isolate one contraction from the other), we implemented “Single Muscle” control mechanisms. Similar to the “Auto-Left” and “Auto-Right” policies used in myoelectric prostheses (discussed above in *Typical Control Mapping*), when playing in “Single Muscle” mode, Momo moves one direction automatically and proportionally changes direction in the presence of muscle stimulation.

Training Objective	Game Design Consideration
Amplitude	• Proportional Speed Control • “Sticky” platforms with high coefficient of friction
Rate	• Jumping over obstacles requires a quick “burst” co-contraction
Isolation	• Differential control policy
Control	• “Icy” platforms with low coefficient of friction • Falling through narrow gaps requires precise navigation

Table 2-1: Meeting standardized training objectives. “The Falling of Momo” was designed from the ground up to cater to the training needs of myoelectric control prosthesis users.

2.6.2 Elements of Game Design

Based on work by Flata et. al. [6], we designed “The Falling of Momo” with specific game design elements in mind. Table 2-2 shows how we incorporated elements of challenge, theme, reward, and progress into our game.

Game Design Element	Implementation
Challenge	• Increasing difficulty over time
Theme	• Momo character and surrounding world
Reward	• Accumulating score and collection of coins
Progress	• Gameplay Record • Cosmetic unlockables

Table 2-2: Designing “The Falling of Momo” using game design elements suggested by Flata et. al. to create engagement.

2.7 Conclusion and Future Work

In our research, we have created a game specifically focused on helping amputees train for the use of myoelectric controlled prosthetic limbs. We have designed “The Falling of Momo” so that it can be engaging for both individuals who are completely new to myoelectric control as well as those with experience.

While other games that incorporate myoelectric control exist, they are either not designed from the ground up with user training in mind, or potentially lack the depth and motivating factors that would keep players interested. To our knowledge, our work is the first casual game designed for muscle training of upper-limb amputees for myoelectric control.

The “Falling of Momo” is the initial outcome on an ongoing design project. We plan to continue our partnership with the local prosthetics clinic by working one-on-one with patients to continue refining and iterating our design according to their needs. We also plan to conduct a comparative study on the effectiveness of user training through gameplay compared to other conventional methods. Finally, we plan to build intelligence into “The Falling of Momo” by implementing adaptive difficulty, which can adjust to the user’s gameplay behavior, and notify users in real time when they make a common training mistake. Our work will allow us to better quantify the effects of game-based training and shed light on the currently conflicting results pertaining to its overall effectiveness.

2.8 Acknowledgments

We would like to thank Scott Bateman, Erik Scheme, Wendy Hill, and the staff and patients of the Atlantic Clinic for Upper Limb Prosthetics for their input and guidance in conducting this research. This work has been supported by the New Brunswick Innovation Foundation and NSERC.

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3 Article 2 – Designing Game Based Myoelectric Prosthesis Training

Aaron Tabor, Scott Bateman, Erik Scheme, David R Flatla, Kathrin Gerling, "Designing Game-Based Myoelectric Prosthesis Training," Proceedings of the ACM Conference on Human Factors in Computing Systems, May 2017, Denver, USA. p1352-1363.

3.1 Abstract

A myoelectric prosthesis (myo) is a dexterous artificial limb controlled by muscle contractions. Learning to use a myo can be challenging, so extensive training is often required to use a myo prosthesis effectively. Signal visualizations and simple muscle-controlled games are currently used to help patients train their muscles, but are boring and frustrating. Furthermore, current training systems require expensive medical equipment and clinician oversight, restricting training to infrequent clinical visits. To address these limitations, we developed a new game that promotes fun and success, and shows the viability of a low-cost myoelectric input device. We adapted a user-centered design (UCD) process to receive feedback from patients, clinicians, and family members as we iteratively addressed challenges to improve our game. Through this work, we introduce a free and open myo training game, provide new information about the design of myo training games, and reflect on an adapted UCD process for the practical iterative development of therapeutic games.

3.2 Author Keywords

Prosthetics; myoelectric; training; games; UCD

3.3 ACM Classification Keywords

H.5.m. Info interfaces & presentation (e.g., HCI): Misc.

3.4 Introduction

Amputees, or limb different individuals, are people who are missing a limb due to amputation or a congenital limb difference. A myoelectric-controlled upper-limb prosthesis (myo) is an electrically-powered device that restores some of the missing dexterous movement in the arm and hand, e.g., by providing wrist rotation and hand closing. Myos typically offer greater functionality than passive or body-powered prostheses because they provide improved dexterity, a larger range of movement, a more natural appearance, and enhanced performance of daily tasks [7].

Myos also have drawbacks (including high cost and weight [7,12,22]), which have led to a high rate of abandonment; rejection rates of up to 75% have been reported [7]. Rejection is a complex, multi-factor process, but one of the key contributing factors is poor early myo operation ability arising from inadequate training [12].

Myos work by detecting electrical signals from residual muscle contractions. These signals act as input to control the artificial limb. Precise control and activation of particular muscle groups is required in order for the device to be used effectively. However, due to lack of experience, unfamiliarity, and muscle atrophy, precise activation of specific muscle groups can be very difficult [8].

Occupational Therapists (OTs) employ training activities to improve patients' muscle activation skills, helping them to learn how to operate and adapt to a myo. Learning to use a myo presents a unique challenge; unlike other therapeutic or rehabilitative programs, the goal of myo training is not to relearn forgotten tasks or regain lost functionality (as would be the case with stroke or physical injury rehabilitation), but is instead to learn to operate a device using muscles in a new and unfamiliar way [8].

The experts interviewed in this study agreed that current myo training approaches limit success for three main reasons. First, they are *boring and unengaging*. Training activities are often utilitarian and amount to little more than simple visualizations of muscle signals. Second, they are often *more difficult than using a real prosthesis*. Overly difficult training activities that provide primarily negative feedback are a source of frustration and discouragement. Further, this causes OTs to question the benefit of training given the potential for unintentionally introducing self-doubt. Third, they are *not accessible outside of the clinic*. Commercial training tools cost thousands of dollars, and require professional placement of sensors and interacting with complex software to set up training activities.

Game-based training tools [4,8,11,12,14,25] have been proposed to address the limitations identified above. Games seek to provide a more engaging experience and stronger extrinsic motivation (e.g., rewards, points, leaderboards) to help offset frustration. When coupled with appropriate technology, games can make training more accessible, allowing training to occur at home.

However, previous work has not engaged limb-different patients while designing games; very little work has explored how training games should be designed to best suit the specific needs of trainees and clinicians. While research considering the needs of end users is prevalent in other therapeutic settings [1,20,21,38], academic efforts towards designing myo training games have focused exclusively on technical issues, and not on the concerns and needs of the people involved (e.g., [4,11,12,14,25]). This direction of focus becomes apparent when considering commercial myo training games, which are widely used [9] but provide few of the motivating elements of game design that create a fun and engaging experience for players [16].

Much like the work of Hernandez et al. [21], our study is a qualitative exploration of game-based myoelectric training, leaving technical and performance issues to future work. First, we developed a prototype based on requirements gathered from previous work, observation of the training process, and discussions with a clinician from a local prosthetics clinic. We then iteratively refined our initial prototype using feedback and observations from a series of adapted user-centered design (UCD) sessions with limb different patients who have previously participated in myoelectric training. We transcribed and thematically analyzed audio recordings of the sessions, which we validated through interviews with subject matter experts. Our themes contribute domain expertise and encode current best practice for the design of future myoelectric training games, as well as therapeutic games in general.

This paper makes four contributions: First, we develop a new game – *The Falling of Momo* – as a starting point for game-based myoelectric training discussions within an adapted UCD process. Second, we present thematic analysis of interview and observation data from limb-different individuals and other stakeholders as a contribution to future work in this area. Third, we outline the process of integrating stakeholder feedback into our iterative game development process. Finally, we discuss the benefits and drawbacks of our adapted UCD process developed for situations when participants are difficult to recruit and follow-up visits are infeasible.

3.5 Background & Related Work

3.5.1 Myoelectric Control

Myoelectric signals are electrical impulses that occur naturally as we contract our muscles. Myoelectrically- controlled powered prosthetic devices (or myos) read muscle signals (using electromyographic sensors – EMG) from residual muscle tissue, and use them as control for motion [28,29]. The simplest myos open and close based on the presence of inner- and outer-forearm muscle activity (known as flexion and extension, respectively). However, many other control schemes exist and can work in combination, including proportional (adjusting the speed of motion proportionally with the intensity of muscle contractions), mode-switching (to enable selection between different types of movement), and pattern recognition techniques (for more natural control mappings) [17,33]. In this study, we focus specifically on proportionally-controlled myoelectric devices (as can be seen in Figure 3-1), since these are by far the most common type of myo.

Typically, surface sensors are positioned within the sleeve of myos (just visible within the sleeve of the device shown in Figure 3-1) such that they sit flush against the surface of the skin, directly above the ideal targeted muscle site (identified by the prosthetist or clinician during the fitting process). Accurate placement of these sensors is critical because inconsistency in placement can negatively affect muscle readings [9]. In many myoelectric muscle training tools, the same EMG sensors are used that are employed in prostheses, which are expensive (a training kit for proportional control consisting of 2 sensors and control box costs ~4000USD) making them unfeasible for use outside of the clinical environment [9].

In our study, we work with a consumer-grade EMG sensing armband, the Thalmic Labs Myo Armband (referred to as the ‘Myoband’ and shown in Figure 3-1), to assess its viability for use with myoelectric training tools. The Myoband is an off-the-shelf input device that costs under 200USD, and even though the fidelity of its EMG sensors is lower than medical-grade equipment, it is likely more than capable of being used for myo training. Even though the Myoband samples at one-fifth the rate of medical grade devices (Myoband: 200Hz, medical grade: ~1000Hz), the Nyquist theorem states that this is adequate to achieve an accurate representation of the underlying EMG signal [25]. The sensors of the Myoband also sample with a lower signal resolution (Myoband: 8-bit, medical-grade: ~16-bit), but research has shown that such a reduction results in only a marginal loss in control accuracy [31]. Further, there are recent examples of the Myoband being used to successfully operate prostheses in a lab setting (e.g., https://goo.gl/o6p2OE).

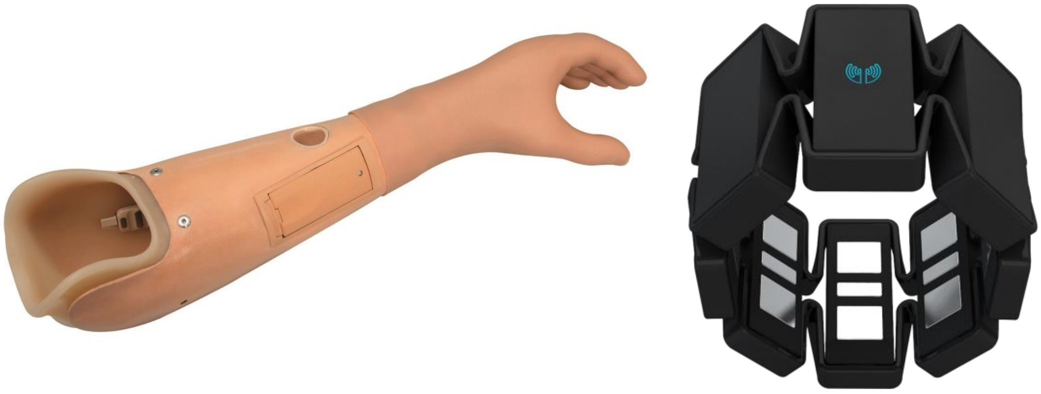

Figure 3-1: (Left) A myoelectric upper limb prosthesis – myo. (Right) The Thalmic Labs Myo Armband – Myoband.

3.5.2 Myoelectric Prostheses Training

3.5.2.1 Traditional Training

The time between amputation and receipt of a prosthesis is known as the pre-prosthetic phase, and is recognized as being a crucial period for training [7]. Experts interviewed agreed that building strength in the patient's musculature during this phase, in turn instilling confidence in use of their residual limb, is key to ensuring long-term success. While the best training approach for many is direct use of a prosthesis, this is often not initially possible (e.g., post-surgery recovery, insurance processing, fabrication times). To fill this gap, training tools can be used. Many clinics use the Ottobock PAULA [9,27] software, which allows EMG sensors to be affixed directly to the affected limb without the need for a final prosthetic socket. The PAULA suite (Figure 3-2) provides feedback tools for visualizing raw EMG activity, a virtual hand simulator, and a game involving navigating a car through a series of gaps.

3.5.2.2 Game-based Training

Past findings related to game-based myoelectric training tools have been conflicting. In one study using the PAULA software suite, it was suggested that game-based training tools are just as effective as traditional techniques, and that training tools could be used interchangeably at the discretion of the clinician or patient [9]. However, a subsequent study suggests that certain training games are no more effective than a total lack of training [13]; the study suggests that while learning may occur within the context of gameplay, these acquired skills might not translate to improved prosthesis use. These conflicting results suggest that the specific challenges associated with designing training games for amputees are not fully understood.

3.5.3 Therapeutic Games

Therapeutic games have recently received a lot of attention, and have been created for people with cerebral palsy [21,39], multiple sclerosis [20], paralysis [34], and who have had a stroke [5,24,32,37]. Findings from research into the participatory design of games for individuals with visual impairment [38] and young people using wheelchairs [19] makes clear that there are no one-size-fits-all solutions for populations that have a wide range of physical capabilities. Balancing the aspects of challenge required for the game to be exciting and effective with the potential vulnerabilities of the intended audience is rarely easy.

While training games should push players to improve their abilities, they should not highlight the player’s weaknesses or limitations [18]. To be most effective for therapists, therapeutic games should be easy to start up and configure (ideally, saving configuration settings in a user profile so they can be easily loaded in future sessions), allow the therapist to change difficulty settings on the fly (to adapt to the patient’s current needs), easily allow the therapist to provide support during gameplay, and track and report patients’ performance over time [3].

While myo training games have been created, these have largely focused on technical and performance issues (e.g., [4,11,12,14,25]), and have not involved limb different patients (e.g., [4,11,14]). Very little focus has been given to creating engaging and enjoyable training experiences, and little is known about what game design challenges are unique to myo training games. Despite varying results in past research [6,9,11,18], the experts interviewed expressed that games are important, as they help engage and motivate their patients and can serve as a troubleshooting tool when a patient's prosthesis is behaving unexpectedly.

Figure 3-2: Ottobock PAULA training suite (raw muscle activity, prosthetic hand simulator, and car game, left to right)

3.5.4 Game Design Principles

Challenge, theme, reward, and progress are known to be key elements that keep players excited and engaged during gameplay [16]. Throughout the design of our game, we have kept these concepts in mind, and we highlight below how our game incorporates these elements. Further information about our game can be found in [35,36].

Research has also shown that strong game design can lead to more than an increased level of engagement. In a study comparing games for psycho acoustic therapy, it was found that players could detect smaller tone frequency modulations when playing a game that was enjoyable and engaging [2], a task which is believed to involve skills related to genetic ability, and not previously believed to improve through training.

3.6 Designing a Myoelectric Training Game

To facilitate the exploration of myo training, we designed and implemented a training game [35,36]. This game was shown to participants during playtest-interview sessions (introduced below) and served as a concrete example to stimulate feedback and discussion. As the study progressed, the game allowed us to easily explore the ideas, criticism, and suggestions that surfaced, and was iteratively improved throughout the study. While it is not customary to begin with a full solution in user-centered design, we felt that this choice would allow us to get the most out of our design sessions, given the extremely limited number of participants available. We recognize that this decision can be viewed as limiting, and we emphasize that the game was a starting point meant to stimulate conversation, and was therefore expected to change considerably throughout the study.

3.6.1 Initial Design Requirements

We worked closely with a local prosthetics clinic based at our university. Our main point of contact was an occupational therapist, Linda (pseudonym). Linda specializes in myoelectric prosthetics and training. She works closely with patients first learning to use a myo, and maintains contact with continuing myo users.

Our initial game design was based on requirements gathered through conversations with Linda, in addition to a demonstration of a typical muscle training session with one of her patients. During our initial requirements gathering, we discovered several insights into myo training:

1. Training focuses on specific aspects of muscle control.
2. The “ideal” outcome of training is isolated control over two opposing muscles. However, this is not always achieved in practice, and control strategies exist to accommodate an individual’s capabilities.
3. A co-contraction impulse (a quick, simultaneous “burst” with both muscles) is used as a mode switching instruction (e.g., to alternate control between grip aperture and wrist rotation).
4. Existing tools provide primarily negative feedback.
5. Current training tools are inaccessible outside of the clinical environment due to high cost.

We observed that certain aspects of myo training differ from other types of therapy, resulting in unique challenges when designing in this space. Unlike other therapeutic processes, the goal of myo training is not to regain lost functionality, range-of-motion, or bodily control (as is the case in stroke and physical-injury treatments), but is instead to adapt to a new reality. Limb-loss is irreversible, and learning to use a myo involves working with unfamiliar muscles and mastering new control techniques. Furthermore, while other therapeutic programs focus solely on bodily movement, myos use proportional control and require the user to additionally have precise control over the duration and intensity of muscle contractions.

From our observations, it was clear that the training process could be improved through the use of established game design principles. It was also clear that games would need to incorporate the mechanics found in the existing control strategies and provide adjustable difficulty suitable for players with a wide range of skill and ability. Finally, games accessible beyond the clinical environment would allow trainees to continue improving between clinical visits, ultimately achieving "ideal" muscle control more quickly.

3.6.2 Initial Game Design: The Falling of Momo

Our initial design, The Falling of Momo (**Error! Reference source not found.**) [35,36], is a casual, survival-style game, where players earn points by descending through a series of rising platforms to avoid being squished by spikes across the top of the screen. Players collect coins that can later be used to purchase new characters, themes and unlockables. We based our design on a casual, familiar style of game because our intended audience spans a wide demographic with varying preferences. The left/right game mechanics were selected because they mapped intuitively to the flexion/extension movements being trained, allowing the desired behavior to be targeted in a natural way.

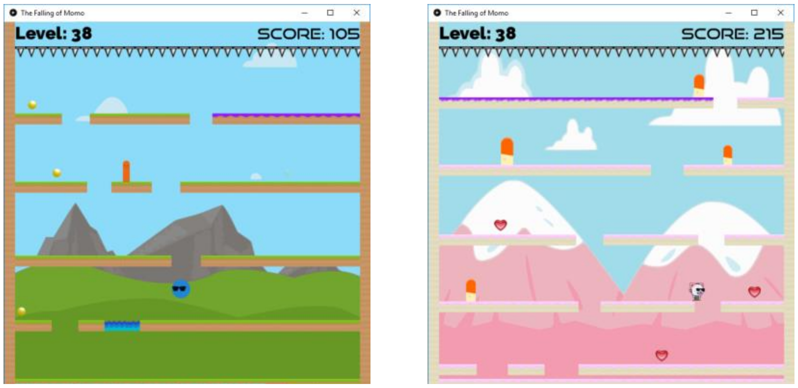

Figure 3-3: The Falling of Momo myo training game with the default theme (left) and the unlocked cat theme (right).

3.6.2.1 Gameplay

Players control their avatar using the Myoband, and controls mirror those of typical prostheses. Momo’s movements correspond to the intensity (for speed) of forearm flexion and extension (for direction). The player can also jump (to avoid obstacles) by performing a co-contraction impulse. Icy (low-friction) and sticky (high-friction) platforms were added so that players would need to use the full range of proportional control. By providing in-game collectables and unlockable items, we were able to provide replay value and positive feedback while still encouraging the player to train their muscles. The rising platforms (which progressively get faster) introduce a time-pressure mechanic, which creates excitement during game play. While certain guidelines may discourage time-pressure [6,15], Momo incorporates suggestions from past research on accessible action games [21] to ensuring both an exciting and accessible experience.

3.6.2.2 Game Evolution

The game was iteratively improved throughout the course of the study using observations, feedback, and suggestions collected during playtest-interview sessions (described below). New features were added on an ad hoc basis as issues were discovered or when explicit feature requests were made. The changes that were made throughout the study include crumbling platforms (for practicing muscle quietness), disappearing coins (to encourage quick collection), a bonus level (for game depth and performance assessment), an over-exertion warning (to indicate when muscle contractions are stronger than necessary), and a second screen containing raw EMG visualization (to allow clinicians to better assess muscle signals during gameplay). We include the motivation and details of several of these new features in our Results section as illustrative examples of how the findings of this study have helped shape the game and a full timeline explaining game evolution can be found in supplementary materials. It was interesting to note that the in-game calibration tools evolved as much as the game mechanics throughout the study; a timeline explaining the evolution of calibration tools can also be found in supplementary materials.

3.7 Study Methodology

To learn more about designing games that provide fun, engaging, and effective myoelectric muscle training, and to assess the viability of the Myoband as a training tool, we conducted a series of 9 playtest-interview sessions with 6 current/past myo users (referred to as patients) and 3 subject matter experts (referred to as experts), each of whom are introduced in Participant Profiles.

3.7.1 Games

Two myoelectric muscle training games were used during playtest-interview sessions: Momo (described above), and a game currently used in our local clinic (referred to as the “car game”), that was developed by the European prosthetics company, Ottobock [27].

The “car game” is part of Ottobock’s [9,27] PAULA software training suite (Figure 3-2) and is controlled using the company’s MyoBoy USB peripheral EMG sensors. Players control the height of a red and blue car using flexion and extension contractions, respectively, as the cars drive forward at a constant speed through a course consisting of a series of walls. The game has no score, but keeps a tally of the number of crashes that occur, so the goal of the game can be inferred as minimizing the total number of crashes. The player avoids crashing into walls by aligning each cars' height with a gap in the approaching wall. The gaps appearing in the series of walls are positioned in such a way that encourages the player to repeatedly sustain a controlled muscle contraction (to get through a high gap) followed by a brief period of rest (to get through a low gap). If the height of the car is not such to allow it to pass through the gap, a red 'X' and a cartoon crash appear on the screen at the location of the crash, but game-play continues.

The game can be configured so that the player is either responsible for controlling a single car (easier), or for controlling both cars simultaneously as they drive through the course in tandem (harder). Additional configuration options allow the player to adjust the speed at which cars drive forward, the size of gaps in walls, and the duration of time that each round lasts. Feedback is also provided to players by a trail (line) that is drawn from the back of the car (creating a line graph effect).

3.7.2 Procedure

3.7.2.1 Patients

Each patient session consisted of a semi-structured conversation focused on the patient's history and experience with both myo training and video games followed by a demo of each game (with presentation order balanced across sessions) where patients were introduced to each game and given a chance to play for 10 to 15 minutes. Following each demo, patients were asked a series of questions about the game and were asked to rate it in terms of frustration, effort, fun, and perceived effectiveness. Patients were then given a chance to provide any additional feedback. To conclude the session, patients were asked to compare and contrast their experiences with both games.

All patient sessions occurred in the examination room at the clinic, with Linda present to ensure that patients were comfortable and to help with game setup (e.g., positioning EMG sensors, setup of car game). At least 2 researchers were present for each session, with one researcher leading the session while the other captured detailed notes. Several patients were accompanied by family members or care-givers (specified in “Participant Profiles”) and, in these cases, their opinions and feedback were also considered.

3.7.2.2 Experts

Expert sessions also consisted of a semi-structured conversation followed by a gameplay demo where feedback on both games was collected. Conversation with experts focused on their experience with training in the clinical setting, the ideal and practical outcomes of training, and their views and opinions on game-based training. Experts were given a demo of Momo, but since every expert was already familiar with the car game, no demo was needed. Two expert sessions occurred in person, and in these cases experts were given a chance to play Momo. Due to geographic distance, the other expert sessions occurred over the phone and a video demo providing an overview of the features and mechanics of Momo was used instead (similar to the video-figure[16] accompanying this paper).

Two researchers were present for each expert session, with one leading while the other captured detailed notes. Linda was the subject of one expert session, but was not present during any of the others.

3.7.3 Participants

Linda initiated contact with all participants. Patient participants came from Linda's existing client-base, and were recruited based on availability (i.e., making a visit for unrelated clinical purposes), willingness to participate, and discretion of clinical staff. Expert participants were recruited through Linda's professional contacts.

Participants were not remunerated for their time, and were aware that their participation was voluntary and that they were free to withdraw from the study at any time without implication on their clinical standings. All participants read and signed an ethical consent form[17] (verbal consent was used during expert phone sessions) which explained the purpose, procedure, and voluntary nature of the study. For participants younger than the legal age of consent, a parent read and signed the consent form on their child's behalf, and was present for the duration of the session.

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[16] The submission of this paper included an accompanying video-figure that can be found in the ACM Digital Library (http://dl.acm.org/citation.cfm?id=3025676) or on YouTube (https://youtu.be/2y9TPDVfQKQ).

[17] Details can be found in REB 2016-081 and REB 2016-106 within the University of New Brunswick Research Ethics Board.

3.7.3.1 Participant Profiles

A total of 6 patient and 3 expert participants were included in the study. Four of the patients were accompanied by a family member. A brief summary of each participant is provided below. The information is factual, but names have been modified to maintain anonymity.

Kyla is an 11-year-old female who plays video games every day for several hours on her PS4, Xbox, and iPad. Kyla uses two myo arms (not worn while playing games) and a powered wheelchair as the result of an amputation, and has some cognitive deficit. She was accompanied by both her mother and caregiver, who helped answer some of the questions. Kyla's mom told us that since using her myos (~ 1 year) she has been doing much better in school.

Stanley is a 50-year-old male, who has been using a myo for over 30 years. Stanley was born without a right forearm, and believes that his myo has become an integrated part of his body; he uses it very naturally (e.g., twiddling fingers, fidgeting with a pen). Stanley had minimal training when he first received his myo (which was common practice at the time), and does not frequently play video games.

Mark is a 20-year-old male born without a left forearm. Mark used a myo when he was younger, undergoing training with Linda. At the age of 12, he stopped using his myo because the weight of the device made it too difficult to use effectively. Mark casually plays Xbox with his friends without the use of a prosthesis or special equipment. Mark is going to college this year, and is reconsidering using a myo to support independent living. During the interview session, Mark was joined by his father.

Justine is a 24-year-old female who was born without a left forearm, and was accompanied by her boyfriend Jon. Justine underwent training and received her myo as a toddler, but stopped using it at age 11 because she preferred the aesthetics of her passive prosthesis. Justine recently started using a myo again to benefit from the additional functionality it provides her and to alleviate repetitive-use injuries that were sustained in her right arm, and completed further muscle training exercises when she received her new arm. Justine casually plays Mario Kart and Donkey Kong with her boyfriend and daughter.

Glen is a 50-year-old male who has been using a myoelectric arm for 32 years. As a result of an accident, Glen had surgery removing his left forearm at the age of 17. Glen trained through practical use, and during his stay in a rehabilitation center following the accident he spent many hours practicing with his new myo arm. Glen enjoys playing cards casually with friends and family, and occasionally plays solitaire on his phone.

Belle is a 10-year-old female (accompanied by her Mom), who was born without a right forearm. She first started using a myo at age 16 months, and continued to use it for several years. Belle more frequently uses a passive arm than her myo, because the weight of the myo is uncomfortable, the passive arm allows her to do physical activity (cheerleading and gymnastics), and she often gets frustrated with her myo because of frequent control problems. Belle casually plays games on her Wii and iPad with friends.

Linda is an occupational therapist as described above in the Initial Design Requirements section.

Stuart is a research engineer who has specialized in the field of myoelectric control of prosthetics for 22 years. Stuart's research focuses on using pattern recognition to create more advanced and natural control strategies.

Ruth is an occupational therapist (OT) with 10 years' experience working with two large prosthetics companies. She has also worked in clinics training myo patients, and in teaching prosthetists and other OTs myo training practices.

3.7.4 Data Collection and Analysis

Data collected during each session consisted of a complete audio recording, in addition to notes taken during the session capturing the researchers' observations. All patient sessions were transcribed, and then independently coded by two authors. The resulting codes were analyzed with a thematic analysis [10]. To remain patient focused, expert sessions were not included in the thematic analysis, but were instead used to help validate themes identified.

Our thematic analysis adopted a deductive approach where findings were organized around predetermined ideas. The three concepts were based on our initial work with Linda, establishing requirements for our game, and included: the challenges experienced in training, the role of feedback (positive or negative) on patient/player experience, and the impact play may have on the therapeutic process.

3.8 Results

3.8.1 Core Challenges in Training

Most importantly, analysis identified a number of themes that fell into views on and challenges in training, with sub-themes addressing training practices, and patient needs.

3.8.1.1 Increasing Access to Training

Patients raised issues related to training practices and access to training; a focus also supported by expert feedback.

The most common response within this theme was the **lack of training programs for patients**. Patients reported receiving little to no training, but there was some evidence that they managed to make do with limited opportunities. For example, Stanley had minimal training and has been successfully using his prosthesis for more than 30 years by learning through practical use. However, experts pointed out that a lack of training may sometimes place important limitations on the functionality that is available to a patient or change how they can operate their prosthesis: This was evident in Stanley's gaming session, where we observed his therapist Linda uncover that he had adopted a non-standard control technique. She noticed this by first watching him play the games, and then confirming with muscle signal visualizations. Rather than contracting continuously to create smooth movement of the prosthetic hand or wrist, Stanley had been using a rapid series of pulses (a quick contraction and release) to control his myo. While Stanley used his myo very naturally, Linda commented that this is not strictly correct and could be limiting if he had a newer myo with a different control scheme.

In this context, experts pointed out that ideally **games should be designed to support a pre-prosthetic training phase** (before receiving a prosthesis), in order to make patients aware of how to contract the muscles that will be used to control their prosthesis. Having a broader perspective on the issue of training practices, experts stressed that the actual process can differ greatly depending on the availability of and access to services. At the local clinic, the clinician had a primary role to work with patients in a training and troubleshooting capacity. However, many other facilities do not provide this level of service and only introduce patients to basic prosthetic maintenance.

A possible solution that came up in patient feedback and expert interviews alike were **game-based opportunities for out-of-clinic myo training**. Belle's mom explained that training outside of the clinic wasn't an option: *"…we haven't really done any sort of training outside the [clinic]... we tend to come in here and let the professionals do it."*. Experts agreed that learning (and mastering) the use of a myo is something that takes time and substantial training, but training occurs in short, intermittent sessions. Currently, experts don't have anything that they can send home with patients so that they can continue to train their muscles between visits, with Stuart pointing out that *"it's difficult to use one of these [myos] … improvement comes in stages … it doesn't all come in the first 3 days..."*. While our work was not directly focused on at-home training, experts were keen on the idea of a robust, low-cost training solution, agreeing that it would be extremely valuable.

3.8.1.2 Managing Muscle Fatigue

Many patients' responses evolved around the **management of muscle fatigue** and the creation of a positive, empowering player experience. In training, patients are asked to activate and use muscles that they have either never used before (in the case of congenital limb differences), or are vastly different from what they have grown accustomed to (in limb loss due to surgical removal). This poses two specific problems. First, certain patients might need to spend a substantial amount of time exploring methods for creating muscle signals that can be usefully detected by a myoelectric sensor. Second, since these muscles have rarely/never been used or are physically limited, patients can tire quickly.

For example, Justine pointed out that fatigue was challenging for her when playing the car game, *"[…] my muscles would get really, really tired, like tired to the point where I couldn't even do it, like I had to take a break … I'd have to stop and I couldn't do it for a minute"*, which could negatively affect her experience and therefore engagement with the game in the long run. Likewise, experts voiced the concern that patients would get overly involved in the game and **lose focus on their level of exertion**, straining their muscles more than necessary, resulting in premature fatigue.

In order to better make patients aware about when they have reached the maximum input threshold, we added the over-exertion warning, a feature that programmatically draws a red warning around Momo when the player contracts harder than they did during calibration. This was beneficial because it allowed both patient and clinician to identify when over-exertion occurred.

3.8.2 Creating an Empowering, Positive Player Experience

Themes concerning the two games often focused on aspects relevant to therapy and how games could contribute to an empowering positive experience and, most importantly, maintain appropriate levels of difficulty to create an encouraging player experience and broaden the appeal of games through adaptable themes.

3.8.2.1 Importance of Appropriate Level of Difficulty

A common theme across patients was the importance of **appropriate levels of game difficulty**. Patients clearly found Momo to be easier and, as a result, less frustrating than the car game. For example, Belle's feelings about the car game were made quite clear, *"I don't understand how this is helping me... It's too hard… I keep smashing into the wall, I'm not very good at this game already."*.

While a positive player experience as the result of gameplay that is perceived as easier is generally desirable, this creates some issues with respect to therapeutic goals, but also patient perspectives on the game. Some patients felt that Momo was more suitable for children or younger players. Mark, for example, acknowledged that the game was probably more appealing to a younger audience, *"Umm, maybe not me, but I guess if you were a kid"*. Even when this feeling was expressed, patients still felt that it was an appealing game, with Stanley pointing out that *"In the eyes of a [child]… there's no question, right?... it even brings out the competitiveness in me, right? The old guy."*

A sub-theme that was prominent among experienced myo users focused on **difficulty differences between the games and real life**, stating that playing either of the training games is more strenuous than day-to-day prosthetic use. In terms of training, there are conflicting interests at play. On one hand, practicing more strenuous exercises can help to build strength and stamina, both of which are important for effective prosthetic use. For example, Justine commented that *"[...] it's probably more work than I have to do when I'm doing regular things using my arm, but… it really gets you practicing using the muscles…".* On the other hand, patients just starting to use a myo may find the strenuous activities discouraging and deter them from further practice, with Glen commenting that *"[...] you're using [your muscles] a whole lot more here [in the game] for somebody learning, I think that would be very frustrating."*.

This suggests that games must carefully balance creating an appropriate amount of exertion with what is achievable for new patients, and should consider how realistic in-game difficulty maps onto using a myo in the real world.

3.8.2.2 Adopting Positive Perspectives on Player Performance

A common theme among all patients that was also backed by expert feedback was the importance of **positive perspectives on player performance**. Overall, patients and experts alike found that Momo offered a positive experience, where the car game, in contrast, did not. While the car game doesn't stop after a crash, the simple red 'X' that is displayed seemed to be enough to create negative emotions among players. For example, Glen pointed out that he was *"[...] no good, I [only] got one through… Agh, I crashed again. I'm trying, but they're coming too fast… I'm [just] trying to crash now".* Yet, other patients didn't seem to mind crashing often because they didn't necessarily see the car game as a game, with Stanley commenting that *"[...] it's no different than going home and doing exercises, right – to get weight off… I would think of it as more of a* *tool.”*. In this context, Linda (expert) pointed out that *"the risk is that [patients] start having a negative opinion about using myo, or that the prosthesis is going to be frustrating too, and then they start with a negative bias"*, underlining the importance of **positive, encouraging player feedback**. In agreement with Abeele [1], this suggests that adding game-like aspects without creating the right experience can be detrimental to patients’ views of their own abilities to control a myo successfully.

3.8.2.3 Perceived Self-Efficacy Through Play

Throughout analysis, the importance of providing playful experiences that **allow patients to increase perceived self-efficacy** emerged.

Within the car game, we observed all patients having difficulty sustaining the exact level of muscle contraction that would cause the car to stay at the right level to pass through the gap. Cars would bounce up and down rapidly, because their movement was mapped directly to noisy sensor readings. This caused patients to feel like they had little control, with Stanley pointing out that *“It’s hard for me to hit the [gaps] … I find the longer that I try to maintain the more it goes down”*. Patients identified the speed of the action and the fact that they had to keep track of two cars at once to be overwhelming elements of the car game, with Justine commenting that *“It got overwhelming I feel – I just got so tired and overwhelmed by the 2 cars”*. Furthermore, we observed a challenge related to time-pressure in games previously commented on by Hernandez and colleagues [21] in the context of game accessibility, recommending not to remove action and challenge from games, but to ensure that it is appropriate and manageable: while both games employ time as a central mechanic, players felt less frustrated when playing

Momo, suggesting that balancing and maintaining achievable player goals is crucial when leveraging games for prosthesis training. Generally, Momo achieved higher levels of perceived self-efficacy by smoothing in-game representation and reaction to often noisy EMG signals. This highlights an interesting challenge for our project: While Momo's responses to player input are – strictly speaking – less accurate, the game provided a more encouraging overall experience. However, one advantage of the car game is that it explicitly displays muscle signals, which is useful to clinicians during a training session, information which is lost when smoothing EMG input as done in Momo. In response, visualizations to support therapists were added to Momo during design iterations (discussed below), but the simplified control scheme was maintained to preserve player experience.

3.8.2.4 Increasing Player Engagement Through Flexible Themes

A theme that was frequently touched upon by patient feedback was the desire to **personalize game themes**.

While Momo offers theme elements around monsters, aliens and castles, one patient expressed clearly what she would like to see: *"I want cats… why wouldn't they make cats? … I really, really, really, really, really, want cats… I love cats! I have 3 cats at my home." (Kyla)*, a change to the game that was also appreciated by other patients. For others, customization wasn't an important feature, but they still recognized the value in it, for example Glen commenting that *"I guess [it's] not for me personally, but I can see that the options to customize it, to make it fit…".*

Given the **broad audience of game-based myo training** (e.g., having to accommodate players of different ages and with different levels of gaming experience), we believe that customization should be further explored as a means of maintaining continuous patient engagement through being able to offer individually relevant game themes.

3.8.3 Improving Therapy through Play

The final set of themes that emerged throughout analysis focuses on the improvements that game-based myo training can bring to therapy by making new information available to patients and therapists alike.

3.8.3.1 Therapy-Relevant In-Game Feedback

Besides encouraging patient engagement with therapy, results suggest that **in-game feedback also offered additional feedback on therapeutic progress**, a feature which was particularly appreciated by patients who otherwise struggle to see little improvements. Stanley explained that the *"...game tells -- tells all of us a little about my control, right? ... I'm learning a little bit about -- about myself, but also about the capabilities of the hand."*. While this effect can also be accomplished through a simple visualization of muscle signals, or using the car game, there were some instances in the use of Momo where its specific mechanics made particular problems more salient. For example, causing Momo to jump in the presence of muscle co-contraction served as an indicator for when patients were having trouble isolating their contractions. This gave a very tangible way for the occupational therapist to convey instructions and feedback, and for the patient to understand what was happening, for example illustrated by a sequence where Linda (expert) pointed out to Justine (patient) that *"When you jump, it usually means that you're using both muscles at the same time… if he's jumping when you don't want him to, just kind of relax, and then try again."*.

Even effective myo users could benefit from feedback as the **games exposed areas where the patients could further improve** their muscle control, and achieve additional/more reliable myoelectric control. For example, Stanley explained that *"[...] it's good to visually see where you stand and it also tells you if there is room for improvement… I could [only] be at 60% and I wouldn't know, right?"*. Without this feedback, patients would have remained unaware of hidden issues in their muscle control.

3.8.3.2 Increased Patient Knowledge About Myos

This theme focuses on the increase of **patient understanding of how their prosthesis works** that can be accomplished through the deployment of games. Initially, we had very few feedback mechanisms to allow patients and clinicians to see their calibrated muscle signals in real time. Immediately, we observed that this was problematic when calibration issues arose – minor adjustments to the calibration were important for both Momo and the car game. We added several features to make the calibration and real time muscle signals visible immediately after calibration and selectively available during gameplay. This immediately facilitated calibrating the device and identifying calibration problems, but also changed how the patients worked with their device. The visualization tools helped patients to better understand their device, and we immediately saw patients and clinicians engage in conversation to work out small problems, for example with Justine commenting that *"I feel like this one [sensor] might* *be a little high *pointing to the on-screen bar growing with muscle contractions*, because he's going that way *points left* when I try to go the other way sometimes"*.

This interaction can be beneficial for patients because it allows them to **get more familiar with how their myo works**, and **engage about it with clinicians in more technical ways**, possibly facilitating troubleshooting and creating a more personalized approach to therapy.

3.8.3.3 Facilitating Myo Training at Home

Beyond its application in clinics, a theme that emerged from analysis was the potential of the Myoband to **enable patients to carry out prosthesis training in their own homes**. Patients responded well to the idea of using the Myoband as a training device, and expressed comfort when asked about home use, for example with Glen pointing out that *"[...] with the armband, I can slide it on, twist it around to where it needs to be, and do the calibration with some training, but yeah, that would be the way to go."*. At-home training could facilitate the initial adaption to myo use, as underlined by Kyla's mother, who stated that she wished her daughter would have had more training opportunities as it was *"a big challenge for her."*. To this end, the use of more affordable off-the-shelf consumer hardware could enable the wider application of training games such as Momo, adding another layer to the training opportunities currently offered through clinics.

When discussing the home use of the Myoband, one concern expressed by the experts was being able to position sensors appropriately on the arms of all patients, which vary widely in terms of size, shape, and the location of sites used for sensing muscle contractions. Training sessions utilizing Momo showed that our prototypical approach was suitable for all participants, demonstrating that the Myoband can be adapted to be viable for many limb-different patients.

3.9 Discussion

We now reflect on our adapted UCD process, the importance of having a positive empowering experience, and the viability of the Myoband as a training tool.

3.9.1 Reflections on our Design Process

We adapted the typical UCD approach for several reasons. Most importantly, we were working with a sensitive population that was difficult to access. Our patients came from a wide geographical area to the clinic for reasons other than our study. As such, our sessions were short (60-90 minutes), with one patient at a time, and there was little opportunity for follow-up. Basing our design sessions on a partially-formed solution proved to be incredibly valuable for both eliciting feedback and encouraging discussion. Having a tangible 'thing' to examine and critique was viewed constructively by our patients and experts, and patients willingly discussed game aspects that were available for them to use, but struggled to conceptualize and reflect on features that were not yet available.

Our adapted design process worked extremely well for us and for our patients. Patients who came later in the process had the benefit of new functionality that allowed them to more quickly address calibration issues, play a more richly-featured game, and receive feedback that ensured their play better aligned with targeted training behavior. While other therapeutic game studies have had the benefit of engaging in a participatory design process and working with a set of patients over an extended period of time (e.g., [18,19]), we feel that this is not practical for many populations such as ours. While more work needs to be done to generalize our approach, we feel that it holds promise as a practical means of balancing the constraints of an understudied population with gleaning meaningful new design knowledge.

3.9.2 Therapeutic Games Need Not Be Unpleasant

Part of the motivation for working with our clinic was that they reported to us the negative feelings that many of their patients have when using previously-developed training tools. While patients usually did not enjoy their training exercises, the clinic still made use of them because they were relatively easy to set up and provided meaningful feedback to both patients and clinicians. However, the experts we spoke with all recognized the potential pitfalls of providing a negative experience to myo patients (hence their focus on facilitating patient success). Part of the reason for this sensitivity to negative feelings is likely due to the extremely high rate of abandonment of myos (up to 75% [7]). While there are many issues that can lead to abandonment (e.g., aesthetics, weight, convenience [22]), frustrations that arise from lack of control over the myo also contribute [12]. While our work does not directly address abandonment, we anticipate that any improvements to the training process will help reduce frustrations due to lack of control, thereby reducing abandonment.

Patients were receptive of Momo for many of the reasons discussed in our results: they felt more in control, negative feedback was minimal, the game started at an appropriate level of difficulty, and it felt more like a genuine game. While both Momo and the car game facilitated practicing the same basic muscle activity, the mechanics of the car game left patients feeling more tired and frustrated. We leave quantitative comparison (e.g., movement precision, training outcomes, abandonment) of Momo to future work, but we are encouraged that both patients and experts felt that Momo provided a better experience.

3.9.3 Myoband Viability and Implications for Home Training

While we started this project assuming that we would only focus on improving Momo's design, we quickly learned that the calibration functionality of our game was of equal importance. Without having easy access to, and meaningful feedback from the calibration, patients would not be able to play our game. Furthermore, without real-time access to performance data, clinicians could miss important information about potential problems with both the calibration settings and a patient's performance. As our tools to calibrate and make use of the Myoband improved, so too did our confidence that it is a viable solution.

As we described earlier, both patients and clinicians were receptive of the Myoband as a training tool. The importance of this finding cannot be understated. Currently, the only other myo training technology costs 4000 USD, is more complex, and requires two people to attach (by positioning the electrodes and securing them with a tensor wrap). In contrast, the Myoband, although not designed for this use, has been at least as robust, provides sufficient signals, is easily positioned by a single patient, and costs less than 200 USD. Because Momo is free and open source (https://github.com/hcilab/Momo.git), this means that we have a viable training tool at a fraction of the cost of the leading commercial solution. We hope that others will be encouraged to start developing myo training games based on our findings, and that others might use and extend Momo in their own myo training research.

3.10 Limitations and Future Work

The adapted UCD process described in this work arose out of the needs of the local clinic and patients. While our process is likely to have confounded some of our findings (as compared to a more traditional approach), it enabled us to introduce quick iterations that maximized the impact of input with a small number of participants and within a short timeframe. We gave careful consideration to the choices in our study design; however, our results must be taken in light of our adapted process. Beginning with a partially developed game may have inadvertently directed/narrowed our exploration of myo training games, and additional results may be found through further exploration.

Likewise, the small number of participants needs to be considered when generalizing our findings. While we believe our findings can help inform the work of designers along with future research, we are planning to continue our collaboration with the clinic to develop a refined training tool that can be used on an on-going basis with patients.

This study has provided evidence that sending Momo home with patients is an important path forward. In further collaboration with the clinic, we are planning to provide Momo at home on a trial basis to further explore challenges and opportunities associated with home-based myo training. In this context, we plan to investigate pathways to maintain long-term player engagement; e.g., through multiplayer features that could connect patients in remote locations.

3.11 Conclusion

This paper presents our work on developing a new myo training game, the Falling of Momo. While games for myoelectric training have been previously proposed, research has focused on technical issues, not on the needs of patients and clinicians to provide a positive, empowering experience that targets key training objectives. Our game was initially developed based on requirements gleaned from our interactions with a local prosthetics clinic. Through an adapted UCD process, we then refined Momo to better meet the needs of both patients and clinicians by adding features that 1) facilitate the training process, 2) provide meaningful feedback on target behavior, and 3) increase engagement.

Our findings provide guidance for the design of myo training games and therapeutic games in general. We highlight that patients felt a need for out-of-clinic training tools and that there is a 'fine line' between striving for targeted training behavior and providing a positive, engaging experience. Through play, patients can better understand their progress, both on areas where they can improve and about the device they are training to use.

Our work opens the door for myo training to be more readily available and accessible outside of the clinic by showing the viability of a low-cost input device and an adapted UCD process that focuses on patient needs and experience, while making rapid progress in the development of an engaging training game.

3.12 Acknowledgements

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4 Article 3 – Quantifying Muscle Control in Myoelectric Training Games

Tabor, Aaron, Wendy Hill, Scott Bateman, and Erik Scheme. 2017. Quantifying Muscle Control in Myoelectric Training Games. I*n Proceedings of Myoelectric Control Symposium (MEC) 2017.* Fredericton, New Brunswick. 4.

4.1 Abstract

Myoelectric training games have recently gained interest for increasing motivation and engagement when learning prosthetic control. However, game-based training has not yet been shown to result in improved performance of functional tasks, which has led to a push for “task-similar” training exercises and a questioning of the merit of training games altogether. This apparent lack of observable skill transfer remains counterintuitive, because games can encourage movements similar to those required for prosthesis control. To better understand the effects of game-based training, we identify a set of “muscle-control metrics” to quantify characteristics of EMG control input that are considered important for two-site proportional control. In this paper, we introduce these muscle-control metrics and describe a myoelectric training game developed in collaboration with patients and clinicians that is able to capture metrics during gameplay. We also outline an on-going data collection study, which will allow us to identify which aspects of a myoelectric training game lead to improvements in input signals.

4.2 Introduction

To take advantage of neural plasticity[18] and maximize potential for success, it is desirable for new myoelectric prosthesis users to begin training as early as possible following amputation (early childhood in the case of congenital limb-difference) [1].

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[18] The original publication mistakenly read *“muscle plasticity”*, which implies a structural or functional change in muscle properties. Early access to training is important, however, because it leverages the changes occurring in the *brain* more so than those occurring in the *musculature*.

However, a delay is often incurred before patients receive their prosthesis due to factors including recovery time, insurance processing, and fabrication and fitting of the prosthesis. While beneficial for keeping patients active while waiting, muscle training activities are often monotonous or lack sufficient feedback, making it difficult for patients to stay motivated [8].

Game-based training tools have been proposed to address the loss of motivation that patients often experience [3,4,5,7]. Muscle-controlled games can provide an engaging experience, making the otherwise monotonous training exercises more enjoyable. Therapists and prosthetists consider training games – and the muscle improvements they create – to be a valuable part of the training process. In practice, even simple games are used early in training to improve understanding, strength, and endurance, without the expectation of achieving functional skill transfer [7].

Despite their widespread use in practice, skills acquired in games have not been shown to transfer to functional prosthetic control, leading some researchers to question the benefit of training games altogether [3,4]. These studies, however, have only looked at coarse game performance (e.g., levels and score) as an indicator of learning, so the reasons *why* success in muscle-controlled training games does not predict improved functional control are still unclear.

To address the lack of information about the nature of improvement in training games and in myoelectric control, we propose a set of *muscle-control metrics* for assessing skill during the pre-prosthetic phase of myoelectric training. These metrics, inspired through conversations with clinicians, more accurately assess performance by quantifying aspects of muscle control that are important for success with a prosthesis. We built the ability to quantify and track these metrics into a training game we previously created through a user-centered design process with patients and clinicians [7].

Our work makes two main contributions: 1) we provide a set of objective and measurable metrics for tracking and assessing changes in muscle control; and, 2) we provide a freely available training game that enables the collection of these new muscle-control metrics. In the remainder of this paper, we describe work on game-based training for myoelectric control, introduce our muscle-control metrics, present our training game, and finally, outline our ongoing data collection that will allow us to better understand the nature of skills acquired through training games, and how they might transfer to functional control.

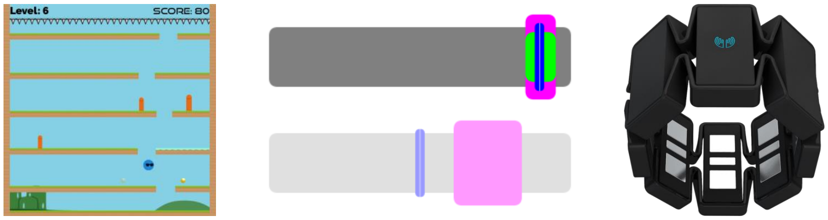

Figure 4-1: Research Tools. a) The Falling of Momo: Myoelectric Muscle-Training Game (github.com/hcilab/Momo.git), b) MyoFitts: Myoelectric 2-DOF Fitts Test (github.com/hcilab/MyoFitts.git), c) Myo Armband: Myoelectric Device (myo.com)

4.3 Background

4.3.1 Myoelectric Training Games

Recent research on training games has shown conflicting results. One study, employing the PAULA software suite, found that game-based tools are just as effective as traditional training approaches and that clinicians and patients can use games and other training activities interchangeably [2]. Conversely, follow-up studies by the same authors have suggested that some training games may be no more effective than a total lack of training. This recent work has suggested that, while patients might acquire skills in the game, they may not translate to improvements in prosthesis control [3,4]. These conflicting results suggest that the specific challenges associated with designing training games for amputees are not fully understood.

4.3.2 Outcome Measures

Assessing a patient's myoelectric ability is crucial for tracking progress over time. Existing measures are divided into two categories: 1) observational, and 2) self-reported [9]. *Observational measures* focus on quantitative, functional metrics such as task completion time, while *self-reported data* tend to focus on subjective elements such as perceived usefulness and embodiment of a prosthesis. Although an important focus during clinical training, control signal quality - an underlying prerequisite for robust myoelectric control – is often overlooked in existing observational metrics.

4.3.3 Games and Training Activities

To support our research in training games, we have developed a game, called *The Falling of Momo* (Figure 4-1a), and a standalone training activity based on acquiring targets, called *MyoFitts* (Figure 4-1b).

Momo is a muscle training game in which the player (blue) navigates their descent through a series of continually rising platforms [7]. Momo's design was aimed at creating a fun and engaging game that requires muscle movements that align with those required in prosthetic control. Flexion and extension contractions move Momo left and right, while a mode-switch co-contraction causes him to jump. Momo's features and design were informed and iteratively developed throughout a user-centered design process. Our process engaged amputee patients and clinicians through play testing and interviews, which we iteratively used to refine our game. Our work (described in [7]) proposes a set of design requirements for building training games that best meet the needs of patients and clinicians.

MyoFitts is a myoelectric targeting test with similar controls. Flexion and extension contractions move the cursor (blue) into the targets (pink: un-acquired, green: acquired), with mode-switching being used to change focus between bars. Unlike Momo, MyoFitts is not a game, but instead is a training activity used in myoelectric control research (e.g., [6]).

Both Momo and MyoFitts are controlled with a two-site proportional control strategy using the Thalmic Labs Myo Armband (Figure 4-1c), a commercially available myoelectric input device, which we have previously assessed as viable for use in training [7]. Both Momo and MyoFitts are freely available tools (see links in Figure 4-1) that incorporate data collection based on the muscle-control metrics outlined below.

4.4 Muscle-Control Metrics

The following metrics are proposed for quantifying muscle control ability and are derived from logs of the EMG data captured during game play.

4.4.1 Muscle-Control Metrics

Several metrics are proposed to quantify common characteristics of muscle signals that are beneficial for all aspects of two-site proportional control.

- ***Isolation:*** When using a prosthesis with difference-based proportional control, greater muscle isolation enables a wider range of proportional speeds.
    - Isolation is computed as the ratio of intentional to unintentional muscle activity. It is calculated by inferring the intended direction of motion (i.e., stronger of the 2 EMG readings), and dividing by the level of unintentional co-contraction (i.e., the weaker of the 2 EMG readings). Periods of impulse (described below) and rest (i.e., both readings below a threshold) are excluded. *Higher is better.*
- ***Over-Exertion:*** Learning to create muscle contractions of an appropriate strength helps patients increase endurance while using a prosthesis.
    - Over-exertion is the weighted-tally of all EMG readings above the calibrated contraction level[19], averaged by the number of samples. Higher values reflect unnecessarily strong contractions. Periods of rest are excluded. *Lower is better.*

4.4.2 Mode-Switch Metrics

Accurate co-contractions allow a prosthesis user to mode-switch accurately, limiting unintentional device movement. Mode-switching, however, is often a source of frustration, even for experienced prosthesis users [8]. Therefore, many of our metrics focus specifically on mode-switching and are calculated over brief periods of co-

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[19] The original publication read *"maximum voluntary contraction level"*. Keep in mind that patients were instructed to contract only with a comfortable, sustainable level of strength during calibration.

contraction. Co-contractions are detected by first identifying the registration time of each mode-switch, then searching forwards and backwards through the log for onset and conclusion times of the co-contraction (Figure 4-3, right). Figure 4-3 introduces terminology and demonstrates each of the metrics described below.

- ***Amplitude:*** Mean height of flexion and extension signal peaks achieved during co-contraction. *Higher is better.*[20]
- ***Width:*** Duration of time between onset and conclusion of the co-contraction. *Shorter is better.*
- ***Rise:*** Duration of time between onset and registration of the co-contraction. *Shorter is better.*
- ***Fall:*** Duration of time between registration and conclusion of the co-contraction. *Shorter is better.*
- ***Phase:*** Duration of time between the peaks of flexion and extension muscle signals during the co-contraction. *Shorter is better.*
- ***Fit:*** Absolute difference in area between the flexion and extension signal curves during the co-contraction. *Smaller is better.*

In agreement with previous results [1,6], our preliminary pilot data suggest that game-based training can lead to improvements in myoelectric muscle control. Figure 4-2

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[20] The height of the signal peaks is measured as a ratio of the contraction levels performed during calibration.

demonstrates how our mode-switch metrics track a pilot participant as they learned to create mode-switch co-contractions over a series of training sessions.

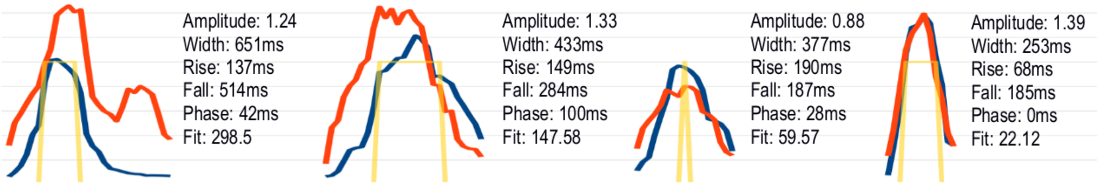

Figure 4-2: Co-contraction Improvements. Each co-contraction depicted was generated by a single participant during a series of 4 pilot training sessions (leftmost: session 1, rightmost: session 4). Red and blue lines represent flexion and extension signals, respectively, while yellow spikes indicate periods when the training system detected a mode-switch. Metric scores are shown to the upper-right.

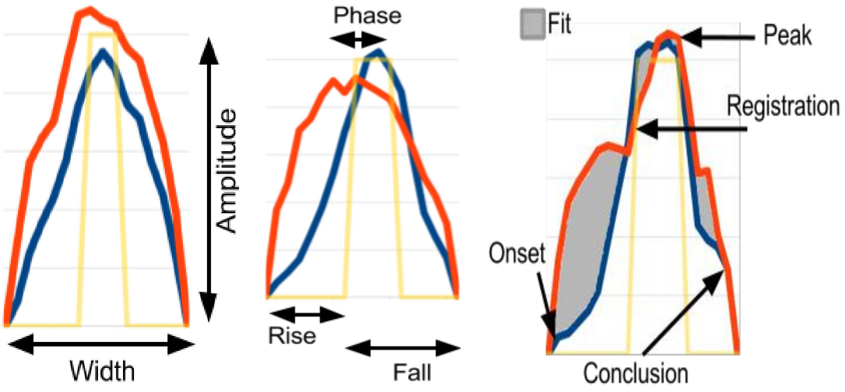

Figure 4-3: Terminology and Examples. Red and blue lines show the levels of flexion and extension muscle contraction, respectively. Yellow spikes indicate when the training system detected a mode-switch.

4.5 Discussion

4.5.1 Transfer to Improved Functional Performance

While our metrics are not yet clinically validated, they are based on principles of two-site proportional control. Because of this, it is likely that they effectively characterize aspects of control not currently captured by coarser measures, such as scores in training games or completion times in functional assessment tasks.

We are currently running a longer-term experiment where new myoelectric users train using our game over a period of ten or more play sessions. In this experiment, we are tracking progress both in game play and through our muscle metrics, enabling a direct comparison between in-game learning and improvements in muscle control.

We believe that the metrics may also have further applications. Analyzing muscle-control improvement in detail allows clinicians to present patients with much more specific, targeted, and quantifiable training goals. Additionally, our metrics can be incorporated into games designed for at-home training and provide targeted feedback and increased awareness of progress made between clinical visits. Finally, our metrics are not specific to games; if EMG logs were collected from other activities (e.g., functional prosthetic tasks), the metrics obtained could be compared to those obtained during training games for discrepancies.

4.5.2 Limitations of the Current Muscle-Control Metrics

Some characteristics typically associated with strong myoelectric muscle control are not captured in our current metrics. Neither *consistency*, the ability to create and sustain a desired level of contraction strength, nor *endurance*, the ability to perform for prolonged periods of time without experiencing fatigue or performance degradation, are reflected in our metrics. Previous studies have assessed improvements in endurance by having participants perform a myoelectric tracking task both before and after training, recording the time at which participants became fatigued [6]. To our knowledge, improvements in consistency have not been assessed in the past.

When first learning myoelectric control, it is common for a patient to attempt a mode-switch several times before succeeding. Unsuccessful co-contractions (i.e., when the patient's attempt was not registered by the training system) hold valuable training information, but are not currently accounted for in our metrics. Incorporating these occurrences could help clinicians provide patients with even more constructive advice.

We observed in our pilots that, as participants got familiar with our training game, they began frequently "sliding into" and "sliding out of" mode-switches (i.e., quickly transitioning between left/right movement and jumps without relaxing muscles between the two phases). It is difficult to algorithmically distinguish between this "sliding" behavior and genuinely problematic impulses, so to avoid artificially inflating mode-switch metric scores we foresee the need to perform a more intelligent identification of mode-switches within EMG logs. It is interesting to question whether this "sliding" behavior is evidence of the development of a bad habit, or of a sense of proficiency and comfort with the control scheme.

4.6 Conclusion

In this work, we introduce a new set of metrics that are well suited to quantify improvement that occurs during myoelectric training games. We suggest that the information provided through these metrics is key to understanding skill transfer between training activities and functional control. Further, we believe our metrics would be beneficial to clinicians as they guide new patients through the training process, allowing them to identify specific deficits in control with greater precision. We have also demonstrated how the metrics can be employed and interpreted through their incorporation into a carefully designed training game, and a commonly used training activity. Our tools are freely available and may help provide critical new findings regarding skill transfer between game-based training activities and real-world prosthesis control.

4.7 References

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5 Article 4 – Improvements in Myoelectric Control over Multiple Game-Based Training Sessions

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5.1 Abstract

While training is critical for ensuring initial success and continued adoption of a myoelectric powered prosthesis, relatively little is actually known about the amount of training that is necessary. In previous studies, participants have completed only a small number of sessions, leaving doubt about whether findings necessarily generalize to a longer-term clinical training program. Furthermore, a heavy emphasis has been placed on functional prosthesis use when assessing the effectiveness of myoelectric training. Although well-motivated, this all-inclusive approach may hide more subtle improvements made in underlying muscle control that could lead to tangible benefits. In this study, a deeper exploration of the effects of myoelectric training was performed by following the progress of 30 participants as they completed a series of ten 30-minute training sessions. Progress was assessed using a newly developed set of metrics that was specifically designed to quantify aspects of muscle control that are foundational to strong myoelectric prosthesis use. Through this work, it was determined that, while myoelectric training does lead to improvements in muscle control, these improvements occur more gradually and continually than has previously been considered. This finding has implications both for best practices in research on myoelectric training as well as aspects of clinical therapy in practice.

5.2 Key Words

Myoelectric Control, Myoelectric Training, Therapeutic Games, Clinical Outcome Measures

5.3 Introduction

Learning to control a prosthesis by any means is a complex and difficult task. Myoelectric control of a prosthesis, which uses the electrical signals generated during the contraction of residual musculature, is arguably even more complex as it requires the user to adapt to a device, but also to learn how to properly contract those muscles.

Training is therefore considered to be an essential step in the rehabilitation process, possibly leading to more effective and prolonged use of a prosthesis [25]. Access to early myoelectric training is also thought to aid in preventing the development and habituation of one-handedness, a mindset that can deter patients from myoelectric control and lead them to abandonment of their prosthesis [3]. Even still, patients may not get enough training in clinical practice. As many as 75% of prosthesis users ultimately abandon their device [2], and when asked about their experience, as many as 30% stated that they did not get the therapeutic attention they needed or desired [14]. This suggests that the phenomenally high abandonment rates are at least partially linked to insufficient training [29].

These inadequacies in myoelectric training are reflected in current research; while training is a popular topic of research, little is known about how myoelectric control develops over time. Many studies have considered only a very short series of training sessions when exploring the effects of training, suggesting that these findings may only be applicable to the very early stages of training. In previous experiments, participants completed as few as 4 [8,9], 3 [4,31], 2 [33,34], and even 1 [5,21,36] training session(s), ranging from 3-80 minutes of total training time. New information about the long-term effects of training can still be gained by exploring myoelectric training over a longer series of sessions.

Furthermore, a heavy emphasis has been placed on functional prosthesis use when evaluating the improvement achieved through myoelectric training. Previous research has focused solely on improvements in specific aspects of prosthetic control when assessing training success, such as matching hand-aperture to a target object size [8,9] or overall completion time of a prosthetic grabbing task [33,34]. Evaluating the effects of training in this way may not provide a sufficiently resolved measure of progress or improvement, because proficient myoelectric control is a complex, multi-skilled task. For example, even though clinical experts focus specifically on developing muscle control in early training [27,29], improvement in these skills may not necessarily result in immediate improvement in prosthetic control, and may therefore be overlooked when training progress is simply judged on functional ability.

In this study, a deeper exploration of how two-site proportional myoelectric control develops over time was conducted to better understand the longer-term effects of training. We followed participants as they completed a series of ten 30-minute training sessions -- a substantially longer series than has been completed in many previous studies. Maintaining motivation throughout a longer series of training sessions can be challenging [31], so a previously developed training game that was specifically designed to promote a fun and successful training experience was employed [29]. Improvement throughout these training sessions was assessed using a newly developed set of metrics that were created to quantify control signal quality and other characteristics known to be important for proficient muscle control [28] (introduced in detail below). We propose that these metrics will more accurately reflect the type of improvement that clinical experts and therapists look for in early myoelectric training.

Through this work, it was determined that myoelectric training does lead to improvement in muscle control, but – as is the case when learning many other complex motor tasks [17] – this improvement occurs more gradually and continually than was anticipated in previous research. In this paper, we introduce the newly developed metrics for assessing muscle control, present the results of our 300-session user study, and discuss the implications that these findings have for myoelectric training both in research and clinical practice.

5.4 Background

5.4.1 Myoelectric Control

Myoelectric control is an approach used to operate a powered prosthesis that continuously monitors the user’s muscle contractions, using the signals acquired as input to control a terminal device [20]. Two-site proportional control, a specific implementation of myoelectric control, is commonly used by trans-radial amputees and operates using inner- and outer-forearm contractions to control the prosthesis (e.g., hand open/close, wrist pronation/supination) [11]. More sophisticated pattern-recognition based myoelectric control schemes exist that arguably provide superior dexterity and a more natural mapping of input to control [10], but have yet to gain widespread clinical adoption. Two-site proportional control remains the most popular choice for upper-limb amputees, and was therefore of particular interest in this study because of the potential for near-term clinical impact. Up to 75% of myoelectric prosthesis users, however, ultimately abandon their device regardless of control scheme [2] – a problem that is at least partially due to insufficient training [29].

5.4.2 Myoelectric Training

When learning to use a myoelectric prosthesis, access to early training is critical [3]. The literature suggests that patients should begin training no later than 30 days following an amputation surgery to maximize their chances for success [13]. The fitting and fabrication of the patient’s prosthesis, however, is often delayed beyond this 30-day period, so virtual training tools are sometimes used in early training. Tools such as the Ottobock PAULA software suite [19] can be used before a patient receives their prosthesis, providing a signal visualizer and virtual prosthesis simulator which can help patients familiarize themselves and build strength in their residual musculature [3].

Previous studies exploring the effectiveness of the Ottobock PAULA suite and other myoelectric training tools have been completed over a very small number of training sessions. Previous studies have consisted of 4 [8,9], 3 [4,31], 2 [33,34], and even 1 [5,21,36] training session(s), ranging from 3-80 minutes total training time. Since many other complex motor-control skills have been shown to develop gradually and continually over time [7,15,17,30], findings from these short studies may only apply to the very early stages of training, meaning that the long-term effects of myoelectric training are still unclear.

Part of the reason for the small number of training sessions completed in previous research on myoelectric training is because existing training tools are monotonous and repetitive, making it difficult for patients and research subjects to stay engaged and motivated throughout training [29,31]. Games have been proposed as a possible solution to this training problem [6,8,9,21] which is why a game was selected specifically as the main training tool used in this study (introduced in detail below).

5.4.3 Assessing Myoelectric Performance

Tools for assessing levels of myoelectric skill and performance are used to evaluate and compare the effectiveness of different types of myoelectric training. Many of these assessment tools focus specifically on real-world, functional use of a prosthesis. The Southampton Hand Assessment Procedure (SHAP) [24] is one such tool intended to assess real-world hand function and consists of a series of timed tasks such as grabbing and moving common objects. Similarly, the Target Achievement Control (TAC) test [26] focuses on pseudo-functional prosthesis use and consists of matching a series of target hand poses with a virtual prosthesis.

Conversely, Fitts-style targeting tasks have also been used in research [22,35], and focus on speed and accuracy of myoelectric control in general. One previous study [21] conducted a preliminary examination of how training could lead to improvements in myoelectric skill by investigating aspects of muscle control such as levels of isolation between muscle sites and overall endurance. However, participants in this study completed only a single training session.

The focus of our work was to explore the improvements in these foundational aspects of muscle control in more detail, specifically examining if and how skills are developed throughout a longer series of training sessions. In this work, a set of metrics was developed to quantify these skills [28], then used to track progress and improvement in muscle control over a series of training sessions (metrics are described in detail below). These metrics were used to demonstrate that muscle control develops more gradually and continually throughout training than has previously been considered.

5.5 Methods

5.5.1 Participants

Thirty healthy, able-bodied participants (68% identified as male, 32% female – mean age: 26.8 +/- 8.3) were recruited to participate in this study, as approved by the University of New Brunswick’s Research Ethics Board (REB #2017-047).

Twenty-nine participants completed a full series of 10 training sessions, while one participant completed 8 sessions before withdrawing due to unrelated reasons. All participants confirmed that they had no previous experience with myoelectric control and completed all training activities using their dominant forearm (self-reported, confirmed with Edinburgh-handedness index [18]).

Training sessions were scheduled at the availability of participants, with restrictions that a participant must complete no more than 2 sessions per day (separated by at least 6 hours), and no fewer than 2 sessions per week.

5.5.2 Apparatus

Two myoelectric-controlled training tools were used in this study: *The Falling of Momo* (*Momo*) and *MyoFitts*. Momo (Figure 5-1a) is an open-source myoelectric muscle training game designed specifically to promote fun and success during training [29]. Players control the descent of the main character, Momo (round blue character), through a series of continually rising platforms, moving left and right with flexion and extension forearm contractions. MyoFitts (Figure 5-1b) is a myoelectric Fitts-style targeting task in which players move an on-screen cursor (blue) into targets of interest (pink/green) using the same controls as Momo. Both programs are controlled using the Myo armband (Figure 5-1c) [16], a commercially available myoelectric input device. A library (github.com/hcilab/MyoProportional) that simulates the dual site differential control post-processing often used in clinical prostheses [12] was used to process raw EMG acquired via the armband before being used as control input for the tools.

All software ran on a laptop connected to an external display that was positioned approximately 2 feet in front of participants. Participants sat in an office chair and were instructed to use the chair's adjustable armrests to maintain a comfortable and natural arm position for the duration of training. The armband was oriented consistently across all participants and sessions according to the manufacturer suggested best-practices (as shown in Figure 5-1c).

After positioning the armband and waiting five minutes to allow the armband sensors to stabilize to participants' skin temperature and humidity, a calibration session was performed to identify which two of the available eight sensors were best positioned to be used for two-site differential proportional control (i.e., to detect inner- and outer-forearm muscle contractions). This calibration was performed using the in-game calibration wizard provided with Momo. The experimenter led participants through the calibration, during which the software assigned sensor mappings and sensitivity settings for flexion and extension signals by selecting the sensor that read the highest signal for each of the two movements. Manual inspection of the muscle sites and an on-screen signal visualization were then used to verify the calibration, and sensitivity settings were adjusted as necessary to allow participants to achieve the full range of proportional input with a comfortable muscle contraction (full calibration details available in the calibration guide[21] accompanying [29]). Consistent calibration settings were used across the Momo game and MyoFitts targeting task to ensure identical control between applications. This process was repeated after donning the Myo armband at the beginning of each session to account for differences in sensor placement and skin impedances between sessions.

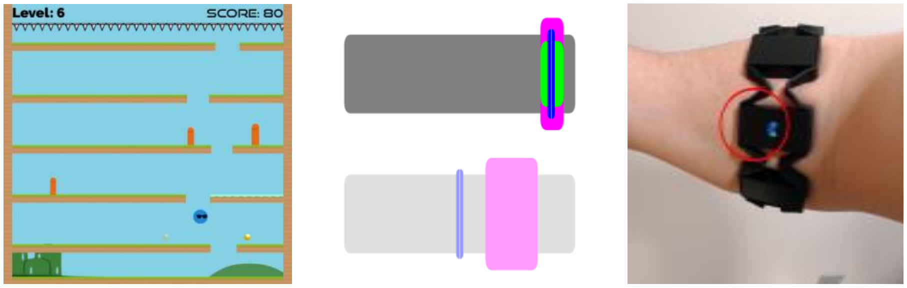

Figure 5-1: Tools used in this study. a) The Falling of Momo, a myoelectric muscle training game b) MyoFitts, a myoelectric Fitts-style targeting task c) Myo Armband, a consumer grade myoelectric input device (oriented according to manufacturer's suggested best-practices on the participant's right forearm – USB charging port facing distally, logo along inner forearm)

5.5.3 Procedure

Each training session lasted approximately 30 minutes and consisted of the same sequence of activities. The first and tenth sessions included an additional demographics and post-study questionnaire, respectively. Informed-consent was given at the beginning of the first session when participants agreed to the study procedure and were informed

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[21] The calibration guide is presented in Appendix C of this thesis.

that they were free to withdraw from the study at any point. Participants were remunerated for their time with a $50 gift-card for a local retailer of their choice, which was given to them at the conclusion of their final session ($5 per session completed). Table 5-1 presents a timeline of activities conducted during each training session.

Participants were instructed to contract naturally with a comfortable and repeatable level of intensity throughout the training sessions. At the beginning of the MyoFitts task, participants were instructed to acquire targets as quickly and accurately as possible. Breaks (~1 min) were offered between each round of Momo and before beginning MyoFitts, and were taken by participants at their discretion. Participants were provided with feedback and encouragement regarding commonly observed issues with their control during Momo gameplay (e.g., pointing out unintentional muscle co-contraction and explaining why this is an undesirable quality), but minimal intervention occurred while completing the MyoFitts tasks. The experimenter left the room while participants completed the per-session questionnaires.

Duration (min)	Activity	Description
5	Armband Calibration	Participants positioned armband on their dominant forearm orienting according to manufacturer’s suggested best-practices (Figure 5-1c) and waited 5 minutes to allow sensors to stabilize to skin temperature and humidity. The experimenter then led participants through Momo’s in-game calibration wizard, where participants mirrored a series of on-screen hand gestures to identify ideal calibration settings (full details in text). Settings were then verified through manual inspection.
20	Momo	Participants played *Momo*, a myoelectric training game. Each round of play began 10 levels below the average level achieved in their previous training session.
3	MyoFitts	Participants completed MyoFitts, consisting of 36 2-dof Fitts targeting tasks. A consistent set of 72 Fitts configurations is presented across all sessions, but presentation and grouping orders are randomized each session.
2	Daily Questionnaire	Participants complete a session-concluding daily questionnaire which includes an adapted NASA-TLX and Likert-style questions on perceived enjoyment and improvement.

Table 5-1: 30-Minute Training Session Schedule

5.5.4 Design

The purpose of this study was to explore how improvements in myoelectric control could be achieved through game-based training activities. Performance and improvement were assessed in several different ways, including in-game performance (i.e., specific to training activity), performance with muscle-control, and performance while completing a myoelectric targeting task, each of which are discussed in more detail in the following sub-sections.

5.5.4.1 In-Game Performance

Average game-level achieved was used to assess in-game performance since Momo, the training game used, naturally progresses through a series of faster and more challenging levels. In each session, participants started rounds of gameplay 10 levels behind the average level they achieved in the previous session. This resulted in approximately 3-5 rounds of play per training session and ensured that an accurate representation of their performance was captured at a fun, engaging, and appropriate level of difficulty.

When calculating average game-level achieved, only rounds of gameplay in which the participant achieved more than 200 points (i.e., approximately 30s of gameplay) were included. This restriction was introduced to ensure that unrepresentative rounds of play did not skew results (e.g., experimenter accidentally clicked "Start Game" button).

5.5.4.2 Performance with Muscle Control

Performance with underlying muscle control was assessed using metrics developed to quantify control signal quality [28]. These metrics were computed offline using EMG control data logged at 60Hz by both the Momo and MyoFitts tools and are presented in Table 5-2. Every row in the EMG log was labelled as belonging to one of 3 periods according to the participant's behavior at that point in time: 1) *calibration* – readings captured during initial armband calibration, 2) *proportional control* – readings captured during left/right movement in Momo or MyoFitts, or 3) *impulse* – readings captured during a mode-switch in either Momo (to make the character jump) or MyoFitts (to switch focus between cursors). Each metric was computed using data from only one of these periods according to the focus of the metric (details in Table 5-2).

Calibration Amplitude was measured as the average amplitude of contractions created during the calibration period at the beginning of each session, measured independently for flexion and extension contractions. While this approach does not capture the amplitude of a maximum voluntary contraction (MVC), it more accurately represents the characteristics of signals created during normal prosthesis use.

Average *isolation*, *over-exertion*, and *speed distribution* were computed using all periods of proportional control within the EMG log by first computing each metric independently for flexion and extension contractions, then combining them by computing the mean.

Mode-switch specific metrics were computed independently for each period of impulse detected in the EMG log, then averaged across all impulses that occurred in a session.

Outliers were removed on a per-session basis independently for each metric by removing sessions that resulted in a metric score that was more than 2 standard-deviations from the normalized per-session mean. An average of *0.81 +/- 0.06* outliers were removed for any particular session-metric combination, and manual inspection of the data revealed that these outliers could often be attributed to a substantial deviation in a participant's calibration settings compared to preceding / succeeding sessions.

5.5.4.3 Myoelectric Targeting in a Fitts Task

Fitts metrics (i.e., *throughput*, *path-efficiency*, *error-rate*) were used to assess participants' myoelectric targeting ability and were computed using additional data logged by the MyoFitts tool. A consistent set of 72 configurations (i.e., target-width / target-distance pairings) was presented in each session in a randomized presentation and grouping order (presented as 36 two degree-of-freedom trials, with each trial consisting of a group of 2 configurations).

Outliers were removed from Fitts results on a per-participant, per-session basis by first grouping trials by their index-of-difficulty (ID), then removing trials with completion times that were more than 2 standard deviations from the mean, independently for each ID.

5.5.4.4 Questionnaire Data

Participants completed a questionnaire following each training session with additional questions included after their final session. Questions administered focused on perceived improvement throughout training (Table 5-3). Each question has been given a unique label (shown in Table 5-3), which will be used to identify it in the Results and Discussion sections.

Metric	Focus	Period of EMG Log	Description	Motivation
Calibration Amplitude	Muscle Strength	Calibration	The level of contraction intensity, corresponding to the raw signal amplitude acquired from the armband during calibration. *Larger is better.*	Strong contractions minimize the impact of unintentional co-contractions, crosstalk, and other signal noise, and facilitate a wide range of proportional input.
Isolation	Proportional Control	Flexion / Extension	Ratio of intentional muscle contraction to involuntary muscle co-contraction. Computed independently for periods of flexion and extension, then averaged across the two. *Larger is better.*	Unintentional co-contractions lead to ambiguity in the myoelectric input signal, and in some control schemes work directly against the intended movement. Better muscle isolation leads to more effective use of proportional control.
Over-Exertion	Proportional Control	Flexion / Extension	A weighted tally of readings with amplitudes that exceed the calibrated 100% limit. Computed independently for flexion and extension, then averaged across the two. *Smaller is better.*	Exerting muscle contractions that are stronger than strictly necessary to achieve accurate control can lead to premature fatigue and muscle soreness. Learning to reliably create muscle contractions of an appropriate strength can lead to increased endurance when using a myoelectric device.
Speed Distribution	Proportional Control	Flexion / Extension	The smoothness (uniformity) of distribution of contraction strengths performed during training (smaller → smoother). *Smaller is better.*	Research [3] suggests that the most successful myoelectric users are those who make use of the full proportional range of myoelectric input. Learning to accurately create contractions of varying strengths allows myoelectric users to operate their device at a variety of speeds.
Amplitude	Mode-Switch Trigger	Impulse	The height of the impulse "peak". Computed independently for flexion and extension, then averaged across the two. *Larger is better.*	Mode-switch triggers are registered by the myoelectric device when the flexion and extension signals simultaneously exceed a threshold. Strong impulses (i.e., large amplitude), allow reliable impulse detection.
Phasing	Mode-Switch Trigger	Impulse	The time difference (ms) between the peak of the flexion and extension signals during an impulse. *Smaller is better.*	Since the "impulse" mode-switching trigger requires both the flexion and extension signals to simultaneously exceed a certain threshold, having both signals peak at the same time increases the reliability of detection.
Width	Mode-Switch Trigger	Impulse	The duration of time (ms) between onset and conclusion of impulse. *Smaller is better.*	Myoelectric devices continuously interpret flexion and extension signals as hand open/close or wrist pronation/supination instructions, even when the user performs a mode-switch impulse. Creating shorter impulses reduces the opportunity for these signals to result in unintentional movement. Specifically, reducing the "rise-time" of an impulse minimizes unintentional movement in the degree-of-freedom which is no longer being controlled, reducing the need for the user to "switch back and correct".
Rise	Mode-Switch Trigger	Impulse	The duration of time (ms) between onset and registration of impulse. *Smaller is better.*	
Fall	Mode-Switch Trigger	Impulse	The duration of time (ms) between registration and conclusion of impulse. *Smaller is better.*	
Fit	Mode-Switch Trigger	Impulse	The area between the flexion and extension signal curves. *Smaller is better.*	Since only the difference between flexion and extension signal amplitudes contributes to device movement, creating impulses where the two signals mirror one another can also reduce unintentional movement while creating mode-switch triggers. Similar to "rise-time" mentioned above, impulses with a small "pre-fit" result in minimal movement in the degree-of-freedom no longer being controlled, reducing the need for the user to "switch back and correct".
Pre-Fit	Mode-Switch Trigger	Impulse	The area between the flexion and extension signal curves, restricted between impulse onset and registration. *Smaller is better.*	
Post-Fit	Mode-Switch Trigger	Impulse	The area between the flexion and extension signal curves, restricted between impulse registration and conclusion. *Smaller is better.*	

Table 5-2: Metrics Used To Assess Myoelectric Control *(appears on preceding page)*. Metrics used to quantify the foundational muscle signal characteristics of strong myoelectric control. Developed in previous research [28], these metrics were identified based on the practical experience and intuition of therapists and clinical experts. This table provides a description of each metric, along with an explanation of how it quantifies an important aspect of proficient myoelectric control.

Label	Freq.	Question	Response Format
Improve Daily	Per-Session	*I performed better today than I did last session.*	7-point Likert[22,23]
Improve General	Post-Study	*My muscle control improved over the training sessions.*	5-point Likert[19]
Improve Momo	Post-Study	*The game helped me improve my muscle control.*	5-point Likert[19]
Improve Continue	Post-Study	*My muscle control would continue to improve if I pursued further training.*	5-point Likert[19]
Plateau Count	Post-Study	*How many training sessions did you complete before you felt like you reached a plateau / stopped improving?*	Numeric[24]

Table 5-3: Questions Administered Throughout Study.

5.5.5 Data Analysis

Because relative levels of improvement were of more interest than absolute levels of skill, all results presented are first normalized on a per-participant basis (according to each participant's results in session 1) before being averaged across all participants in each of the ten sessions. This allows the extent of learning and improvement to be more easily compared between subjects. Results were considered to be significant for p-values

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[22] Likert scale: 1- Strongly Disagree, 5/7 – Strongly Agree.

[23] All participants responded 4 – Neutral following the first training session.

[24] Participants either provided a numeric response (i.e., 1-10) or indicated that they had not yet reached a plateau in performance.

of less than 0.05 and all results are reported with their corresponding inter-participant standard error of mean (SEM).

To investigate whether significant improvement in myoelectric control occurred over the entire course of training, metric scores from the first and final sessions (session 1 and session 10) were compared using a one-way ANOVA. Because many previous studies have consisted of 4 or fewer training sessions, the same analysis was applied between metric scores from session 1 and session 4 to highlight possible differences between our findings and results similar to those expected after completing a shorter training series.

Due to a technical issue, the Momo portion of training (i.e., game-levels achieved, 20-minute EMG log) was not recorded for one participant during session 3. However, all data from the MyoFitts portion of the training session was captured and recorded correctly. This participant was excluded from the calculation of average game-level achieved for that session, but all other metrics were computed from the MyoFitts portion of training and are included in the results presented.

5.6 Results

5.6.1 In-Game Performance

In agreement with previous studies [6,8,9,21], significant game-specific improvement was observed over the course of training (Figure 5-2). Participants achieved significantly higher in-game levels after completing the series of training sessions. Participants progressed 78.4% +/- 8.6% further through gameplay in session 10 compared to session 1.

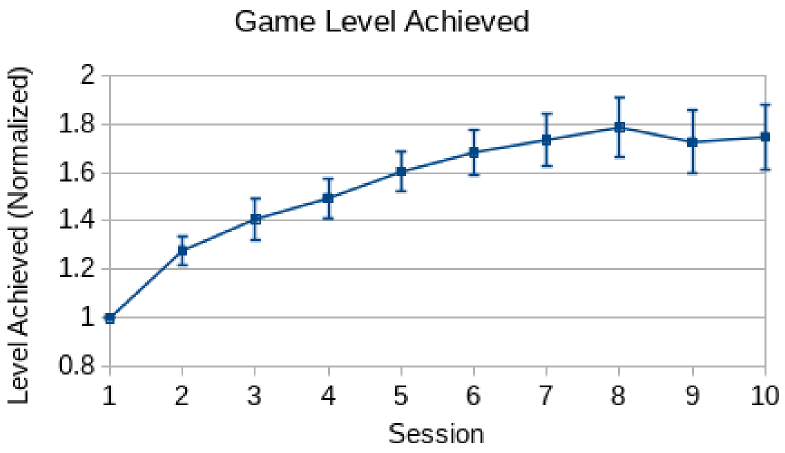

Figure 5-2: Average in-game level achieved during training sessions. Normalized per-participant, then aggregated across all participants. Participants achieved significantly better in-game performance following training.

5.6.2 Improvement in Muscle Control

Significant improvements in the newly introduced muscle control metrics were also observed upon completion of training. Participants achieved a 14.3% +/- 4.7% increase in calibration amplitude (Figure 5-3), and improved significantly in their ability to use proportional control (i.e., significantly improved levels of isolation, over-exertion, and dynamic-range – Figure 5-4). Significant improvements were also observed in phasing, width, rise, fall, fit, and pre-fit after their 10th training session (Figure 5-5). It should be noted, however, that no significant improvement was observed in many of these metrics after participants had only completed their 4th training session. A full breakdown detailing per-metric levels of improvement is presented in Table 5-4.

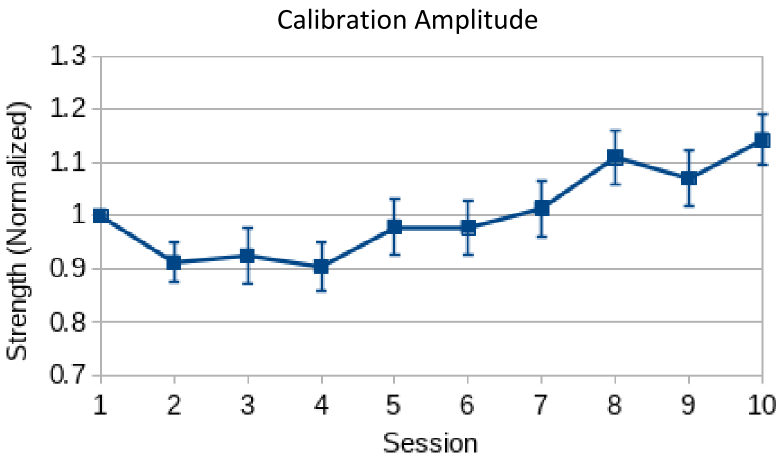

Figure 5-3: Contraction strength during armband calibration. Normalized per-participant, then aggregated across all participants. Participants created significantly stronger contractions after training ($p < 0.05$).

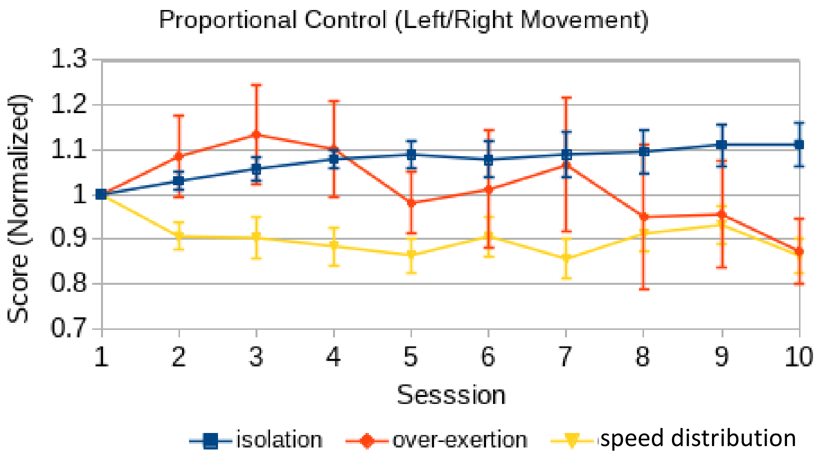

Figure 5-4: Muscle-Control specific metric scores. Normalized per-participant, then aggregated across all participants. Participants created more isolated contractions, with contraction-intensity distributed more evenly across the available amplitude band.

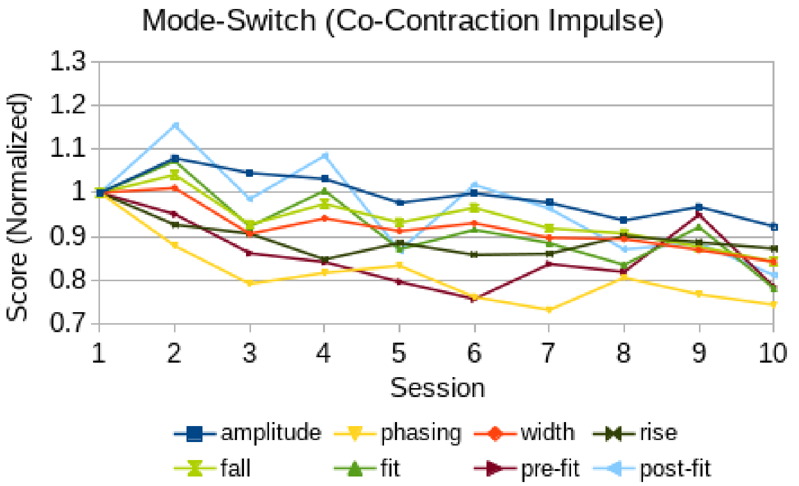

Figure 5-5: Mode-Switch specific metric scores. Normalized per-participant, then aggregated across all participants. Participants improved significantly ($p < 0.05$) in their ability to create mode-switch impulses. Error-bars have been omitted for viewing clarity, but SEM values and significance are presented for each metric in **Table 5-4**.

Metric	Session 4	Session 10
Calibration Amplitude	-9.6% (4.5%) *	+14.3% (4.7%)
Isolation	+7.9% (1.9%)	+10.7% (2.2%)
Over-Exertion	-10.2% (8.1%)	+12.8% (4.7%)
Speed Distribution	+11.6% (3.4%)	+12.7% (3.6%)
Amplitude	+3.2% (3,7%)	-3.1% (3.4%)
Phasing	+18.3% (7.2%)	+25.3% (6.2%)
Width	+5.8% (3.4%)	+8.5% (3.9%)
Rise	+15.2% (2.7%)	+10.7% (2.6%)
Fall	+2.5% (4.2%)	+8.5% (4.8%)
Fit	-0.5% (10.1%)	+17.3% (6.7%)
Pre-Fit	+15.9% (6.4%)	+21.2% (6.2%)
Post-Fit	-8.5% (11.3%)	+12.5% (9.1%)

Table 5-4: Improvement in Metric Scores. Average level of improvement observed after completing 4 and 10 training sessions. Each entry indicates the percent of improvement since session 1 (positive – improvement, negative – degradation) and the inter-participant SEM in parenthesis. Green cells indicate significant improvement ($p < 0.05$), while red cells indicate insignificance ($p >= 0.05$). Red cells with an asterisk (*) indicate a significant degradation in performance ($p < 0.05$).

5.6.3 Myoelectric Targeting in a Fitts Task

Significant improvements extended beyond the context of the Momo training game. Participants achieved a 72.8% +/- 2.8% decrease in error-rate while performing the MyoFitts targeting task, while increasing path-efficiency and throughput by 48.6% +/- 4.7% and 142.7% +/- 10.8% respectively, upon completion of training (Figure 6).

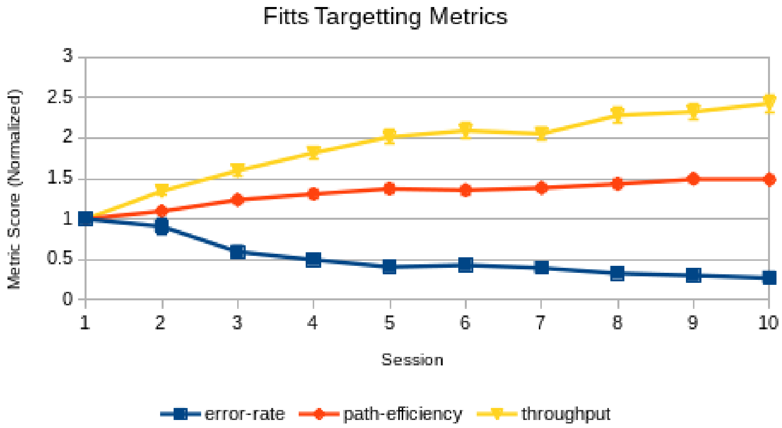

Figure 5-6: Performance in MyoFitts across training sessions. Normalized per-participant, then aggregated across all participants. Participants achieved improved throughput, path-efficiency, and error-rates after training.

5.6.3.1 Questionnaire Data

The improvements in muscle control were also reflected in responses to the questionnaires. Figures 7, 8, and 9 present questionnaire responses in detail. Participants reported feeling a small but consistent sense of improvement following each training session (Figure 5-7 – Improve-Daily – 5.2/7.0). Participants also reported that they had improved over the course of training as a whole when reflecting back upon completion of the study (Figure 5-8 – Improve-General – 4.7/5.0). Furthermore, 90% of participants attributed this improvement to the training game (Figure 5-8 – Improve-Momo – 4.4/5.0).

Even after completing ten sessions, however, 87% of participants felt that they would continue to improve if given the opportunity to complete further training (Figure 8 – Improve-Continue), and no one reported feeling like they had achieved a plateau in improvement before the completion of their 5th training session (Figure 5-9 – Plateau-Count).

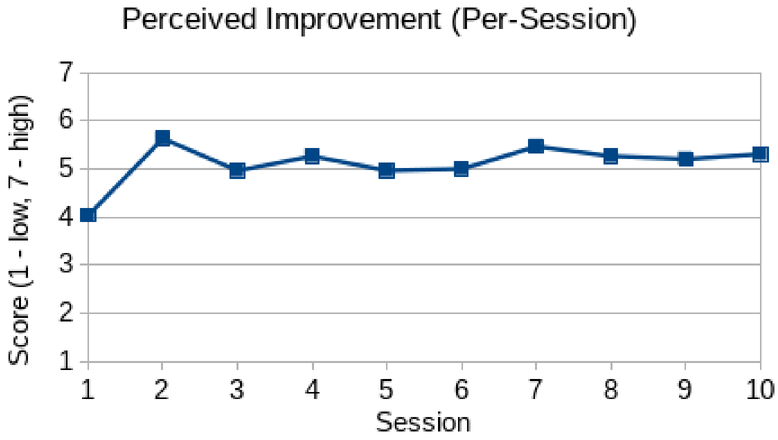

Figure 5-7: Per-session questionnaire responses (Improve-Daily). Participants consistently reported feeling a sense of improvement from one session to the next throughout the study. All participants were instructed to respond with "4 – Neutral" following the session 1, since they could not yet refer back to the previous day of training as specified in the question.

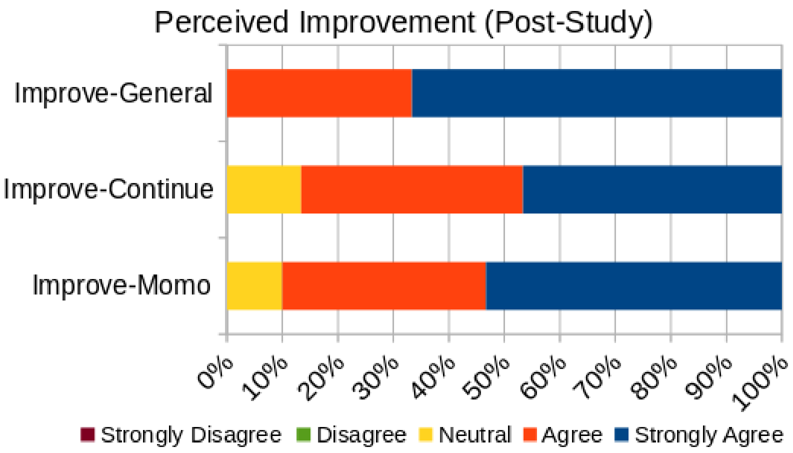

Figure 5-8: Post-study questionnaire responses (*note that no one responded with Strongly Disagree or Disagree*). All participants agreed that they had improved throughout training (Improve-General), and 90% of participants attributed this improvement to the Momo game specifically (Improve-Momo). Furthermore, 87% of participants felt that they would continue to improve if given the opportunity to complete more training (Improve-Continue).

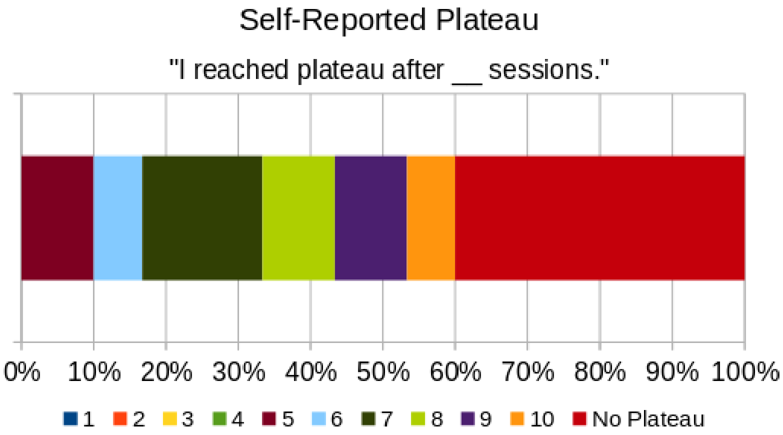

Figure 5-9: Post-study questionnaire responses. 40% of participants reported that they had not yet reached a plateau in improvement at the conclusion of the study (Plateau-Count). No one reported reaching a plateau earlier than after completing 5 training sessions.

5.7 Discussion

5.7.1 Gradual, Continual Progress and Improvement

The results of this work suggest that progress made in underlying muscle control came more gradually than has generally been anticipated in previous myoelectric training research, which has presented findings after participants completed 4 or fewer training sessions [4,5,8,9,21,31,33,34,36]. However, in this study, no one reported reaching a perceived plateau in performance earlier than their 5th training session. Metric scores reinforce this finding; many metrics failed to show a significant improvement after participants completed their 4th training session, even though improvement in these same measures was ultimately observed upon completion of the full 10-session series (Table 5-4). While participants reported small, consistent improvements in their muscle control after each training session, 87% reported they believed they would continue to improve in aspects of their muscle control beyond the 10th session if given the opportunity to continue training.

These results are a reminder that learning myoelectric control is a difficult and complex process, and suggests that assessing performance at early stages of myoelectric training may not be reliable or representative of how an individual will perform after lengthier amounts of training, such as through the prolonged use of a prosthesis. While it is likely that the slope of the learning curves may differ with different training activities, it is likely that the gradual, continual nature of improvement is something inherent in myoelectric control. This has been demonstrated in other complex motor-control tasks such as throwing darts [15], serving a volleyball [30], or fabricating hand-rolled cigars

[7] (see [17] for more examples). Our findings suggest that new myoelectric prosthesis users do not reach a performance ceiling as quickly as was thought to be the case in previous research, which has implications for both experimental and clinical best-practices (discussed in the following sections).

5.7.1.1 Implications for Experimental Best-Practices

These findings suggest that, even though short-term studies have mainly been conducted in the past, a substantial amount of training is required before a plateau in skill is reached. Depending on the intentions of the study, this may present significant implications for future study design. For example, in studies aiming to evaluate the effectiveness of a new myoelectric control scheme or prosthetic device [23], participants should already be at a plateau in performance before beginning assessment as the intended target audience for the device will be experienced, life-long users. These results suggest that reaching this plateau in performance may take longer than has previously been considered in the literature, which could ultimately influence the acceptance of the device in practice. Unless it can be shown that the relative performance between control schemes or devices under test remains consistent throughout the training process, decisions made early in the learning phase may not hold.

Similarly, in studies that seek to compare the effectiveness of various training approaches [5,8,9,33,34], results based on the early effects of training may not necessarily be representative of long-term training in general. Given our findings, it is quite possible that in shorter studies, participants simply did not have enough time to realize the full benefits of training.

5.7.1.2 Implications for Clinical Best-Practices

Research suggests that fitting a new prosthesis user as early as possible will set them up with the greatest chance for success [1,3,13]. Therefore, a decision regarding the type of control that a new patient will use often happens very early in the training process. For example, a decision to use a single-site on/off control scheme (as opposed to two-site proportional) may be made after only one or two training sessions with a patient initially experiencing difficulty achieving isolation between muscle sites. However, our results suggest that evaluating an individual's capacity for myoelectric control at this early stage may not necessarily provide an accurate representation of their ability, because the patient is likely to continue to improve and progress with more training and practice. This is important because this early decision may prevent patients from otherwise using a device that has a wider range of control and increased functionality, which could possibly lead to an improved likelihood of long-term acceptance.

While some clinics do employ therapists and specialized staff who help guide new patients through myoelectric training, this is not the case in general [29]. Our findings stress the importance of myoelectric training and how providing patients with more access to relevant training gives them the best opportunity to achieve long-term success with a myoelectric prosthesis.

5.7.2 Introduction of New Performance Metrics

The focus of this research was to explore how foundational aspects of muscle control develop over time. To accomplish this, we developed and introduced metrics that quantify and assess muscle control skill and underlying control signal quality. While it is left to future work to perform a rigorous validation of these metrics in a clinical setting, we believe that the metrics hold value because they are based on the experience and expertise of clinical therapists who specialize in myoelectric training with amputees [28]. In short – these metrics are not strictly “new” ideas, but instead quantify the characteristics of muscle control that therapists already identify as indicators of proficient myoelectric control [21,27,29].

5.7.2.1 Achieving Functional Transfer

While we do not strictly demonstrate (*or set out to demonstrate*) a transfer of skills developed during training to direct and immediate improvement in real-world prosthetic tasks, we believe that these findings provide evidence that training games (and muscle training in general) provide therapeutic value and can help lead to this ultimate end-goal.

First, even though functional transfer has been given heavy emphasis in previous studies [8,9,33,34], therapists and clinical experts often do not use (*or envision using*) muscle training games for this purpose. In practice, games are predominately used in early, pre-prosthetic, training where therapeutic goals include identification and strengthening of muscle sites as well as the development of the foundational skills required to succeed with myoelectric control [3,27], so judging games on their ability to create direct and immediate functional improvements is not necessarily clinically accurate or relevant.

Furthermore, our results suggest that participants improved in skills that are relevant for functional two-site proportional control. For example, improvements in isolation and dynamic-range suggest the ability to achieve smooth, reliable control of grip aperture and wrist rotation at a variety of speeds. Similarly, improvements in phasing, fit, and rise-time indicate the ability to achieve robust and reliable mode-switch triggers while minimizing unintentional hand/wrist movement – a common source of frustration, even for experienced prosthesis users [32]. In fact, the "Motivation" column of Table 5-2 was included to highlight how the metrics that participants achieved improvement in relate directly to skills required to achieve effective prosthesis control.

5.7.3 Games Enable Valuable, Engaging Training

Several previous studies have presented conflicting results regarding whether or not training games provide therapeutic value [6,8,9,21]. In light of the results of this study, it is quite possible that discrepancies between these previous studies may be a consequence of the relatively short series of training sessions completed by participants. Our results indicate that muscle control does improve through continued practice and training, demonstrating that games can be designed to provide therapeutic value.

Another previous study exploring myoelectric training identified a lack of participant engagement and motivation to continue training as limiting factors when attempting to complete a longer series of training sessions [31]. We, however, completed this study with a nearly zero participant attrition rate (one subject withdrew after 8 sessions for unrelated reasons). In fact, several participants continued training beyond the 10-session series (without additional remuneration) simply because they wanted to beat their previous high scores. This demonstrates the value and importance that well-designed game-based tools can bring to both myoelectric training and research.

5.8 Future Work

5.8.1 Observing a plateau in improvement

One of the goals of this study was to identify a clear, consistent point of plateau in the training process. Despite significant improvements, however, no such plateau was identified with certainty, and questionnaire responses reinforced the notion that participants had not yet reached a plateau in their skill development.

Future work will extend on the current study design by completing an even longer series of training sessions (albeit with fewer participants) in search of a clear, consistent plateau across participants. This information would hold valuable insight for best-practices in experimental design as well as in real-world, clinical training programs.

5.8.2 Linking Muscle Control to Function Prosthesis Use

While improvement in muscle control has been demonstrated through the results of this study, the muscle control metrics used have not yet been clinically validated. One of the main assumptions of this work was that muscle control is a foundational aspect of prosthesis use, implying that improvements in muscle control would translate to improved functional use of a prosthesis. Further research must be done to confirm this assumption.

5.8.3 Extension to Pattern-Recognition Based Control

This study focused specifically on two-site proportional myoelectric control, because of the immediate clinical relevance of the control scheme. Pattern-recognition based myoelectric control, however, has been heavily researched for decades

[10,11,12,22,23,25,35], and is now becoming a popular choice in many clinics. We are in the process of extending Momo and this study to include pattern-recognition based controls, and exploring how game-based training can be used in this broader context.

5.9 Conclusion

In this study, 30 participants were followed as they completed a series of ten 30-minute game-based myoelectric muscle training sessions. Participants achieved significant improvement in foundational aspects of muscle control. However, this improvement occurred more gradually than has been anticipated in previous research. While we do not provide a definitive recommendation for the number of training sessions required, because learning rates may differ for different training activities, the gradual and continual nature of improvement is likely inherent in learning myoelectric control, as is the case when learning many other complex motor-control skills. Our findings provide evidence supporting the therapeutic value in muscle training games, and stress the importance of adequate, relevant myoelectric training in both research and clinical settings.

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6 Chapter 6: Discussion, Future Work, and Conclusion

6.1 Overview

In this chapter, a reflection on the research as a whole is presented. The broader implications of this work that span across the series of articles presented in this dissertation are discussed and opportunities for future research that have surfaced as a result of these findings are identified. Finally, the contributions of this research are summarized, highlighting how this work is not only relevant to myoelectric muscle training, but holds value for the research and design of therapeutic games in general.

6.2 Discussion

6.2.1 Research Motivation Rooted in Therapeutic Goals

It is important to note that, throughout the project, design decisions and research motivations all related back to the set of therapeutic goals identified during initial discussions with clinical therapists. From the beginning of this project, several key training criteria were of particular interest (taken directly from Article #2: Designing Game-Based Myoelectric Training).

- Training focuses on specific aspects of muscle control.
- The "ideal" outcome of training is isolated control over two opposing muscles. However, this is not always achieved in practice, and control strategies exist to accommodate an individual's capabilities.
- A co-contraction impulse (a quick, simultaneous "burst" with both muscles) is used as a mode switching instruction (e.g., to alternate control between grip aperture and wrist rotation).

- Existing tools provide primarily negative feedback.
- Current training tools are inaccessible outside of the clinical environment due to high cost.

The initial version of the game was intentionally designed with mechanics to specifically target these goals. Many of the discussions with patients and clinical experts that occurred during iterative design sessions revolved around these goals – as new features were added and the game experience refined, a more effective environment for developing these underlying foundational skills was being created.

When the focus of the research turned towards evaluating the therapeutic value of the game, it again seemed natural and intuitive to build upon the originally identified therapeutic goals, and the inspirations for many of the "muscle-control" metrics introduced through this research are rooted in these original training objectives.

Upon completion of the longitudinal study, it is interesting to note that some of the most substantial improvements in muscle control made by participants were captured by the metrics that directly relate back to the training objectives identified by therapists and clinicians (e.g., "isolated control over two opposing muscles" → isolation, speed distribution; "a quick simultaneous 'burst' with both muscles" → rise, phase, pre-fit). In a sense, this research has come full circle, and the important characteristics of muscle control that clinical experts previously identified through their experience and intuition have been quantified.

6.2.2 Foundational Muscle Control vs. Functional Transfer

In some ways, the findings of this research conflict with other studies that suggest that myoelectric games provide little value as training tools (e.g., [1,2]). It is likely that these studies have failed to find value – not because of an inherent inadequacy in training games themselves – but instead because of the "all or nothing" approach that was taken when evaluating games. These studies focused exclusively on achieving functional transfer and attempted to show that the skills acquired during gameplay could result in an immediate improvement in "real-world" prosthesis use, deeming anything less than this as a failure. However – as discussed throughout this dissertation – this approach conflicts with the opinions of many clinical therapists who do not necessarily expect to achieve functional transfer during the early stages of training in which games are intended to be used, but instead aim to help patients identify, strengthen, and build the foundational muscle control skills needed to later be successful with myoelectric control.

It is also likely that the "all or nothing" approach taken by these studies [1,2] reflects a current gap in clinical outcome measures. Currently, measures are either tied directly to functional performance as often measured by time (e.g., completion time of SHAP test) or are self-reported, subjective questionnaires (e.g., embodiment/acceptance of device) intended to capture progress as it relates to indirect therapeutic goals. While clinicians are certainly aware of the foundational muscle control skills required to achieve prosthetic proficiency (and actively use their experience and intuition to coach patients towards improving theses skills), there were previously no quantitative metrics to assess a patient's performance or improvement in these foundational muscle control skills. This was the main motivation for creating the muscle-control metrics, and it is likely that the information captured by these metrics will help clinical therapists provide patients with accurate, personalized feedback during training, ultimately leading to better prosthetic control and long-term success for patients.

The metrics introduced in this work have not yet been clinically validated, but it has been shown that learning and improvement in the metrics can be elicited through practice and training. Furthermore, the metrics are straightforward, intuitive, and based on the experience and expertise of clinical therapists; the metrics are not so much a “new idea”, but instead are a formalized, quantified representation of qualities that clinical experts already look for in muscle control. While the improvements observed in muscle control metrics do not prove that a patient will ultimately achieve more proficient prosthetic control, this work provides strong evidence of improvement in myoelectric skill. These more subtle, but significant improvements during the training phase may lead to better adoption rates, more appropriate selection of control paradigms, and possibly functional improvement through longer-term use.

6.2.3 New Guidelines for Designing Therapeutic Games

Momo was designed under the consideration of a wide-ranging review of therapeutic games, best practices, and design guidelines that have been identified through previous research (see **Best Practices for Designing Therapeutic Games, ch. 1**). Through the iterative design and testing processes, several additional design considerations have been identified which add to this body of knowledge and will be useful for the future design of myoelectric muscle training games as well as the design of therapeutic games in general. In this section, these new design insights are introduced and discussed.

6.2.3.1 Allow Therapists to Pause, Rewind, and Replay

First, several suggestions for facilitating the set-up and calibration phases of game-based therapy are presented. During experimental game sessions, participants were often coached on aspects of their muscle control by pointing out certain characteristics on the raw EMG visualization window, only to have it scroll out of view before the participant could re-focus their attention. This problem is not unique to the game designed in this research, as similar scenarios were observed with other existing training games during design sessions with prosthesis users and clinical experts – it is very difficult for players to simultaneously focus their attention on both the gameplay and their raw EMG. Creating the ability to “pause”, “rewind”, and “replay” the raw signals and corresponding gameplay would provide therapists with tangible, cause-and-effect style examples of the current issues in a patient’s muscle control, allowing the patient to more easily identify and correct their problematic areas and streamline the training process.

6.2.3.2 Include a Practice / Testing Stage

Another common issue observed during gameplay sessions was a difficulty fine-tuning calibration settings. It was fairly common for the sensitivity of one sensor to be either slightly too high or too low which resulted in Momo unintentionally “pulling” left or right each time the player jumped. This problem was easy to fix (i.e., slightly adjust the calibration sensitivity sliders) but testing the recalibration was difficult because the need to jump in a particular direction only surfaced during specific situations within the game. Adding a practice stage – outside of the main game rounds – where players could freely move left, right, and jump over obstacles in an unconstrained environment would have easily resolved this problem, making testing easier and further facilitating the calibration process. A similar resolution could be applied to any game (or training tool in general) that requires the player to calibrate the input device based on their personal needs.

6.2.3.3 Giving Patients Control is Empowering

An additional benefit of having players aware of (or in control of) the calibration process was that it increased their familiarity and understanding of myoelectric control. Players directly saw their progress as they developed better muscle control through the continual decrease of sensitivity and activation threshold settings. Eager players could also "challenge themselves" by further reducing calibration settings (i.e., setting a targeted behavioral goal) and working to achieve success in this more difficult environment. A similar idea of "goal setting" and "challenging oneself" has been discussed in research exploring gamified treatment of chronic lower-back pain through audio feedback where patients could "push themselves" by adjusting the thresholds at which the audio cues were triggered [5]. Giving patients control over their goals and progress in therapeutic situations can help personalize the experience, empower the patient and motivate them to continue training.

6.2.3.4 Benefits of Multiplayer Gameplay

Throughout this project, the addition of a multiplayer experience was often proposed. Through the research findings, it has become clear that multiplayer is not only a “nice to have” feature that could help create more engaging gameplay, but is a valuable tool that could improve the overall therapeutic experience. Incorporating multiplayer elements between limb-different patients (or otherwise affected patients in therapeutic games more generally), or between limb-different and able-bodied individuals could be further explored as a potentially fruitful topic of research. Creating an experience that can be enjoyed equally by everyone causes the extrinsic motivation for therapeutic adherence (i.e., “I’m playing this game because of external motivations – it will make me a better prosthesis user”) to become more intrinsically generated (i.e., “I’m playing this game because I’m having fun with my friends – and this is something they enjoy too!”) and can lead to more long term therapeutic adherence. Furthermore, by enjoying and engaging in an experience alongside (and using the same controls as) everyone else, gameplay can help build towards indirect therapeutic goals such as acceptance and embodiment, reinforcing the similarities – rather than the differences – between patients and able-bodied individuals.

6.2.4 Suitability and Implications of a Consumer-Grade Device for Training

The success achieved by patients and participants throughout this research demonstrates the viability of using an accessible, consumer-grade input device for use in myoelectric muscle training. Comparing the technical specifications of the myoband to medical-grade input devices shows that the myoband is capable of accurately capturing and representing the player's myoelectric input (see Table 1-1). Furthermore, the EMG processing stages performed in a typical two-site proportionally controlled clinical prosthesis currently in use have been replicated within the game by creating custom libraries for acquisition and processing of the EMG captured through the armband (for more information, see **Appendix A**). Finally, while the armband was originally envisioned and designed for able-bodied users, this work demonstrates that it can be used successfully with a wide range of amputee and congenitally limb different patients. The armband has conformed to differences in forearm shape, size, and muscle structure, and has worked accurately and reliably throughout our design and testing phases.

6.3 Future Work

6.3.1 Momo @ Home

In addition to the issues of existing myoelectric muscle training solutions being boring, repetitive, and frustrating, training is currently only accessible to patients within the clinical environment due to the high cost of medical-grade equipment and the sophisticated setup that requires clinical expertise. One of the main motivations for using the myoband – a consumer-grade input device – was to investigate the feasibility of out-of-clinic muscle training. During this project, the training game developed was sent home with a new prosthesis user who was in the process of getting their first myoelectric arm. Over the course of 6 weeks leading up to the receipt of their prosthesis, this patient played the game at home, and is now happily (and successfully) using their myo arm.

Enabling training beyond the clinical environment is another huge motivation for myo games. Not only do games provide patients with easier access to training that allows more frequent practice, they provide therapists with better insight into patient progress between clinical visits, allowing them to provide patients with better feedback. This is certainly an area worth further research, and future work could include a more formalized case-study centered around the use of training tools (and games) at home.

6.3.2 Rich Game Experience and Indirect Therapeutic Goals

Many of the existing muscle training games focus exclusively on physical aspects of training such as muscle strength and control. While the game developed in this research was designed to create a more fun and engaging player experience, it still focuses largely on *direct* therapeutic goals, aiming to help patients develop strong, consistent, and reliable muscle contractions. *Indirect* myoelectric training games are still largely unexplored, and it is likely that a rich, in-depth game experience can foster a deeper intrinsic motivation and lead to further therapeutic benefit. As discussed earlier (**Therapeutic Games**), games that can be enjoyed beyond their initial novelty by both affected and able-bodied individuals can help stimulate intrinsic motivation. Furthermore, carefully designed game experiences and in-game characters (that highlight player *abilities*, rather than their *disabilities*) can instill a sense of autonomy in patients, which could increase acceptance, embodiment, and long-term adoption rates.

Future studies could build upon this work as well as other research that focuses on tailoring narrative to specific audiences (such as the work by Gerling et al. on games for wheelchair users [3]), and explore how character, narrative, and player-autonomy can be used to achieve indirect therapeutic goals in the context of myoelectric muscle training.

6.3.3 Wider Range of Game Input Modalities

To date, the input modalities used to control the game have intentionally been restricted to demonstrate its validity as a proof-of-concept muscle training game. However, this restriction has had the consequence of limiting the complexity of the game design. One way to accommodate a rich, deep game experience is through more sophisticated game input. This additional input could come from the myoband itself (by leveraging the armband’s onboard accelerometer and gyroscope, or by using more intelligent forms of myoelectric control), or from a different input device altogether, such as a keyboard, mouse, gamepad, or touch screen (similar to preliminary work by Prahm et al. [4]). Future studies could make use of this larger input space to investigate rich, complex games in which muscle training is a component – but not necessarily the main focus – of gameplay, because these types of games could further increase patient engagement, leading to increased training success and long-term adherence.

6.3.4 Pattern Recognition Controls

While two-site proportional control is the most commonly used control strategy in commercially- and clinically-available myoelectric prostheses, more advanced pattern recognition techniques may be considered superior as they enable movement in more degrees of freedom and a more natural and intuitive mapping between user input and prosthesis control. Fortunately, many of the same foundational muscle control skills trained through Momo will benefit users of pattern recognition based myoelectric control; future work should investigate how games that incorporate pattern recognition based control schemes can be used to help patients achieve success with these devices.

Additional metrics could also be incorporated that capture information specifically related to robust and repeatable pattern generation.

Furthermore, the optimal configuration for pattern recognition based-control systems (e.g., sensor count and position, feature set, confidence rejection-levels) is still an active and heavily debated topic of research. Given the findings of this work, games that make use of pattern recognition based-controls could be used to better explore and evaluate its benefits over longer term training and evaluation periods.

6.4 Conclusion

This research has revolved around the central theme of myoelectric muscle training games, progressing through the ideation, design, and evaluation of the training game, "The Falling of Momo". Through this research, it has been demonstrated that games can be designed to be fun, engaging, and effective myoelectric muscle training tools. The use of myoelectric training games (and accompanying metrics) to track patient improvement and progress over time was also proposed. Finally, this work has identified design insight for future research and development – both of which can readily be applied to therapeutic games in general.

This work makes a significant contribution to the field of myoelectric muscle training games by:

1. ***Introducing a low-cost, easy-to-use training game*** that makes use of a commercially available input device and requires no expert supervision. The game focuses specifically on targeting therapeutic goals that promote success with myoelectric control.

2. ***Uncovering design insight for promoting a fun, informative, and positive myoelectric training experience*** through a series of user-centered design sessions with experienced prosthesis users and clinical experts. This design insight was incorporated into the game through an iterative development process, and will help inform the design of other therapeutic games in the future.
3. ***Identifying new muscle-control metrics*** that quantify the foundational characteristics of muscle control needed to achieve proficient use of a myoelectric prosthesis. These metrics allow patient progress to be assessed in a way that more accurately represents the therapeutic goals identified by clinical experts during early training.
4. ***Demonstrating that improvement in myoelectric control develops gradually and continually*** by conducting a 300-session user study. This finding has implications for both research and clinical aspects of myoelectric training.

Since its initial design, the game has been commended by patients from the local clinic and clinical experts from across North America, was awarded "Best Game" by a panel of expert judges at the CHI-Play 2016 research conference, and has been used to help a new patient train in preparation for their new myo arm. The game is currently being used as a training tool in the local prosthetics clinic, and has been received enthusiastically by patients going through myoelectric muscle training. This research demonstrates that games can be designed to be engaging, effective, and informative training tools, and contributes not only to the specific field of myoelectric muscle training games, but to research in therapeutic games in general.

6.5 References

1. van Dijk, Ludger, Corry K. van der Sluis, Hylke W. van Dijk, and Raoul M. Bongers. "Learning an EMG controlled game: task-specific adaptations and transfer." PloS one 11, no. 8 (2016): e0160817.
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3. Gerling, Kathrin, Kieran Hicks, Michael Kalyn, Adam Evans, and Conor Linehan. "Designing movement-based play with young people using powered wheelchairs." In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, pp. 4447-4458. ACM, 2016.
4. Prahm, Cosima, Ivan Vujaklija, Fares Kayali, Peter Purgathofer, and Oskar C. Aszmann. "Game-Based Rehabilitation for Myoelectric Prosthesis Control." JMIR serious games 5, no. 1 (2017).
5. Singh, Aneesha, Nadia Bianchi-Berthouze, and Amanda CdeC Williams. "Supporting Everyday Function in Chronic Pain Using Wearable Technology." In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, pp. 3903-3915. ACM, 2017.

Appendix A. EMG Processing Details

A.1 Overview

The EMG data collected from the Myo armband is subject to a series of processing steps before ultimately being used to control the movement of the in-game character. This document provides the details of this processing.

EMG processing is divided into 5 main phases, which are the topics of each of the following sections. Figure A-6-1 provides an overview of how these phases transform the raw data.

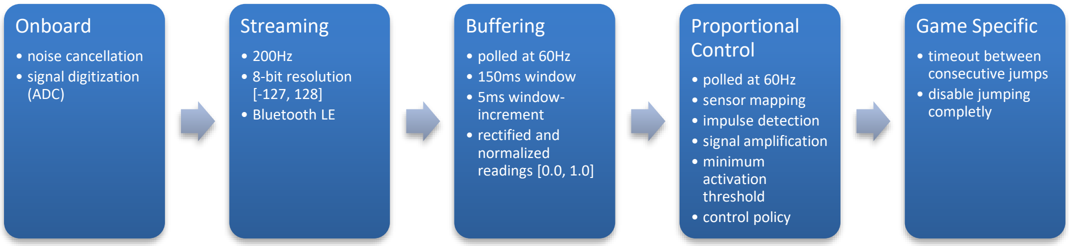

Figure A-6-1: An overview of the 5 phases of EMG processing. EMG data is processed in a pipeline fashion, with the output of each phase used as input to the next.

A.2 EMG Processing Phases

A.2.1 Onboard

"Raw" EMG data is captured from the 8 armband sensors and digitized to 8-bit resolution (values in range [-127, 128]) at a frequency of 200Hz. While labelled as "raw" signals, the readings are passed through several noise-cancelling filters implemented within the hardware of the armband (using the **`myohw_emg_mode_send_emg`** mode specified in the Myo armband official Bluetooth spec: https://github.com/thalmiclabs/myo-bluetooth). These filters remove artifacts such as interference from nearby electrical appliances or power lines as well as the ~60Hz spikes introduced from the user's heartbeat.

Data is sent from the armband to the game using the Bluetooth Low Energy (also known as BLE, or Bluetooth Smart) protocol described in the Bluetooth 4.0 specification. EMG data is split across 4 notify-only attribute channels to accommodate certain bandwidth restrictions inherent in the protocol. Each transmitted message contains two contiguous EMG samples, which are separated appropriately once received by the client. Additionally, EMG samples are not accompanied by a timestamp, but this information can be deduced by the client because the armband samples at a constant 200Hz frequency and samples are sent across the 4 notification channels round-robin style in a consistent ordering.

For more information about the onboard signal processing, or details about the armband's BLE communication protocol, please refer to the following articles:

- http://developerblog.myo.com/myo-bluetooth-spec-released/
- http://developerblog.myo.com/myocraft-emg-in-the-bluetooth-protocol/

A.2.2 Streaming

Once received by the game, the messages are separated into individual EMG samples and assigned an appropriate timestamp. At this stage of data-processing, each sample has the form…

```
{<timestamp>, [r0, r1, r2, r3, r4, r5, r6, r7]}
```

…where `r0-r7` are the readings of each of the 8 EMG sensors at time `timestamp`. Each of the 8 readings is normalized to the range [-1.0, 1.0].

This stage of the processing is conducted by the `MyoStream` project (https://github.com/hcilab/MyoStream). Conceptually, this stage exposes an infinite stream of EMG samples, which are in turn used by the later stages of processing.

A.2.3 Buffering

Since EMG data is sporadic and noisy by nature, it is common practice to buffer the most recent samples, aggregating them before further use. Our game buffers readings into a 150ms sample window, computing the mean absolute value (MAV) across this window. While no window increment was explicitly specified in our code, it can be inferred to be 5ms, limited by the 200Hz sampling rate of the armband.

This stage of data-processing is conducted by the `MyoBuffer` project (https://github.com/hcilab/MyoBuffer), which exposes a `poll()` method that returns an 8-element array…

```
[r0, r1, r2, r3, r4, r5, r6, r7]
```

…where `r0-r7` represents the MAV of each EMG sensor over the current 150ms sample window (range: [0.0, 1.0]).

A.2.4 Proportional Control

This stage of processing transforms the buffered EMG reading into a dictionary/map of game movement input according to user-specific configuration settings.

A.2.4.1 Mapping a sensor to LEFT and RIGHT movements

During calibration, one of the 8 sensors is identified as the "ideal muscle site" for capturing each of the flexion and extension muscle contractions (which map to left and right game movements, with the exact mapping depending on which forearm the armband is worn). Only readings from these 2 sensors are selected and processed further for use as game input, with the other 6 sensor readings ignored.

A.2.4.2 Amplifying the sensor reading appropriately for the player's calibrated muscle strength

To compensate for varying levels of muscle strength between players, the left and right readings may be amplified. This ensures that even players with lower levels of muscle strength will be able to achieve the full range of movement speed during gameplay. During calibration, a *maximum attainable contraction level*[25] is captured for each of the left and right movements. This stage of processing scales the current sensor reading as a percentage of this *maximum attainable contraction level*. Readings above the *maximum attainable contraction level* are simply expressed as values greater than 100%.

---

[25] In practice when calibrating the maximum attainable contraction level, players are instructed to perform a comfortable, normal level of muscle contraction, without straining their muscles. While this creates a slight misnomer, the amplification processing still functions as expected, and is in accordance with the levels of muscle contraction required when controlling a prosthesis and with best-practice suggestions from clinical experts.

A.2.4.3 Ignore noise by filtering with a minimum activation threshold

Some players exhibit a small amount of muscle activity, even while their muscles are at rest (this is normal for new players, and reducing this "noise" is a common goal of pre-prosthetic muscle training). To eliminate jitter and make the game easier for new players, all readings smaller than the *minimum activation threshold* (configured during calibration) are explicitly set to 0. The remaining input range is scaled accordingly so that it still accounts for the full range of proportional control (e.g., a sensor reading of 21% with minimum activation threshold setting of 20% would result in a scaled reading of 1.25%).

A.2.4.4 Detect Impulse

A third "aggregate" reading is calculated at this stage of processing. The current reading is considered to be an **impulse** if both the left and right readings are above 80%. An impulse is used as a mode-switching instruction when controlling a prosthesis (e.g., to switch between controlling grip-aperture and wrist-rotation), and is used to make the character jump in our game.

A.2.4.5 Apply one of several common prosthesis control policies

Some prosthesis users have trouble achieving contraction isolation or sustaining a prolonged contraction. There are several standard processing algorithms used in prostheses to alleviate these issues. One of the following algorithms is applied to the readings, according to the player's configuration settings. The processing algorithms are:

RAW: The simplest algorithm. Neither the LEFT nor RIGHT reading is affected. Values are not truncated (i.e., readings greater than the maximum attainable contraction level are expressed as values greater than

100%). This algorithm is mainly used for calibration and visualization purposes (e.g., the over-exertion warning ring)

DIFFERENCE: The standard control algorithm. Only the difference between the left and right readings contributes to game movement input. The larger of the left and right readings is set to the difference between the readings; the smaller of the 2 readings is explicitly set to 0. All readings are truncated to the range [0.0, 1.0].

MAXIMUM: An algorithm to alleviate muscle isolation issues. Only the greater value of the left and right readings contributes to movement input. The larger value of the left and right readings is unaffected; the smaller of the 2 readings is explicitly set to 0. All readings are truncated to the range [0.0, 1.0].

FIRSTOVER: An algorithm to alleviate issues related to sustaining a prolonged and isolated contraction. Once either the left or right reading exceeds the minimum activation threshold, the other is ignored (i.e., explicitly set to 0) until the reading drops below the threshold again. All readings are truncated to the range [0.0, 1.0]. This algorithm is useful when a patient can reliably create a quick contraction, but has trouble sustaining the contraction without activating the opposing muscle.

This stage of processing is conducted by the MyoProportional project (https://github.com/hcilab/MyoProportional). This stage exposes a poll() method that returns a 3-element dictionary…

```
{"LEFT": <reading>, "RIGHT": <reading>, "IMPULSE": <reading>}
```

…where the range of the `LEFT` and `RIGHT` readings depend on the control policy applied in step 5, and the IMPULSE reading is either 0.0 (not an impulse) or 1.0 (an impulse).

A.2.5 Game-Specific

During gameplay, an asynchronous thread maintains the buffered window of EMG samples. Once per frame (~60Hz), the `MyoProportional` class is polled for current EMG readings. These readings are converted to force vectors and passed to the box-2D physics world that maintains the state of the objects within the game. Several game-specific convenience transformations are applied at this stage, such as introducing a minimum time between consecutive jumps and disabling jumping completely within the bonus level.

Appendix B. Iterative Game Improvements

B.1 Overview

The Falling of Momo was iteratively improved over the course of the study. New game features were added based on observation and feedback collected during playtest-interview sessions, and additionally when explicit requests for new content were made. The following tables provide a timeline of the game evolution that explain the mechanics of each new feature and the motivation for including it, in addition to noting which version each patient tested during their demo. Table B-1 introduces in-game features, while Table B-2 discusses features pertaining specifically to calibration tools.

B.2 Game-Specific Evolution

Ver.	Patients	Game Feature	Motivation
1.0	Kyla	Game is as described in *Article 2 – Designing Game Based Myoelectric Prosthesis Training*.	See article 2.
1.1	Stanley	Breakthrough platforms: Certain gaps appear that contain a barrier obstructing progress. Player must either a) dwell, or b) triple-jump, on top of barrier to "break through" and proceed.	Practicing a) muscle quietness, and b) co-contraction impulses is an important aspect of training.
		Adaptive Difficulty (hooks): Momo's sprite appears anxious in the top region of the game area (close to the spikes), and happy in the bottom region. These hooks were intended to later be used to adjust the rate of progression through the game levels based on the player's performance.	Patients with varying levels of muscle control will progress through game at different rates. Added as an adaptive balancing mechanism to avoid boring or frustrating patients.
1.2	Mark, Justine	Disappearing Coins: In-game coins fade, and eventually disappear as time progresses.	Encourages player to progress through platforms as quickly as possible, enabling more accurate assessment of player's ability.
		Bonus Level: A separate, under water level consisting of a series of platforms with uniformly spaced breakthrough platforms, and an abundance of coins. Player enters bonus level by falling through a special "portal" gap.	The Bonus Level a) Adds game depth b) Controlled environment and uniform gap separation allows accurate assessment of player's ability.
		More customization options: Additional characters, obstacles, and themes to select from.	Themes to interest a broader audience. Certain themes requested explicitly, such as the "Kitty Cat" theme.
1.3	Glen, Belle	Improved Direction Assistance: A control mode that aids in directing player towards nearby gaps. Maximum attainable speed slows as player approaches gap to eliminate the possibility of 'skidding' across gaps.	Greater accessibility for patients at initial phases of training. Patients having difficulty controlling the timing and intensity of contractions can still succeed.
		Over-exertion Warning: A visual warning (red ring) appears around Momo when player contracts harder than necessary (specified in sensitivity settings). Intensity and thickness of warning increases with severity of over-exertion.	Excessive contraction strength can lead to unwanted co-contraction and premature fatigue, both of which are detrimental to training and prosthesis use.
1.4[26]	Mikayla, Anthony, Sloan	Impulse Bonus Mode: Player performs a mode-switching impulse to break through bonus level platforms. Character animation consists of Momo swinging a pick-axe upon impulse.	Mode-switching impulses are an important aspect of myoelectric control, and new bonus mode creates additional opportunity to practice. Character animation adds elements of story and depth to the game experience.

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[26] At the time of publication (Article #2: Designing Game-Based Myoelectric Training), version 1.4 of the game had not yet been completed. User-centered design sessions with these 3 participants were completed following the writing and publication of this article.

		EMG Logging: Player input generated throughout gameplay is now logged to a data file.	Characteristics of control signal quality and myoelectric proficiency in general can be quantified through offline analysis of EMG data. Tracking this data over time provides insight into patient progress.

Table B-1: In-game features added during the iterative development of The Falling of Momo

B.3 Calibration-Specific Evolution

Ver.	Patients	Calibration Feature	Motivation
1.0	Kyla	Countdown Capture: Player is guided through a calibration procedure that displays action to perform, and captures reading at the end of a countdown.	Abandoned because countdown was either a) not long enough for player to read instructions, or b) too long to sustain a contraction.
1.1	Stanley	User-driven Capture: Player mirrors on-screen instructions (cartoon hand demonstrating flexion and extension), and presses spacebar to capture calibration reading.	Relieves sense of urgency during calibration. Player has time to read instructions (if unfamiliar with game) or quickly complete (if already familiar)
		Forearm Aware Calibration: Player specifies which forearm they are using to play game. On-screen calibration instructions are adapted accordingly (cartoon hand matches the forearm specified)	On-screen calibration instructions were generic (i.e., “if using left forearm…, if using right forearm…”) and difficult for patients to follow.
		In-game, EMG sensor readings: An optional bar (shown in the bottom right corner of the screen) displays real-time sensor readings (in percent) for flexion and extension.	A troubleshooting tool for clinicians observing a training session. The source of earlier difficulties with game control was ambiguous (i.e., attributed to technology, or muscle control issues).
		Calibration “Smart Suggestions”: Following gameplay, a message is shown to suggest to user that calibration settings are too sensitive / not sensitive enough when appropriate.	Another troubleshooting tool. Provides a hint to players unfamiliar with the game to better assess whether difficulties are because of muscle control, or improperly calibrated armband.
1.2	Mark, Justine	Manual Calibration: Player has the option to manually assign sensors (labelled 0-7 on Myoband) for flexion and extension muscle sites.	Achieving successful auto-calibration was difficult for patients who had muscle isolation issues, had only a single muscle site, or had smaller forearms that required securing the Myoband with elastic straps.
		Simple Sensitivity Adjustments: Consolidated sensitivity settings into a single slider on calibration menu.	Re-designed calibration interface to resemble the sensitivity gain dials (i.e., a “volume” knob) on the medical sensors that clinicians are familiar with.
		EMG Bars: A real-time visualization of sensor readings [shown as two horizontal bars] shown on calibration menu.	Allowed patient to validate the accuracy of a calibration, and make fine-tune adjustments to sensitivity settings before beginning gameplay.
1.3	Glen, Belle	Raw EMG Graph: A real-time, graphical visualization of muscle activity, shown in a separate window. Flexion and extension are shown as line-plots and periods of co-contraction are highlighted in yellow.	Patients and experts agreed that visualizing raw muscle activity was a strength of other training tools. Access to raw muscle activity allows clinicians to better troubleshoot issues with control.
1.4[27]	Mikayla, Anthony, Sloan	Independent Activation Threshold: The lower signal cut-off threshold (below which all muscle activity is ignored) can now be adjusted independently for flexion and extension muscles.	Some patients only experience unintentional contraction in one of their forearm muscles, or unintentional co-contraction when moving Momo in one direction. This feature enables more fine-tuned calibration adjustment.

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[27] At the time of publication (Article #2: Designing Game-Based Myoelectric Training), version 1.4 of my game had not yet been completed. User-centered design sessions with these 3 participants were completed following the writing and publication of this article.

		Calibration Menu Redesign: Position and labelling of various calibration settings (e.g., gain, activation threshold) are adjusted to facilitate ease-of-use.	Location of sensitivity sliders (directly above EMG Bars) inaccurately represented the purpose of the setting and was misleading for users. Position and scale of activation threshold sliders now creates a natural control-display relationship between the settings value and resulting outcome.

Table B-2: Calibration-specific features added during the iterative development of The Falling of Momo

Appendix C. The Falling of Momo – Setup/Instruction Manual

C.1 Step 1. Wearing the Armband

Positioning the armband on your forearm is an important step in the calibration process, and ensures consistent control throughout gameplay. Slide the armband up your preferred forearm, almost to your elbow as shown below. The band should be snug enough to avoid inadvertent movement/slippage during gameplay, but not so tight as to cause discomfort; adjust the fit of the band using the 8 provided clips. For optimal performance, Thalmic Labs suggests wearing the armband with the **logo positioned along your inner forearm and micro-USB charging port pointing toward your hand, away from your body** (the orientation shown below).

Note the following when wearing the armband:

- *Allow sufficient time (~5 mins) for the temperature of the armband's sensors to equalize with your skin temperature. The readings captured by the sensors are significantly affected by temperature.*
- *Do not shift the armband (either up/down along the forearm, or rotating around the forearm) throughout the duration of gameplay as this will greatly affect your calibration. If the armband is shifted, a re-calibration should be performed.*

C.3 Step 2. Launching the Game

Before proceeding, please ensure the following:

- The armband is charged and in “discovery mode” (i.e., the blue logo on the armband will slowly flash on and off) by gently stretching the band, or shaking your forearm.
- The Bluetooth dongle (a small blue USB key, provided with the myo armband) is installed in one of your computer's USB ports.

To begin playing The Falling of Momo, follow these steps:

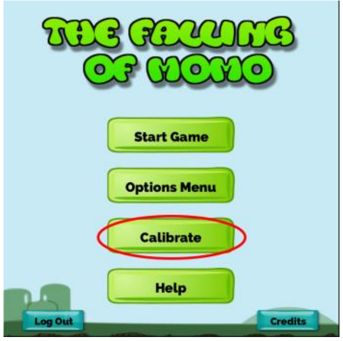
1. Start the game by double-clicking on the “The Falling of Momo” icon on the Desktop.

2. When the game window appears, login using the id “000”.

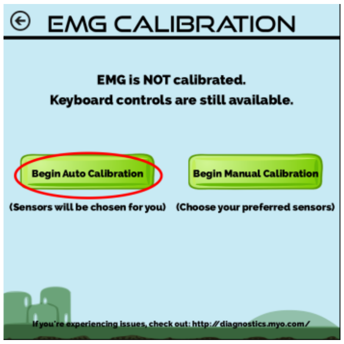
3. After successful login, the armband should display a solid blue indicator light on sensor #3, as shown (the blue logo may still slowly flash on and off).

C.4 Step 3. Automatic Calibration

Automatic calibration is the quickest and easiest way to get started playing The Falling of Momo. Follow these steps unless you have been instructed otherwise, or experience difficulties achieving a usable calibration:



1. Click the "Calibrate" button from the Main Menu (also accessed from the Pause Menu).

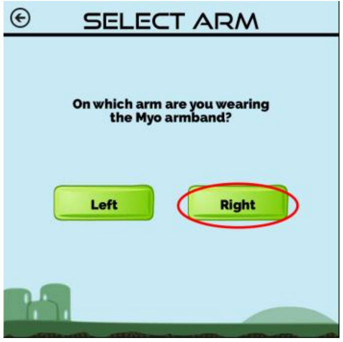

EMG CALIBRATION

EMG is NOT calibrated.
Keyboard controls are still available.

(Sensors will be chosen for you)
(Choose your preferred sensors)

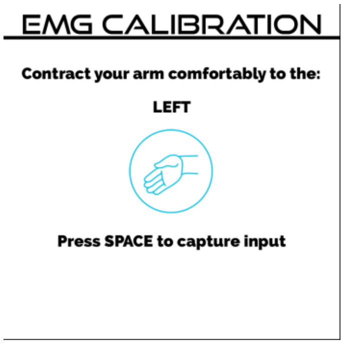
If you're experiencing issues, check out: http://diagnostics.myo.com/

2. Click the "Begin Auto Calibration" button.


SELECT ARM

On which arm are you wearing the Myo armband?

3. Select whether you are wearing the armband on the left or right forearm.

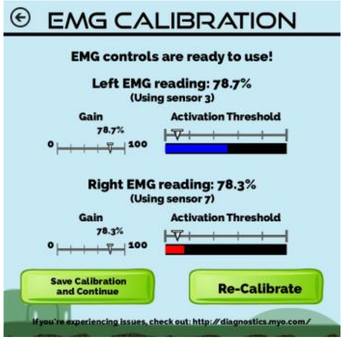

EMG CALIBRATION

Contract your arm comfortably to the:

LEFT

Press SPACE to capture input

4. Match each of the following on-screen hand movements by steadily holding your hand/forearm in the appropriate position. *Contract naturally, with a normal level of exertion; do not over-exert your muscles during the calibration phase.* During each movement focus on contracting only the current forearm muscle of interest, keeping the opposing forearm muscle quiet. Press the SPACEBAR to capture each reading when ready.


EMG CALIBRATION

EMG controls are ready to use!

Left EMG reading: 78.7%
(Using sensor 3)

Right EMG reading: 78.3%
(Using sensor 7)

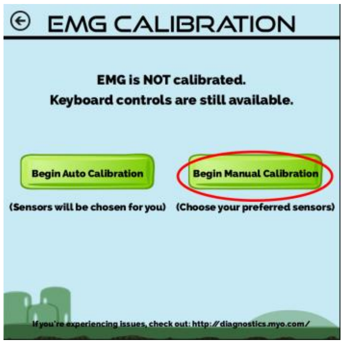
If you're experiencing issues, check out: http://diagnostics.myo.com/

5. Upon success, you will be presented with the Calibration Settings Menu. Validate your calibration by closely watching the 2 bars independently rise as you slowly move your hand/forearm from full flexion, through relaxation, to full extension. If you experience difficulties achieving a successful calibration, try manually assigning sensors by following the **Manual Calibration** steps below.

C.5 Step 4. Manual Calibration

If you experience difficulty achieving a usable calibration with the **Automatic Calibration** steps, it is possible to manually assign a sensor to each of the flexion/extension muscle sites. Follow these steps to perform a manual calibration:

1. Click the "Calibrate" button from the Main Menu (can also be accessed from the Pause Menu).

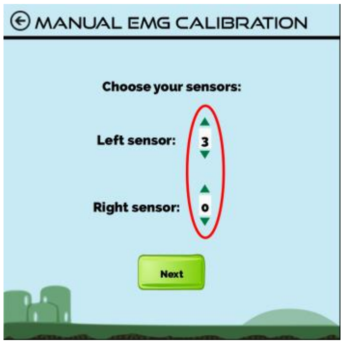


EMG is NOT calibrated.
Keyboard controls are still available.

(Sensors will be chosen for you) (Choose your preferred sensors)

If you're experiencing issues, check out: http://diagnostics.myo.com/

2. Click the "Begin Manual Calibration" button.

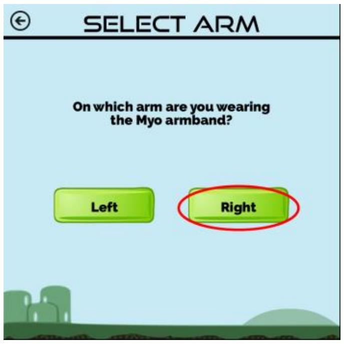


Choose your sensors:

Left sensor: 3

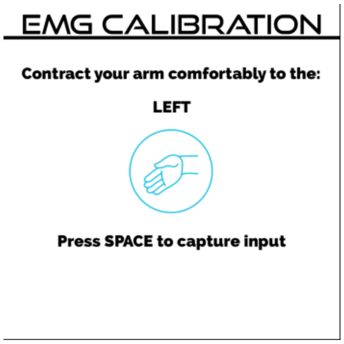
Right sensor: 0

3. Select the appropriate sensor ID for the left and right movements (ID's are labeled on the armband).



On which arm are you wearing the Myo armband?

4. Select whether you are wearing the armband on the left or right forearm.

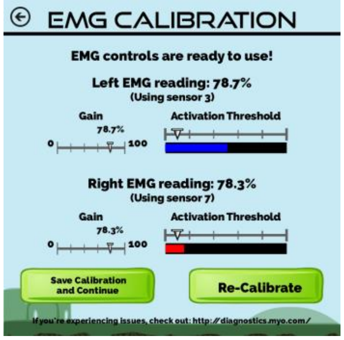


Contract your arm comfortably to the:

LEFT

Press SPACE to capture input

5. Match each of the following on-screen hand movements by steadily holding your hand/forearm in the appropriate position. *Contract naturally, with a normal level of exertion; do not over-exert your muscles during the calibration phase.* During each movement focus on contracting only the current forearm muscle of interest, keeping the opposing forearm muscle quiet. Press the SPACEBAR to capture each reading when ready.



EMG controls are ready to use!

Left EMG reading: 78.7%
(Using sensor 3)
Gain 78.7%

Right EMG reading: 78.3%
(Using sensor 7)
Gain 78.3%

If you're experiencing issues, check out: http://diagnostics.myo.com/

6. Upon success, you will be presented with the Calibration Settings Menu. Validate your calibration by closely watching the 2 bars independently rise as you slowly move your hand/forearm from full flexion, through relaxation, to full extension. If you still experience difficulties, try **Adjusting Calibration Settings** as outlined below.

C.6 Step 5. Adjusting Calibration Settings

After completing initial calibration, several settings can be adjusted to improve the in-game controls.

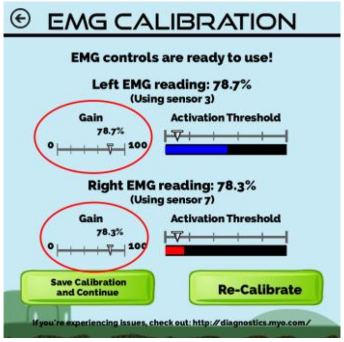
Sensor Gain

To compensate for players with varying levels of muscle strength, adjust sensor gain. Selecting a higher gain corresponds to a greater amplification of the raw muscle signal (i.e., higher "sensitivity"), which can be useful for players with weaker muscle strength. Adjust gain when:

- you have trouble filling the EMG bar with natural, normal muscle contractions (i.e., gain is *too low*)
- the EMG bar fills very quickly, even from minimal muscle contraction (i.e., gain is *too high*)
- the EMG bar remains significantly full, even when your muscles are at rest.

To adjust the sensor gains, following these steps:

1. Click the "Calibrate" button from the Main Menu (can also be accessed from the Pause Menu).



EMG controls are ready to use!

Left EMG reading: 78.7%
(Using sensor 3)
Gain 78.7%

Right EMG reading: 78.3%
(Using sensor 7)
Gain 78.3%

If you're experiencing issues, check out: http://diagnostics.myo.com/

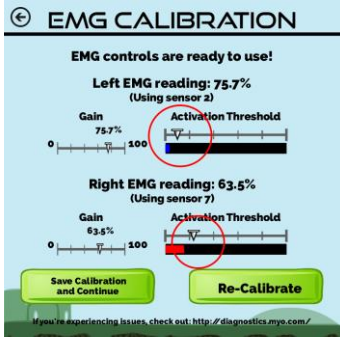
2. One muscle at a time, perform natural, normal strength muscle contraction and adjust gain as follows:

⇲ if the EMG bar does not reach its maximum, adjust the slider up (i.e., toward 100%)
⇲ if the EMG bar fills quickly, even with small contractions, adjust the slider down (i.e., toward 0%)

Activation Threshold

Some players have trouble sustaining muscle quietness, which can result in jittery movement when the player attempts to keep Momo still. Adjusting the *activation threshold* setting can be used to help players in this situation. Any muscle activity below the *activation threshold* will be ignored during game play and result in no movement. To adjust the activation threshold, following these steps:

1. Click the "Calibrate" button from the Main Menu (can also be accessed from the Pause Menu).



EMG controls are ready to use!

Left EMG reading: 75.7%
(Using sensor 2)
Gain 75.7%

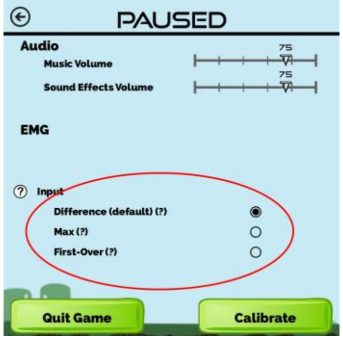
Right EMG reading: 63.5%
(Using sensor 7)
Gain 63.5%

If you're experiencing issues, check out: http://diagnostics.myo.com/

2. Adjust each activation threshold sliders such that it is slightly higher than the corresponding EMG bar while the player is at rest. This ensures that any unintentional muscle activity will not result in "jitter" during game play.

Control Policy

Several *control policies* have been implemented in The Falling of Momo. These *control policies* are used in real upper-limb prostheses to help individuals who experience difficulties achieving isolated or sustained contractions. The control policy can be selected from the in-game Pause Menu (by pressing either SPACEBAR or ESC during game play).



Music Volume 75

Sound Effects Volume 75

Difference (default) (?) ●

Max (?) ○

First-Over (?) ○

Select one of the 3 control policies listed under **Input**:

- *Difference*: Only the difference between the left and right sensor readings contributes to in-game movement. To move quickly, the player must be able to reliably perform isolated contractions.
- *Max*: Momo moves (proportionally) per strength of the larger of the left and right sensor readings; the smaller of the two readings is ignored. This policy is appropriate for individuals who have trouble performing isolated contractions.
- *First-Over*: Momo moves (proportionally) in the direction of the first sensor reading to exceed the *minimum activation threshold* and continues to move in this direction until the sensor drops below the threshold. Throughout this duration of time, the opposing sensor reading is ignored. This policy is appropriate for individuals who have trouble sustaining strong, isolated contractions, but can control which muscle contracts first.

C.7 Troubleshooting

If you experience difficulties setting up or playing The Falling of Momo please don’t hesitate to reach out to us, as we’ll be happy to help:

Scott Bateman	1 (506) 447-3336	scottb@unb.ca
Aaron Tabor	1 (506) 262-0170	aaron.tabor@unb.ca

The following tips may help resolve several common issues that arise:

The blue lights on the armband will not turn, even when I stretch the band and shake my arm.

- The batteries in the armband may be dead. Even when not in use, the armband may stay awake and drain battery power. Charge the armband using the provided charging cable and wall-plug.

Before I start the game, the armband vibrates when I move my muscles.

- This is normal. The armband has built in software that recognizes different muscle patterns and vibrates when it recognizes them. Once the Momo game starts, armband vibration is disabled.

The indicator light is solid blue, even when I am not playing the game.

- This indicates that the armband is actively connected to another device (e.g., an old connection from previous game play, or accidentally connected to a nearby phone/tablet). Plug the armband into its charger for a few seconds to reset it.

The armband will not connect to the game, even in discovery mode (i.e., blue flashing logo).

- Ensure that the blue USB-dongle is inserted fully into one of the laptop’s USB ports.
- Reboot the computer.

The in-game calibration repeatedly reports “No Armband Detected”.

- This can occur if the player starts the game and logs in before the armband is awake / in discovery mode (i.e., blue flashing logo). Restart the game by exiting normally and following steps #1 and #2 of this guide.

The armband disconnects during game play, and no longer allows me to control Momo.

- This occasionally happens, especially when there are other active Bluetooth devices (phones/tablets) nearby. Restart the game by exiting normally and following steps #1 and #2 of this guide.
- If the issue persists, try disabling Bluetooth settings on other nearby devices or moving to another room

Curriculum Vitae

Candidate's full name: Aaron William Tabor

Education

October, 2017 - Masters in Computer Science (MCS)

University of New Brunswick

Fredericton, New Brunswick, Canada

May, 2015 - Bachelor of Science in Software Engineering (BScSWE)

University of New Brunswick

Fredericton, New Brunswick, Canada

Awards and Recognitions

September, 2017 - NSERC Alexander Graham Bell Canada Graduate Scholarship

July, 2017 - NBHRF Rising Star: Researcher of the Month (Masters Category)

October, 2016 - CHIPlay 2016 Best Game Award

May, 2016 – Mitacs Accelerate Grant (declined)

September, 2015 - NBIF New Brunswick Graduate Scholarship

September, 2011 *to* May, 2015 - Deans List (BScSWE)

September, 2011 *to* May, 2014 - Edwin Jacob Special University Scholarship

September, 2011 - UNB Third Century Fund Scholarship

June, 2010 - NBIAA Raymond Legere Sportsmanship Award

May, 2010 - Male Sportsmanship and Leadership Award

November, 2009 - NBHSFL Bill Glendenning's Sportsmanship and Academics Award

July, 2009 - Royal Canadian Legion Leadership Camp Invitation

April, 2009 - University of Waterloo Math Contest, School Leader

Work Experience

September, 2015 *to* December, 2016 –Faculty of Computer Science, UNB

Lab Instructor and Mentor: Matlab for Engineers

January, 2014 *to* September, 2014 - NB Power

Reduce and Shift Demand (Smart-Grid) - Project Management Team

May, 2012 to May, 2013 - Populus Global Solutions

Software Development and Quality Assurance

Publications

Tabor, Aaron, Wendy Hill, Scott Bateman, and Erik Scheme. 2017. **Quantifying Muscle Control in Myoelectric Training Games**. *In Proceedings of Myoelectric Control Symposium (MEC) 2017.* Fredericton, New Brunswick. 4.

Tabor, Aaron, Scott Bateman, Erik Scheme, David R Flatla, Kathrin Gerling. 2017. **Designing Game-Based Myoelectric Prosthesis Training**. *In Proceedings of the ACM Conference on Human Factors in Computing Systems*, May 2017, Denver, USA. p1352-1363.

Tabor, Aaron, Scott Bateman, and Erik Scheme. 2016. **Game-Based Myoelectric Training**. *In Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*, pp. 299-306. ACM, 2016.

Tabor, Aaron, Alex Kienzle, Carly Smith, Alex Watson, Jason Wuertz, and David Hanna. 2016. **The Falling of Momo: A Myo-Electric Controlled Game to Support Research in Prosthesis Training**. *In Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts* (2016): 71-77.

Presentations

August, 2017 – Myoelectric Control (MEC) 2017

Quantifying Muscle Control in Myoelectric Training Games

June, 2017 – Atlantic Education Graduate Research Conference (AEGSC) 2017

Designing Game-Based Myoelectric Prosthesis Training

May, 2017 – Conference on Human-Factors in Computing (CHI) 2017

Designing Game-Based Myoelectric Prosthesis Training

April, 2017 - UNB Graduate Research Expo 2017

The Falling of Momo, Myoelectric Muscle Training Game: Poster and Live Demo

October, 2016 – Symposium on Computer-Human Interaction in Play (CHIPlay) 2016

The Falling of Momo, Myoelectric Muscle Training Game: Poster and Live Demo

April, 2016 - UNB Graduate Research Expo 2016

Improving Garbage Collection in the JVM using Transactional Memory