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AUGMENTED REALITY FOR ADVANCED PROSTHETIC TRAINING IN NON-AMPUTEES

Lauren Deus
University of Rhode Island, ldeus159@gmail.com

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AUGMENTED REALITY FOR ADVANCED PROSTHETIC TRAINING IN NON-AMPUTEES

BY

LAUREN DEUS

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OF

LAUREN DEUS

APPROVED:

Thesis Committee:

Major Professor	Susan E. D’Andrea
Committee Member	Matthew J. Delmonico
Committee Member	Dhaval Solanki
URI Graduate School Dean	Brenton DeBoef

UNIVERSITY OF RHODE ISLAND
2023

ABSTRACT

Prosthetic abandonment is highly prevalent among upper extremity amputees, which can be attributed to issues of comfort, function, and ease of use (Biddiss and Chau 2007). While recent advancements in prosthesis design have improved sensory feedback and control mechanisms, acceptance rates of prostheses have not improved (Bates, Fergason, and Pierrie 2020). Prosthetic training, however, has been observed to have a significant influence on prosthesis acceptance, with special consideration for the quality of training received (Salminger et al. 2022). To date, there is no consensus on the most effective delivery of prosthetic training, although participants that are more satisfied with their prosthesis report having greater feelings of motivation and comprehension regarding the training they received (Prahm et al. 2018; Gaballa et al. 2022). The use of emerging technologies for rehabilitation offers users a stimulating and innovative experience not able to be achieved through conventional rehabilitation alone (Vinolo Gil et al. 2021). Among the latest technology used is augmented reality (AR), which overlaps the real and virtual worlds. Few studies have investigated the effects of AR for prosthetic training, and their findings do not indicate if there was a transfer of skills.

To better understand the effectiveness of AR prosthetic training on motor learning, this study observes able-bodied individuals using a body-powered bypass prosthesis as they engage with the AR training game, *ARm-Strong*, to assess improvements in physical function. Thirty-two participants who had never used a bypass prosthesis, were included in this study. Sixteen of those

participants were randomly allocated to receive the AR training intervention and sixteen acted as controls and did not receive AR training. The University of Rhode Island IRB approved this study.

Chapter 1, *Review of Literature*, provides background information about prostheses, causes of rejection of prosthetic devices, and training techniques to enhance prosthesis engagement.

Chapter 2, *Augmented reality for advanced prosthetic training in non-amputees,* presents the manuscript for this project. In this study, the effectiveness of a novel augmented reality prosthetic training game was evaluated, in terms of physical function and cognitive enjoyment. The results indicated that motor function improved, irrespective of receiving three sessions of prosthetic training or not. Participants did indicate that they were highly engaged and engrossed by the AR training game. The implications of this study's findings for future research are addressed. This manuscript is in preparation for submission to *PLOS ONE.*

Chapter 3, *Summary,* provides a review of the results and limitations, and discusses potential directions of future research.

The Appendices provide additional details about thesis Abbreviations (A) and Supplemental figures (B).

ACKNOWLEDGEMENTS

I would like to express my gratitude to my advisor, Dr. D'Andrea, for presenting this project to me; thank you for your guidance and confidence throughout this process. Additionally, I would like to thank my committee for their valuable insight. I would also like to recognize Jason Maikos and his colleagues at the VA in Manhattan for their contribution of the prosthesis. Thank you to Kristen Baxter for professional advice. Lastly, thanks to Leah Wohlbach for her assistance in this project.

PREFACE

This thesis is in manuscript format. It is the result of academic and research support from the Department of Kinesiology at the University of Rhode Island, Kingston, Rhode Island.

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CHAPTER 1 REVIEW OF LITERATURE

To support the manuscript in the following chapter, this first chapter provides additional background information about prostheses, factors contributing to prosthesis rejection, and novel techniques to enhance prosthesis acceptance. The last section lists the specific aims of this thesis project.

1.1 Limb Amputation

The estimated global prevalence of limb loss in the year 2017 was 57.7 million individuals (McDonald et al. 2021). In the United States alone, there are nearly 185,000 amputations performed each year (Ma, Chan, and Carruthers 2014). Limb loss may be categorized by upper and/or lower extremity(ies), depending on the effected body segment(s). Upper extremity amputations are less frequent, for every one upper limb amputation there are approximately four lower limb surgeries (Fahrenkopf et al. 2018). Despite the higher prevalence of lower limb amputees, Desteli et al., (2014) found that upper limb amputees were more limited in their movements and maladaptive to their prostheses compared to lower limb amputees. Further, those with upper limb amputations reported higher levels of depression and anxiety (Desteli et al. 2014). The findings of Desteli et al., warrant further investigation of upper extremity prosthesis users.

For example, quality of life in individuals with upper limb amputations may be affected by the degree and etiology of their limb loss. Upper extremity amputation can occur proximally at the transhumeral level or forequarter level, which includes the arm, scapula, and clavicle. Distal amputations occur at the transradial or transcarpal level, which are also referred to as below elbow or partial hand amputations respectively. Limb loss can also occur at joints, namely, shoulder disarticulation, elbow disarticulation, and wrist disarticulation. Amputation at the transradial level is among the most common upper extremity surgery performed and is often the result of unexpected traumatic incidences including car accidents, work-related experiences, or military casualty (Ziegler-Graham et al. 2008).

After a limb loss, the individual and their team of healthcare providers including a prosthetist, occupational therapists, and/or physical therapist, collaborate to develop a prosthesis that meets the needs of the amputee. Principally, the prosthetic device is designed for the purpose of re-establishing the individual's personal autonomy (Constantin et al. 2022). Considerations when selecting an optimal prosthesis include appearance, control, cost, durability, sensory feedback, functionality, training time, and maintenance, which all may influence the user's acceptance of a particular device (Carey et al. 2015).

1.1.1 Types of upper extremity prostheses

Upper extremity prostheses are classified into either passive or active devices. While passive prostheses are visually appealing and resemble a natural limb, they do not act to enhance physical function. Contrarily, there are multiple control mechanisms for active devices (i.e. body-operated versus externally powered) which influence the level of function that may be achieved by a prosthesis user. Externally powered devices are controlled through myo-electrical stimulation (i.e. energy within the muscle) or through pneumatic processes. Myoelectric prostheses receive input from residual muscle activation, detected through surface electromyography (sEMG) electrodes within a prosthetic socket, to perform a desired movement. For example, extrinsic hand muscle function is often conserved in amputations at the transradial level and below. Thus, myoelectric protheses have the capability to detect neuromuscular firing of residual forearm musculature, which is often processed as opening and closing actions of a terminal device (Kuiken et al. 2017; Zhou and Rymer 2004). However, prosthesis users' ability to successfully recruit motor units is complex and requires considerable physical and cognitive effort. Several issues exist with myoelectric prostheses, among them being that they are highly sensitive to skin quality and electrode placement. Suboptimal preparation has the potential to cause disruptions in the electrical signaling and create a delayed response of the terminal device. Because myoelectric devices are not innate to most individuals, it generally takes a great deal of training to efficiently utilize them (Carey et al. 2015).

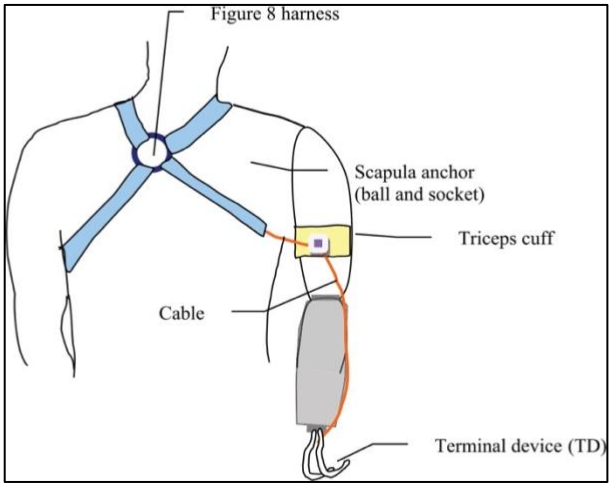

Fig 1 Posterior view of a body-powered prosthetic for a transradial amputation (Ayub, Villarreal, Gregg, and Gao, 2016).

The alternative to externally controlled prostheses is body-powered devices. Conventional body-powered prostheses are a one-degree-of-freedom control mechanism intended for grasping motions (Bloomer and Kontson 2020). In Figure 1, the suspension harness and cable system allows an individual to control the terminal device by means of upper-body muscular contractions (Ayub et al. 2017). When an individual produces flexion at the shoulder joint to grasp an object in front of them, tension is generated in the cable, causing the terminal device to open. Subsequently, relaxing one's shoulder (by bringing their arm by their side) will release the tension of the cable, causing the device to close. The body-powered prosthesis with suspension harnessing is the preferred prosthetic design because it provides proprioceptive feedback through tensile activity in the cable. Body-powered designs are more natural, and less fatiguing compared to myoelectric devices that rely on visual feedback only. In addition, the affordability and accessibility to body-powered devices is appealing. As in the case of the present project, they are commonly used in research when studying the population of upper extremity amputees (Bloomer, Wang, and Kontson 2020; S. L. Wang, Bloomer, and Kontson 2018; Williams et al. 2021; Wallace et al. 1999; Haverkate, Smit, and Plettenburg 2016; Weeks, Wallace, and Anderson 2003).

1.1.2 Bypass devices for simulating prosthetic function

Prosthetic simulators or bypass prostheses are devices used by able-bodied individuals to mimic both body-powered and myoelectric prostheses. Since the population of individuals with upper limb loss is small, statistical power is often not achieved when studying this population. The purpose of recruiting limb-intact participants to wear a bypass device is to imitate the function of prostheses designed for amputees and to achieve greater statistical power when conducting research (Haverkate, Smit, and Plettenburg 2016; Bouwsema, van der Sluis, and Bongers 2014; Williams et al. 2021). The mechanical differences between bypass devices and traditional prostheses have been investigated (Bloomer and Kontson 2020). For example, the length of the terminal device varies in regard to bypass prostheses because it must accommodate individuals with an intact limb i.e. either lying adjacent to the intact limb or acting as an extension of the limb (Figure 2) (Wilson, Blustein, and Sensinger 2017). The results of Williams, et.al., 2021, indicate that bypass prosthesis users and individuals with transradial prostheses use comparable movements to complete tasks, irrespective of terminal device orientation. Investigations into prosthesis training, use, and function are needed yet are difficult to conduct given the small percentage of upper

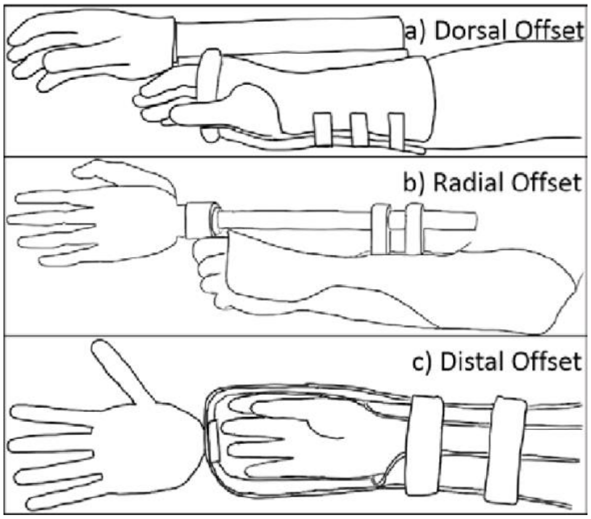

Fig 2 Variations of terminal device orientations of upper extremity bypass prostheses (Wilson et al., 2017)

extremity amputees. Bypass prostheses are advantageous in that they are a valid and reliable tool to simulate prosthesis use and warrant statistically powered studies which contributes to the strength and applicability of the research findings.

1.2 Prosthesis Rejection

Individuals with upper limb loss are often unsatisfied with their prosthesis, leading to abandonment of the device (Biddiss and Chau 2007). Additionally, quality of life is compromised (Desteli et al. 2014) in those who reject their prosthesis because they may not be able to return to their normal routine, including job-related duties and living independently (Yamamoto et al. 2019). Prosthesis rejection has been an issue for over 30 years (Burrough and Brook 1985) and can be attributed to factors of comfort, weight, and function (Salminger et al. 2022). New prosthesis designs are currently being developed to solve the issues related to the physical characteristics (i.e. comfort and weight) of the devices. The actual function and use of prostheses can be differentiated from the physical characteristics, because it is highly dependent on the user’s ability to control the device.

A primary feature related to prosthesis function has to do with prosthesis training. Prosthetic training has been recognized to improve motor learning and movement strategies, resulting in improved functional performance (Bloomer, Wang, and Kontson 2020). This is imperative to the overarching goal of prosthetic training, which is to function independently. In addition, quality of life in amputees is often reflective of their level of self-governance.

Prosthesis training is beneficial for amputees after they undergo the amputation surgery, shortly after they are fitted with a prosthesis. The longer an amputee waits to be fitted for and learn how to use a prosthesis, the compliance to a device lessens and the difficulty to use a device increase (O′Keeffe 2011). Additionally, the quality of training is more effective than the quantity of training received, especially because perceived usefulness is correlated with prosthesis acceptance (Salminger et al. 2022; Bloomer, Wang, and Kontson 2018). Training is essential so that individuals properly learn how to manage life with their new device, and research has indicated that amputees who do not receive training become frustrated and abandon their device. In a study by Jang, et.al., 2011, 7.3% of upper limb amputees received prosthesis training. Further, 21.6% of participants in that study stated that prosthesis training was important and useful (Jang et al. 2011). The results of that study identify a weakness contributing to prosthesis rejection; a large portion of individuals are not properly trained to use their device which is a concern since it is a prominent desire of amputees.

In a study conducted by Resnik, et.al., (2019), 776 veterans with unilateral upper limb amputation (97.3% male, mean age 63.2±14.1 years, mean age since amputation 31.3±18.4 years) were surveyed regarding their satisfaction and quality of life. Notably, 33.7% of prosthesis users did not receive training to use their current device and an even greater percentage of veterans (49.9%) stopped using a prosthetic device at some point in their lives, indicating ”fit/comfort”, ”lack of function”, and “too much fuss” as the main reasons for abandonment (Resnik et al. 2019). The results from that study suggest there may be a causal relationship between aspects of prosthetic training (e.g., length of sessions, frequency, and mode of training) and device compliance, which is in need of further investigation.

1.2.1 Conventional prosthesis training

General guidelines for prosthesis training have been published to provide insight for clinical application. First, a team of specialists are involved in guiding an individual through the process of recovery after an amputation to return to normal life. Prosthetists and occupational therapists outline basic steps of care for upper limb amputees including wound healing, preprosthetic training, prosthetic training, advanced functional training, and discharge planning. The prosthetic training stage of the model is imperative to enhance independence and improve functional performance. Prosthetic training begins with an orientation to the prosthetic device, then individuals practice operating and controlling the mechanisms of the prosthesis, and finally progress to performing tasks and activities of daily living with the prosthesis (Smurr et al. 2008). Control training consists of performing repetitive drills with the prosthesis to get accustomed to its capabilities. Activity training requires unilateral and bilateral object manipulation to complete tasks with only the prosthesis and tasks together with the intact limb, respectively (Kristoffersen et al. 2021; Resnik et al. 2018). Prosthesis training measures are practical and monotonous, which leads individuals to frequently experience frustration and loss of interest, leading to prosthesis rejection (Espinosa and Nathan-Roberts

2019). There is no gold standard for prosthesis training, hence researcher developments are focused on designing a physically and mentally engaging rehabilitation experience to enhance prosthesis acceptance (Latour 2022). The amount of time needed to progress through prosthetic training protocol varies from person to person depending on the needs and function of individuals. Prosthetic training should be tailored to the goals of each prosthesis user to increase acceptance of the prosthesis and advances in function should be assessed periodically (Østlie et al. 2012).

1.2.2 Clinical measures to evaluate upper limb prosthetic performance

Performance-based outcome measures are used to evaluate prosthesis users progress toward achieving specific goals and allows researchers to determine the effectiveness of training based on their progress. A variety of measures have been developed and validated, each with its own set of subtasks and rating scale. Common measures to quantify and determine change in prosthesis function over time include the Activities Measure for Upper Limb Amputees (AM-ULA), Jebsen Hand Function Test (JHFT), Box and Block Test (BBT), Clothespin-Relocation Test (CPRT), and the Southampton Hand Assessment Procedure (SHAP) (S. Wang et al. 2018). The BBT and CPRT are concerned with the speed it takes to perform a single skill repetitively, while the SHAP, JHFT, and AM-ULA are composed of a series of subtasks associated with activities of daily living.

The validity of the JHFT has been positively correlated with the Disabilities of Arm, Shoulder and Hand Questionnaire (DASH), a valid and reliable performance-based outcome measure of upper limb disorders. Further, the JHFT can distinguish individuals with impaired hand function (Sığırtmaç and Öksüz 2021). Specifically, the JHFT measures unilateral dexterity to complete activities of daily living, and has previously been used to identify improvements in prosthesis function (Dromerick et al. 2008; Bloomer, Wang, and Kontson 2020).

1.3 Advanced Technology to Increase Prosthesis Acceptance

To enhance the psychological experience of learning, researchers have used virtual training techniques in populations with chronic conditions. The results of these interventions support virtual rehabilitation to supplement conventional therapy (Berton et al. 2020; Checa and Bustillo 2020; Faria et al. 2016; Feng et al. 2019; Leong et al. 2022; Perry et al. 2018; Saeedi, Ghazisaeedi, and Rezayi 2021). A virtual version of the BBT has been used with amputees and able-bodied controls and has demonstrated not only improvements in physical function, but is mentally engaging as well (Hashim et al. 2021; Yoshimura et al. 2020; Lambrecht, Pulliam, and Kirsch 2011). Gaming and specifically the use of game-based tools for rehabilitation provides an appealing, entertaining, and stimulating concept for learning (Janssen et al. 2017; Cheung and Ng 2021; Boeker et al. 2013). The use of extrinsic motivation (e.g., wanting to achieve a goal or earn a reward) increases persistence which counteracts discouragement when performing difficult tasks (Tabor et al. 2017). There are different types of virtual environments that game-based learning can be delivered through, depending on the objectives to be achieved.

1.3.1 Augmented reality

Augmented reality (AR) is a novel technology that projects virtual holograms into the real world. Virtual reality (VR) is a similar technology to AR although it is important to distinguish between the two of them. Virtual reality programs are entirely computerized environments that may be interacted with in three dimensions. Augmented realty allows for an overlapping of computerized objects in the real-world. Thus, AR creates the perception of a more natural and safer setting for analyzing rehabilitation and training techniques (Liu et al. 2017).

The effectiveness of VR for assessing physical function (Checa and Bustillo 2020; Faria et al. 2016; Feng et al. 2019; Perry et al. 2018; Yoshimura et al. 2020; Lambrecht, Pulliam, and Kirsch 2011) has been well documented in the literature compared to AR, and studies that have been published using AR concern Parkinson’s Disease and stroke patients (Leong et al. 2022; Bank et al. 2018; Vinolo Gil et al. 2021). One of the first examples of using AR technology to create a gaming experience for upper extremity prosthetic rehabilitation was conducted in a study by Melero, et.al., 2019. They designed an AR dance game, *Upbeat,* featuring a virtual dance instructor through the Microsoft Xbox Kinect system. The purpose of the game was for participants to mirror the instructor’s movements, which involved joint actions of the upper limbs. The effectiveness of the game was assessed based on how many movements were correctly performed by the participant. The pilot study of the game *Upbeat* supports AR as an engaging rehabilitative tool (Melero et al. 2019), but it was not tested with any type of prosthetic device.

Another study using AR for prosthesis training evaluated functional performance of 13 able-bodied individuals. All participants completed the CPRT at baseline. Half of the participants then received AR training (i.e. the intervention group). Participants in the intervention group were positioned in front of a clothespin case to perform the CPRT while wearing the Oculus Rift virtual reality headset. Displayed through the headset was a virtual clothespin, virtual target bar, and a virtual prosthetic arm that was overlayed onto participants' real arms. Participants were instructed to grasp the clothespin (which was positioned over the clothespin case in the real world) with the virtual arm and relocate it onto the target bar. A post-assessment CPRT was performed by all participants. The results of the study found that the virtual CPRT was effective in transferring skills in AR to improve performance in the real world with a physical prosthetic, and performance was significantly better than the control group that did not receive any training (Boschmann et al. 2021). However, the CPRT is a measure of repeatability and does not evaluate prosthesis user's ability to perform activities of daily living which is a primary objective of prosthesis training.

1.3.2 Microsoft HoloLens2

The Microsoft HoloLens2 mixed reality headset has been recognized as a safer alternative to rehabilitation compared to VR-based modalities. The

HoloLens' large field of view, spatial mapping, and wireless hand and eye-tracking capabilities make it advantageous for at-home rehabilitation. In a study by Sharma et al., 2019, an AR prosthetic training protocol was introduced using the HoloLens2. Improvements in motor skills, evaluated by the average time to complete tasks e.g. CPRT, were apparent after a 10 day period of virtual prosthesis training (Sharma et al. 2019). However, virtual prosthesis training is not the same as training with a physical prosthesis and may lack the embodiment and engagement of users during the AR experience.

1.3.3 Cup-stacking games

Motor function training that encompasses movements such as reaching, grasping, and moving objects, strengthens neuromuscular control after traumatic injuries (Muratori et al. 2013). Movement execution times improved after engaging in cup-stacking tasks in individuals who had a stroke (Binks et al. 2023), however, this type of task has not been evaluated in other populations with upper extremity dysfunction. Additionally, there is no evidence of a virtual cup-stacking game and if motor learning effects would transfer from this modality.

Augmented reality prosthetic training is a novel, advantageous approach to rehabilitation. There is a need to explore useful, engaging, and intuitive prosthetic training protocols to enhance user satisfaction. Therefore, the purpose of this study is to evaluate the effectiveness of an AR cup-stacking game in users with a body-powered bypass prosthesis.

1.4 Project Aims

1.4.1 Problem statement

The effects of augmented reality training on motor function when using a bypass prosthesis have not been investigated. The impact of augmented reality training via the *ARm-Strong* game on feelings of engagement, engrossment, and immersion is unknown.

The goal of this project is to examine if augmented reality training via the ARm-Strong game affects motor function using a bypass prosthesis and if improvement in performance in the ARm-Strong game is correlated with feelings of engagement, engrossment, and immersion.

Specifically, this project investigates the effects of augmented reality game-based training by comparing the change in function of a control group who does not receive AR training and an intervention group that receives 3 sessions of AR training via the *ARm-Strong* game. A validated questionnaire is used to assess the impact of the AR training. The results of this project could help validate augmented reality as an effective strategy to supplement conventional prosthetic training. Positive feelings towards this type of training may have the potential to increase prosthetic acceptance by motivating users to adhere to and complete training protocols.

1.4.2 Project aims

Aim 1: *To observe individuals using an upper limb bypass prosthesis as they participate in three sessions of AR training with the augmented reality game, Arm-Strong, and to compare the change in functional performance before and after the AR intervention.*

Hypothesis: Because prosthesis training is an important aspect of motor learning, participants who receive AR training via the *ARm-Strong* game (i.e. the intervention group) will have a greater improvement in motor function than those who do not receive training (i.e. the control group).

Aim 2: *To correlate individual's change in training performance with their Augmented Reality Immersion (ARI) questionnaire score, which assesses feelings of engagement, engrossment, and immersion upon completion of AR training through ARm-Strong.*

Hypothesis: Individuals with a greater change in AR game performance (indicated by decreased overall time to complete the game) after three training sessions, will report greater feelings of engagement, engrossment, and immersion (designated by a higher rating/score).

CHAPTER 2 AUGMENTED REALITY FOR ADVANCED PROSTHETIC TRAINING IN NON-AMPUTEES

This study, authored by L Deus, L Wohlbach, and SE D’Andrea, examined the effectiveness of augmented reality prosthetic training in thirty-two able-bodied participants. The following paper is in preparation for submission to *PLOS ONE.*

Augmented reality for advanced prosthetic training in non-amputees

Lauren Deus, Leah Wohlbach, Susan E. D'Andrea

Department of Kinesiology, University of Rhode Island

Statements and Declarations

Conflict of Interests: The authors declare no competing financial interests.

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Contributions: SED conceived the study. LD and SED were responsible for the design. LD and LW performed the experiments and the analysis. LD and SED interpreted the results. LD, SED and LW drafted the manuscript. LD and SED edited the manuscript. All authors approved the final version submitted and are accountable for all aspects of the work.

Abstract

Prosthetic abandonment is highly prevalent among upper extremity amputees (UEA), partly due to lack of engaging and motivating training to use their devices. Augmented reality (AR) systems can be used for rehabilitation, and are advantageous because they offer stimulating, goal-oriented experiences for participants to immerse themselves in while performing repetitive tasks to improve function. Thus, in this study, the effects of a novel AR prosthetic training game, and the transfer of skills to a functional performance assessment involving tasks of daily living were investigated.

Thirty-two able-bodied participants, sixteen allocated to receive AR training and sixteen received no training, donned a bypass body-powered prosthetic device to engage in a functional task assessment, evaluated at two time points. The AR group used the bypass prosthesis to engage in the AR training game, *ARm-Strong,* on each of three training sessions. AR group participants completed a questionnaire at the end of the intervention to evaluate their feelings on the AR game.

On average, individuals in the AR group were significantly more efficient at using the bypass prosthesis to complete functional tasks compared to the control group, however, the rate of improvement was similar between groups. Individuals who engaged in the AR training felt positive feelings of engagement, engrossment, and immersion towards the application although the impression of immersion was significantly less than that of engagement and engrossment.

The results of this study support previous findings that AR training is an engaging and motivating experience, and motor learning can be achieved through this type of training. Future implications of the results may benefit prosthesis users by enhancing user experience during prosthetic training and ultimately lead to better rehabilitation and overall adherence to the use of the prosthetic device.

Keywords: prosthesis abandonment, augmented reality, prosthetic training

Introduction

In the United States, approximately 185,000 limb amputations are performed each year (1). The prevalence of limb loss was approximately 2 million individuals in the year 2014 and is expected to increase one and half times that by the year 2050 (2). Trauma-related events remain the most common cause of upper extremity amputations (UEA), primarily effecting adult males who are otherwise healthy and often return to work following recovery (3). For individuals with UEAs, upper extremity range of motion and residual motor function is dependent on the level of limb loss. Distal amputations occurring below the elbow have less of an impact on neuromuscular performance than a shoulder or transhumeral amputation (4). Amputations at the transradial level occur most frequently (5), which preserves elbow function despite the loss of wrist joint movements. In order for individuals with UEA to maintain high quality of life and perform tasks associated with daily living and occupational responsibilities, prosthetic devices are designed to replace the role of the missing limb.

Technology has advanced the quality of artificial limbs so that they more accurately appear and function as real limbs. However, many designs require a great deal of energy and force to be effective, which often leads to fatigue and worse, prosthesis abandonment (6). Among the individuals with UEA who reject their body-powered prosthesis, more than 50% say they are dissatisfied due to one of three reasons: the device is uncomfortable, it has limited range of motion and capabilities, or they were not properly trained to use the device and therefore lack motivation and knowledge to be able to use their device (7,8). While improvements in comfort and function of prostheses are necessary and desired by users, these concerns are well-documented in the literature. Prosthetic training, however, is a more ill-defined concept and unresolved issue.

It is essential for prosthesis users to receive prosthetic training, as it provides the foundation for teaching individuals how to control their device so that they may integrate using their prosthesis throughout their daily living (9). A survey on prosthesis satisfaction of Veterans found that 23.9% of individuals with UEA never received instruction on how to use their body-powered device (10). Consequently, those individuals who did not receive training were dissatisfied with their device. Thus, optimizing prosthetic training will benefit the population of upper extremity prosthesis users, granting them the opportunity to achieve a higher level of autonomy and contentment throughout their lives.

The principles of physical and occupational therapies for rehabilitation involve performing high repetition, task-specific exercises to increase neuroplasticity in the brain-regions related to motor function. The conventional prosthetic training methodology has resulted in successful outcomes for prosthetic users, mainly an improvement in ability to perform tasks (11–14). However, traditional prosthetic training is monotonous and often leads individuals to develop an internal focus of attention, which can deter user’s accuracy and progress (15). The theory of attentional focus postulates that skill training may be more effective when users have an external focus of attention (i.e. on accomplishing the task) rather than on internal thoughts (i.e. how to move to accomplish a task) (16).

Game-based training is advantageous for prosthetic training in that it directs the user’s attention externally through goal-oriented tasks resulting in increased retention and efficiency of motor learning (17,18). Game-based approaches to rehabilitation seek to enhance the psychological commitment that is required when working to restore a person’s abilities (11–13,17,19,20). When psychological components of therapy (such as engagement, engrossment, and immersion) are fulfilled, adherence to therapy is more likely to increase and lead to greater gains in physical function (21). Recently, researchers have investigated the effects of serious games on prosthesis acceptance. Game-based learning combines the repetitive tasks performed in therapy sessions with a stimulating environment, which has shown improvements in adherence while still achieving higher motor function capabilities (20,22). Particularly, advanced technologies in the form of virtual and augmented reality are being used in the healthcare setting.

Augmented reality (AR), unlike virtual reality, allows for an overlapping of virtual and real-world environments. Traditional rehabilitation supplemented with AR game-based training stimulates goal-directed behaviors by providing real-time feedback (23), which increases motivation and enjoyment towards an experience (24,25). Augmented reality is also advantageous in that it offers virtual hand tracking capabilities, which increases user engagement and immersion within the AR environment (15,24–32). Current games for prosthetic training allow users to adopt the controls of a virtual hand to engage with virtual adaptations of common rehabilitative measures, such as the Box and Block Test of manual dexterity and the Clothespin Relocation Test (15,24,26,27,33,34). While these endeavors have contributed to a better understanding of AR and its potential for prosthetic training, no studies have allowed the participant to use their own prosthesis to interact with gaming elements; previous studies have only allowed participants control of virtual prostheses which appear within the game environment to manipulate gaming elements. Thus, it is unknown if users may experience greater embodiment and functional benefits from using a real prosthesis to interact with virtual elements in an AR environment.

Previous investigations of prosthetic training often recruit participants from able-bodied populations to simulate prosthetic function. While simulated studies do not directly translate to the experiences of prosthesis users, they are a reliable alternative (32). In prosthetic training research, bypass prostheses are devices meant for able-bodied participants to simulate wearing a prosthetic. These devices are advantageous because they expand the opportunity to conduct statistically powered studies as it is often difficult to recruit amputees for participation. Additionally, bypass devices support the internal validity of research studies because the same device can be used by all participants and all able-bodied users have no prior experience using the device compared to actual amputees who often do not share the same level or type of experiences.

Therefore, bypass prostheses can be used to conduct investigations aimed at improving prosthetic training, which impacts the satisfaction of prosthesis users. Thus, the purpose of this investigation is to assess the effectiveness of an AR prosthetic training game, *ARm-Strong,* in able-bodied individuals using a bypass prosthesis. User engagement and enjoyment upon interacting with the AR game will also be evaluated. This study seeks to contribute to the literature on the effectiveness of AR for rehabilitation, specifically its physical and cognitive impact on upper limb prosthesis training.

Materials and Methods

Participants

Thirty-two able-bodied participants were recruited for this study, which was sufficient to reach statistical power. To be included in this investigation, participants were between the ages of 18 and 65 years, and had no prior experience using a bypass prosthesis. A diagnosis of a severe communicative or cognitive disorder, and/or susceptibility to photosensitive seizures excluded individuals from participating in this study. Participant characteristics are listed in Table 1. This study was approved by the University of Rhode Island Institutional Review Board (Protocol Number: 1991645). All participants provided written informed consent prior to participating in the study.

Participants were randomly allocated to either the AR intervention group (AR-INT; n=16) or the control group (CON; n=16). Participants in the CON group received no training between pre- and post-measurements of hand function and were instructed not to use a prosthesis in between visits. The AR-INT group participated in the game-based training during all visits and had hand function evaluated before and after training (Fig 3).

Table 1. Participant characteristics

	CON (n=16)	AR-INT (n=16)
Age; yrs		
Mean (SD)	26.19 (11.71)	29.81 (10.69)
Sex		
Male	2	8
Female	14	8
Handedness		
Left	3	1
Right	13	15

Fig 1. Experimental study design.

Experimental setup

A body-powered bypass prosthesis, featuring a voluntary opening Otto Bock System Hand (Otto Bock; Duderstadt, Germany) terminal device, carbon-fiber socket, Bowden-cable, manual wrist rotation and harness were constructed for the investigation. Participants wore a Kunto elbow compression sleeve on their arm to prevent abrasion from the Bowden-cable. The bypass device was then attached to their left arm and the straps adjusted for each participant. To simulate prosthetic function of an amputee, able-bodied participants grab hold of a stationary grip embedded inside the socket. Motor function of the particular limb in use is then operated through the terminal device, which in this study was oriented distal of the participant's hand. To operate the prosthesis, users manipulate their body movements to create tension in the cable-harness system, which causes the terminal device end to open and close (Fig 4).

Experimental protocol

Control group

Control group (CON) participants were tested during two visits, which were approximately 8-12 days apart. On the first visit, participants were fitted with the bypass prosthesis on their left arm and were familiarized with how to control the device (i.e. extending their left arm and internally rotating their shoulders to open and close the device). All participants wore the bypass prosthetic on their left arm. The left side was chosen to more realistically reflect the level of difficulty of amputees when they first learn to use a prosthetic device as the majority of the population (90% of individuals) are right-dominant (35).

Baseline functional performance was assessed using the Jebsen Hand Function Test (JHFT) in the bypass device. The JHFT is a standardized, objective assessment of motor function using simulated activities of daily living (36,37). Tasks include writing, turning over 3-by-5 inch cards (Fig 5), picking up small common objects, simulated feeding, stacking checkers, and picking up large heavy and light objects. On the second visit, participants completed a post-assessment of the JHFT using the bypass prosthesis.

AR-INT group

Participants in the AR-INT group were tested during three visits; each visit was approximately 4-6 days apart. On the first visit, participants were fitted and familiarized with the bypass prosthesis and completed the baseline JHFT. Participants were then introduced to the *ARm-Strong* AR prosthetic training game. The purpose of the AR training is to encourage participants to improve motor function using a prosthesis through a goal-oriented task, which means they are not focused on their movements but rather the objective of the game. The ARm-Strong game is custom software designed in the Unity 3D gaming platform. The game is used in conjunction with the Microsoft HoloLens, an AR headset which consists of a self-contained, holographic computer that enables the user to engage with digital content with hand gestures and interact with holograms in their real-life environment. By leveraging the complex hand tracking capabilities of the HoloLens2 and the object modeling capabilities of the Unity 3D platform, the terminal devices of the upper extremity prosthetics can be used in the AR environment to provide engaging rehabilitation games for UEA prosthesis users.

The participants were seated and donned the HoloLens2 headset and engaged in the ARm-Strong AR game, while wearing the bypass prosthesis (Fig 6). During AR game use, users observed a holographic scene displayed in front of them consisting of six virtual plastic cups (each cup was a different color) displayed on a virtual table. Pictured above the table and cups were six smaller cups (one of each color cup on the table), arranged in a pyramid by random color orientation, which served as the reference image. The HoloLens hand-tracking capabilities allowed participants to select and position the holographic cups using direct touch with the prosthesis, as if they were picking up a real object.

While playing the *ARm-Strong* game, participants were instructed to arrange the cups on the table to match the reference image as quickly as possible using the bypass prosthesis. AR training was done at each visit for the AR-INT group. Participants performed three trials of the game, at each of the three visits. The time to complete the cup stacking was recorded for each trial. All AR training sessions were monitored by a member of the research staff.

On the third visit after the AR training protocol, the JHFT was performed again to determine if participants had improved functional performance. Participants in the intervention group were given the validated Augmented Reality Immersion (ARI) questionnaire to assess their level of interest and motivation in the AR training (38). The questionnaire consisted of 21 questions on the topics of engagement, engrossment, and immersion. Engagement is recognized as the first level of total immersion, in which participants have general feelings of interest towards the AR game and acknowledge its usability. The next level, engrossment, refers to a deeper emotional investment in the AR game, where one might focus their attention, senses, and thoughts more on the game than their surroundings. The highest level of total immersion that one can experience allows users to feel as if they truly exist within the AR environment, and they are un-interrupted by real world phenomena while interacting with the game (39).

Data analysis

For the JHFT, time to complete each task was recorded in seconds. A cumulative time was calculated by adding all task times. Change in JHFT performance was calculated by finding the difference of the pre- to post-assessment cumulative times.

For the *ARm-Strong* intervention, time in seconds was recorded for each of the three trials and totaled to generate a cumulative game performance time on each visit. Change in *ARm-Strong* performance was calculated by finding the difference in total time from visit one to visit three.

Instructions for completing the ARI questionnaire were provided to all AR-INT participants. They were to indicate on a 7-point scale (ranging from “1” - totally disagree to “7” - totally agree), as to how they perceived the AR training game. Average rating of the 21-item questionnaire was calculated for each participant, as well as the average rating for each sub-category (engagement, engrossment, and immersion).

Statistical analysis

G*Power 3.1 was used to perform a power analysis to determine the necessary sample size based on a similar study which assessed functional performance (i.e. time to complete tasks) of a bypass prosthesis user (40).

The following input parameters were used: two tails, d=1.051177, alpha=0.05, power=0.8. Statistical analyses were conducted using IBM SPSS Statistics version 28.0.1.1. Participant characteristics were expressed as mean ± standard deviation. A Shapiro-Wilk test was used to test for normality of the data.

To investigate the primary aim, the differences of the outcome measure, the JHFT, between two groups at multiple timepoints were compared. A two-way mixed ANOVA was calculated to assess the Group x Time interaction for the JHFT. The “group” variable was used to differentiate participants in CON and AR-INT. The “time” variable was split into pre- and post-JHFT scores (i.e. total time in seconds to complete the assessment). Using the data from participants in the AR-INT group, a Spearman’s correlation was conducted to assess the strength of a relationship between two variables (i.e. to compare individual’s improvements during AR training with their improvements in motor function). On their first and last visits, participants performed three trials of the ARm-Strong game. The total time of each visit was calculated so that the difference in time over the course of the intervention could be used to assess the effectiveness of the training. The JHFT was performed at two timepoints (pre- and post-intervention), thus, there is a degree of change that occurred for each participant. The change in JHFT (in seconds) was correlated with the change in game performance (difference in total time to complete *ARm-Strong* from visit three to visit one).

To investigate the secondary aim, a second Spearman's correlation was computed to assess the relationship between participant's performance during AR training and their perceptions of the AR training game, *ARm-Strong.* Each participant's change in *ARm-Strong* game performance (i.e. the difference in total time from first to last visit) was correlated to their average rating for all questions on the ARI questionnaire. Each participant's average rating for each topic within the questionnaire (i.e. engagement, engrossment, and immersion) was explored using two-tailed paired t-tests, to assess the difference in values between each sub-category.

Results

Thirty-one participants (CON, n=16; AR-INT, n=15) were included in the analyses for this study, with the exclusion of one participant due to inability to complete the training protocol.

Functional performance outcomes

Participants in the AR-INT group completed a pre- and post-JHFT, which were on average 11.56±3.31 days apart, with three sessions of AR training (via the *ARm-Strong* game) in between assessments. The CON group completed a pre- and post-JHFT (mean 9.31±1.25 days apart), with no AR training in between assessments. The JHFT, which assesses fine and gross motor hand function using simulated activities of daily living, was used to explore potential differences in motor learning between groups (i.e. CON v. *AR*-INT). There were no outliers, as assessed by examination of studentized residuals for values greater than ±3. Data was normally distributed according to the Shapiro-Wilk test of normality (CON, p=0.23 and 0.47; AR-INT, p=0.27 and 0.88), at the pre- and post-intervention time points, respectively. There were improvements in motor function in both groups (Fig 7). The average decrease in time to complete the JHFT was 85.75 seconds in the intervention group and 116.09 seconds in the control group.

The two-way mixed ANOVA revealed no significant Group x Time interaction, $F(1, 29) = 0.626$, $p = 0.435$, partial $n^2 = .021$, which may have been attributed to a violation of the assumption of variances, as assessed by Levene's test, $p < 0.05$. However, there was a significant main effect of assessment time points, $F(1, 29) = 27.70$, $p < 0.001$, partial $n^2 = .489$ and the main effect of group also showed statistical significant difference $F(1, 29) = 17.28$, $p < 0.001$, partial $n^2 = .373$.

Effect of augmented reality prosthetic training on physical function

To further investigate an association between AR training and functional performance outcomes in each participant in the AR-INT group, a Spearman's rank-order correlation was used. The variables of interest were 1) the difference in time from pre- to post-assessment of the JHFT, correlated with their 2) change in total time to perform the *ARm-Strong* game from their first to final visit. The relationship between these variables was monotonic, as assessed by visual inspection of a scatterplot. There was a significant positive effect between variables; a greater improvement in the AR training was moderately associated with a greater improvement on the JHFT (increased quickness is indicated by a negative change in time), $r_s(13) = .514$, $p < 0.05$ (Fig 8).

Association between the physical effects of training and user perceptions of the augmented reality game, *ARm-Strong*

A Spearman's rank-order correlation was run to assess the relationship between each participant's change in total time to play the AR game (i.e. the difference in time from first to last visit) and their average rating of how involved they felt with the game (i.e. their average rating on the ARI questionnaire). There was a monotonic relationship, as assessed by visual inspection of a scatterplot. However, there was no statistically significant correlation between AR game performance and feelings of immersion, $r_s(13) = .147$, $p = .602$.

Each question on the ARI questionnaire pertains to one of three hierarchical sub-categories (engagement, engrossment, and immersion), which may be used to establish one's level of total immersion. The t-tests revealed that on average, participants reported similar ratings of agreement for the sub-categories of engagement and engrossment (5.68±0.74 and 5.47±0.95, $p = 0.295$). When the immersion sub-category was compared to each of the first two categories, there were significant differences, indicating that individuals felt less total immersion than engagement (*p* = 0.002) and engrossment (*p* = 0.005) (Table 2 and Fig 9).

Table 2. Summary of differences in engagement, engrossment, and total immersion

T-test	*t*	*df*	*p*
Engagement x engrossment	1.088	14	0.295
Engrossment x immersion	3.299	14	0.005*
Engagement x immersion	3.721	14	0.002*

Sub-categories of the ARI questionnaire.
*=significant differences between categories
ARI=Augmented Reality Immersion

Discussion

This study explores a novel AR game for prosthetic training, which improved in-game performance as well as the transfer of skills to functional performance to complete real world tasks. Prosthetic training with the AR application demonstrated improved quickness and efficiency to complete tasks, which is a marker of motor learning. User feedback of the AR game was positive, indicating that individuals felt immersed in the experience which may indicate willingness and motivation to adhere to a training schedule which will foster better functional implementation of the prosthetic (17,18). The results of this study support motor learning through an innovative prosthetic training system, which is important to consider for developing future patient-tailored rehabilitation protocols.

Aspects of this study showed an improved ability to complete functional tasks in both groups (those who received training and those who did not). It is expected for motor learning to occur when individuals receive prosthetic training, which has been observed in the literature (41–44). The present study demonstrated that the AR application, *ARm-Strong,* allows individuals to control a body-powered bypass prosthesis to interact with virtual gaming elements. Additionally, participants were able to improve their ability to operate the device upon interacting with the *ARm-Strong* training system, which we can project will enhance upper extremity prostheses users' functional performance as well.

This study evaluated perceptions of the AR experience which is a crucial consideration regarding the practical implementation of a training protocol. The results indicate that the AR-INT group was highly engaged and engrossed during training. Previous studies have evaluated user experience after engaging with AR rehabilitation systems, and also found that AR training is an immersive experience that gives users a sense of realism (24). Advantages of AR training applications over conventional training have been recognized including the portability of the devices, personalized feedback to users, and increased user excitement towards the tasks (23). The positive feedback acknowledged from studies using AR for rehabilitative training suggest that AR may lead to increased prosthesis acceptance, although this was beyond the scope of this study and should be a topic of future research.

The present study has several strengths; the AR training game, *ARm-Strong,* provides users a novel experience, overlapping the virtual and real worlds in a first-person view which enhances the practicality of the training.

The AR-INT group may have experienced a learning effect, which is an inherent benefit of the training and shows that motor learning was achieved. The game experience was regarded as engaging and engrossing, which are concepts that influence adherence and improved outcomes of rehabilitation (26).The game used in this study can be expanded upon by adding more features, such as adding additional “levels” of prosthetic training, such as flipping and rotating the cups (which involves increased range of motion with the prosthetic).

The limitations of this study include the use of the same prosthetic device for all participants, regardless of handedness. Amputees are fitted a customized prosthesis to meet their individual needs which was not possible in the present study, although the harness was adjusted to accommodate participants. Additionally, the use of a bypass device does not directly translate to the experience of upper limb amputees, which is an aspiration for future direction. The three-session intervention protocol was based off of the results by Huinink et al. (2016), who found that body-powered bypass prosthesis users were significantly quicker at operating a prosthesis after three training sessions (40). While increased functional performance was observed in the present study after three training sessions, there was no follow-up assessment to determine the long-term effects of training which could be a consideration for future research. The AR game itself could incorporate more realistic scenes to improve the highest level of total immersion as indicated by

ARI scores, although participants in this study still felt engaged and engrossed by the game.

Conclusion

This study demonstrates that AR prosthetic training improves functional performance in individuals using a bypass prosthesis. This type of training provides users with a unique and engaging experience which can promote ongoing utilization. These findings could impact prosthetic training for amputees, by increasing motivation and thereby adherence to using their device. Developing effective mechanisms to enhance prosthesis acceptance is essential so that prosthesis users can achieve tasks in their daily life.

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CHAPTER 3 SUMMARY

Prosthetic training is essential for upper extremity amputees to adapt to their new lifestyle, using a prosthesis to interact with the world. Amputees are consistently unsatisfied with the quality of their devices and often feel that they do not receive beneficial training (Pezzin et al. 2004). Thus, researchers have conducted studies using game-based approaches to prosthesis training, aimed at improving physical function and user satisfaction.

Augmented reality and virtual reality technologies are influencing the setting of rehabilitation, specifically because they are new and engaging experiences for patients compared to traditional therapies (Denche-Zamorano et al. 2023). When comparing these different technological applications, AR offers real-time feedback and a sense of immersion in both the real and virtual worlds simultaneously, unlike with VR (Venkatesan et al. 2021). In a study by Anderson and Bischof (2014), participants reported greater interest and competency, and decreased amount of effort and pressure after engaging with an augmented reality interface compared to a virtual game for myoelectric prosthesis training. Similarly, the present study determined the effectiveness of a novel AR prosthesis training game and found that users were highly engaged and engrossed. Studies using AR for myoelectric prosthesis training are based on the control of a virtual prosthesis; the present study is among the first to demonstrate AR hand-tracking capabilities while using a prosthesis, allowing participants to more directly interact with virtual gaming elements.

Additionally, this study was unique in that it was the first study to use the AR game, *ARm-Strong,* which is intended for upper extremity prosthesis training. Upon interacting with the *ARm-Strong* game, participants demonstrated greater efficiency to control the bypass device. The *ARm-Strong* game has great potential, as many additional features can be added to increase the difficulty and enhance motor learning. While the game has already been received as an engaging and motivating experience, it has the potential to incorporate greater immersive elements.

Another advantage of this study was the use of valid and reliable outcome measures; the Jebsen Hand Function Test is used in occupational and physical therapies for upper extremity rehabilitation and can reveal real improvements in function. Lastly, the Augmented Reality Immersion questionnaire which is specifically designed to assess the effectiveness of AR applications.

3.1 Summary of project findings

The results of the manuscript in Chapter 2 found that individuals improved across sessions, when receiving AR prosthetic training and transfer of skills improved their motor function as assessed by performing tasks of daily living. There was not a significant difference in functional performance between those who did and did not receive training, although those who received training performed the task at a faster rate. The AR training was engaging and engrossing to participants during gameplay although the sense of immersion was significantly lower than that of engagement or engrossment.

3.2 Project limitations

At baseline, the control and intervention groups had significantly different performances related to the functional assessment. Thus, an interaction could not be observed. One individual’s data could not be used for the analyses performed in this study due to inability to complete the training protocol. This suggests that the AR protocol may be difficult for some users. The bypass device used in this study does not directly translate to the function and use of a prosthesis by amputees, however, bypass devices are often used to simulate prosthetic function. The prosthetic was described as uncomfortable by some users, although they did not feel they could not complete any part of the intervention due to the discomfort. There is little consistency in the amount of training necessary for prosthesis users since there is variability in the type of device used and the time since prosthesis fitting; participants received three sessions of training using the bypass prosthesis with the AR game, which may not be enough exposure to attain optimal functional performance. However, it has been noted that the quality of training received is more influential to physical and cognitive outcomes achieved compared to the quantity of training (Salminger et al. 2022).

3.3 Future directions

Whether prosthesis acceptance rates are improved by novel AR prosthetic training game, *ARm-Strong,* is unknown. Improvements in function and engagement during AR training was observed, suggesting users may adhere to this type of therapy for long-term device use. Expanding upon the current game to incorporate additional elements of traditional prosthetic training may also be worthy of future investigation. Future study designs should consider that the control group receive traditional prosthesis training so that the effects of virtual cup-stacking be compared to real cup-stacking. The control group would then have an equal number of interactions with the prosthesis, thereby enhancing the internal validity of the study. Lastly, it is important to test this system on amputees and different types of prostheses, which poses a wide range of future direction in research endeavors.

APPENDIX A. ABBREVIATIONS

AR	augmented reality
CON	control group
AR-INT	augmented reality intervention group
JHFT	Jebsen Hand Function Test
VR	virtual reality

APPENDIX B. SUPPLEMENTAL FIGURES

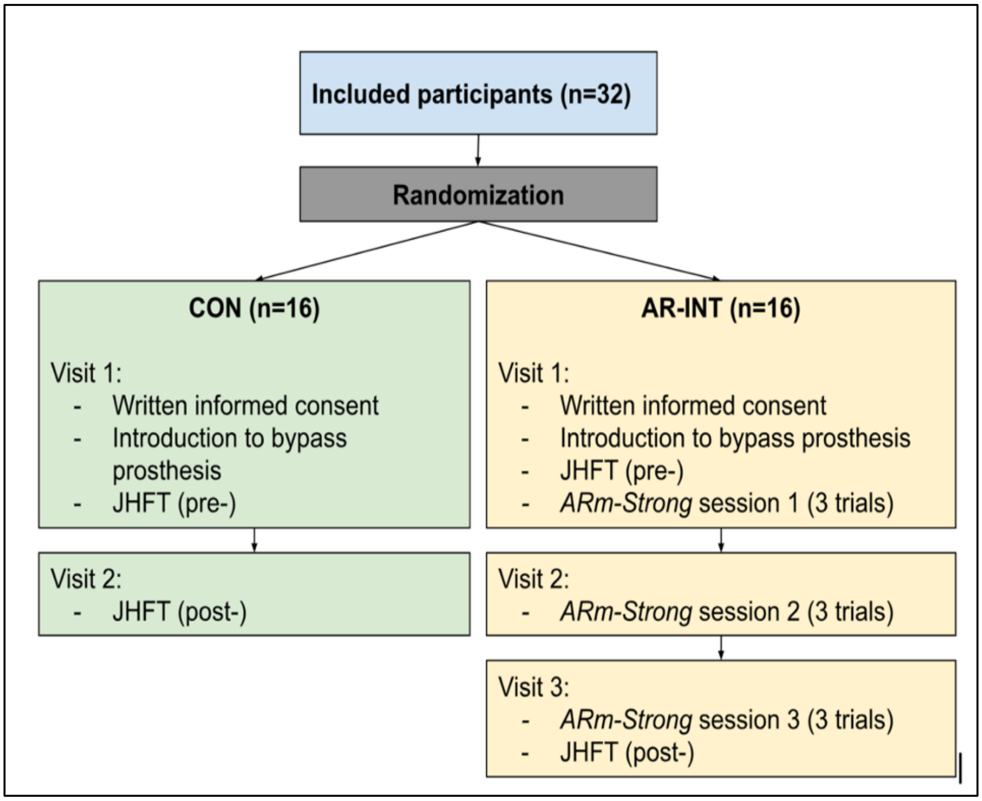

Figure 3 Experimental study design

ARm-Strong refers to the AR training
JHFT=Jebsen Hand Function Test

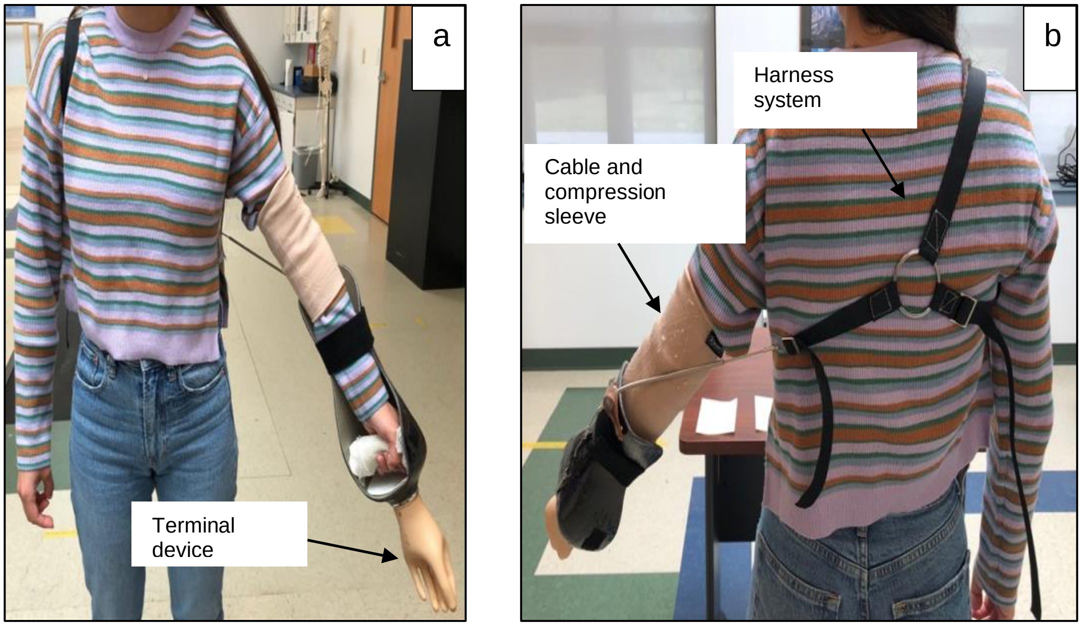

Figure 4 Orientation of the bypass prosthesis on a participant

(a) Anterior view; (b) Posterior view

Figure 5 Performance of the card-turning task of the JHFT using a bypass prosthesis.

A participant is wearing the bypass prosthesis oriented on their left arm. They are instructed to complete a seven-task functional assessment using the prosthesis only. The card-turning task asks that individuals turn five, 5x7 index cards over on a table in order from right to left. The time to successfully complete the task is recorded.

JHFT=Jebsen Hand Function Test

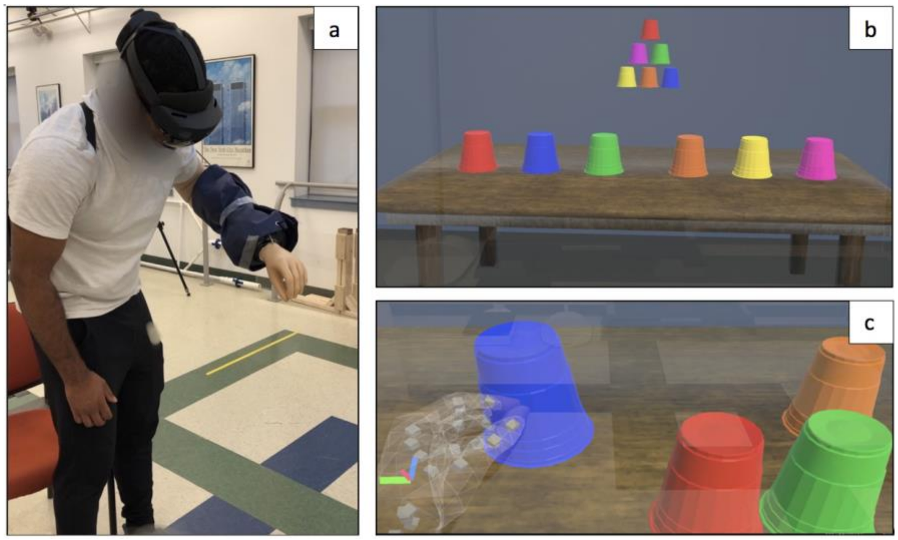

Figure 6 ARm-Strong prosthetic training game

(a) Participant wearing the bypass prosthesis and Microsoft HoloLens2 headset to play the AR training game, ARm-Strong; (b) ARm-Strong game setup when launching the app. Participants stack the cups on the table to match the configuration depicted in the pyramid scheme; (c) A Participant grasping a virtual blue cup using the bypass device

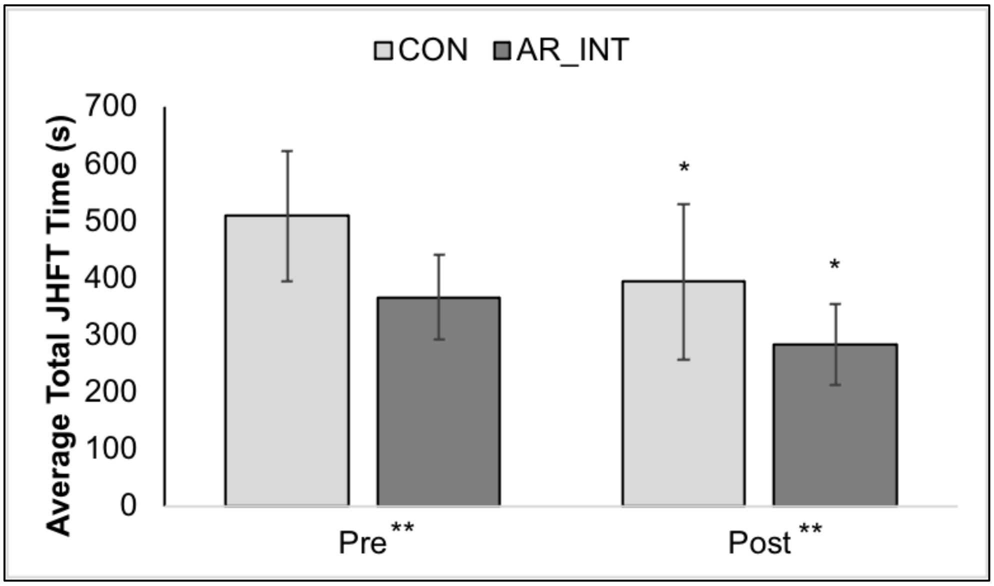

Figure 7 Mean ± SD of average total JHFT times assessed pre- and post-intervention

Both groups (CON and AR_INT) significantly improved in their time to complete the JHFT from pre- to post- assessment. The AR_INT group was significantly faster at completing the JHFT compared to the CON group, at both assessment time points.

Faster time (in seconds) indicates better performance.
*=significant main effect of time, p<0.05
**=significant main effect of groups, p<0.05
JHFT=Jebsen Hand Function Test; SD=standard deviation;
CON=control group; AR_INT=augmented reality intervention group

Figure 8 Correlation between change in JHFT and change in ARm-Strong performance

A change in ARm-Strong performance is moderately correlated with a change in JHFT performance. Participants who completed the ARm-Strong game faster also exhibited a more efficient time to complete the functional assessment, the JHFT.

JHFT=Jebsen Hand Function Test

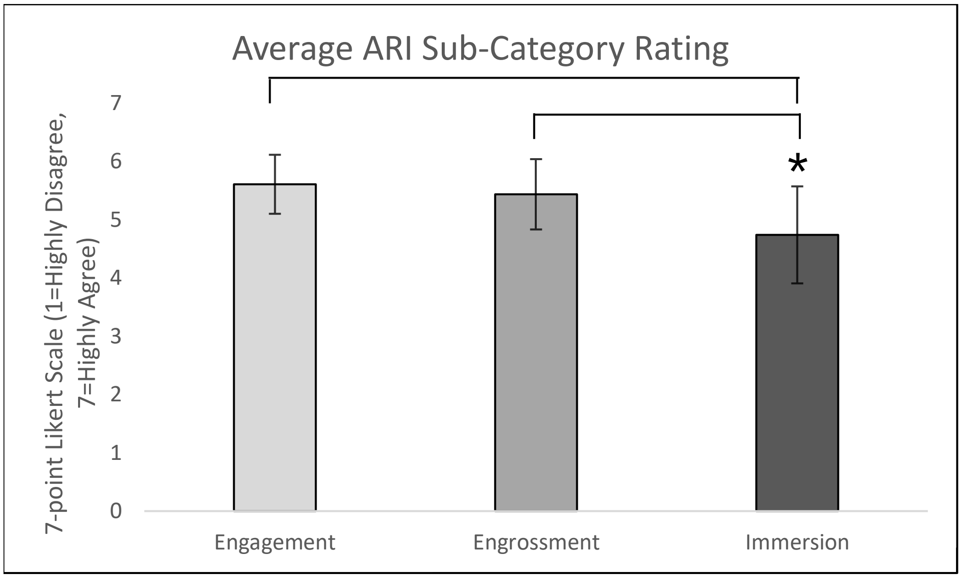

Figure 9 Average rating for each subcategory of the ARI questionnaire

The 21-item ARI questionnaire has questions that pertain to one of three sub-categories: engagement, engrossment and immersion. Engagement is seen as the lowest level of interest in an experience, whereas immersion is the highest level of captivation an individual can attain. Individuals who completed AR training rated their level of agreement for each question. The average ratings for each sub-category were deciphered, indicating that users felt similarly engaged and engrossed in the AR training, and did not feel as immersed.

ARI=Augmented Reality Immersion
AR=Augmented reality
*=significant difference $p<0.05$

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