The Development of a Platform Interface With the Use of Virtual Reality to Enhance Upper-Extremity Prosthetic Training and Rehabilitation

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The Development of a Platform Interface With the Use of Virtual Reality to Enhance Upper-Extremity Prosthetic Training and Rehabilitation

by

Ashley D. Knight

A dissertation submitted in partial fulfillment of the requirements of the degree of Doctor of Philosophy Department of Chemical and Biomedical Engineering College of Engineering University of South Florida

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Keywords: Kinematics, Biomechanics, Amputee, Motion-Analysis, Optimal-Model

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DEDICATION

I dedicate this dissertation to honor the life and memory of Trey Haines. The abundant amounts of love, support, and encouragement he provided me my first couple years in the doctoral program, lasted long after he deceased, giving me the motivation I needed to complete this dissertation, for him. I am forever thankful for his great love and support.

I would also like to dedicate this dissertation to my parents, Jeff and Jill, and my sisters, Chelsea and Natalie. I would not have been able to complete this dissertation without their constant love and support throughout the entire process.
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This dissertation focuses on the investigation and development of an effective prosthetic training and rehabilitation platform with the use of virtual reality to facilitate an effective process to return amputees to the highest level of independence and functioning possible. It has been reported that approximately 10 million people live with a limb loss worldwide, with around 30% being an upper-extremity amputee. The sudden loss of a hand or arm causes the loss of fine, coordinated movements, reduced joint range of motion (ROM), proprioceptive feedback and aesthetic appearance, all which can be improved with the use of a prosthesis and proper training. Current literature has shown prosthetic devices to provide limited function to users in a variety of areas including hand operation, functionality and usability, all which could be improved with proper rehabilitation and training. It has been exhibited that a large percentage of amputees abandon or reject prosthesis use mostly due to limited function and lack of training or knowledge of the device. It has been reported that untrained amputees will adjust their body in an awkward or compensatory body motion rather than repositioning a joint position while performing a task with a prosthetic device. This causes misuse and improper function that has been shown to lead to significant injuries. An effective prosthetic training and rehabilitation regime would be advantageous in returning the patient to the highest level of independence and functioning possible, with proper use of their prosthetic device. A successful training and rehabilitation program would allow an amputee to improve their ability to perform with optimal motion and use all prosthetic control capabilities.
This dissertation describes the development of a stick figure model of the user’s motion in real-time and a character avatar animating the individualized optimal goal motions. The real-time model directly corresponds to the user’s motion, with the option to have the character avatar simultaneously animating an optimal goal motion for the user to follow. These were implemented into the Computer Assisted Rehabilitation Environment (CAREN) system (Motek Medical, Amsterdam, Netherlands) to provide real-time visual feedback to the users while performing specified training and rehabilitating tasks. A ten camera Vicon (Oxford, UK) optical motion captured system was used with the CAREN system capabilities to track body and upper extremity prosthetic segments during range of motion (ROM), activities of daily living (ADL), and return to duty (RTD) tasks, with and without the use of the virtual reality visual feedback. Data was collected on five able-bodied subjects and five subjects with a unilateral transradial amputation using their personal prosthetic device.

Through investigation and development, a preferred and effective way to display the visualization of the real-time and optimal models were revealed. Testing the subjects with and without the virtual reality visualization, exhibited the effectiveness of providing visual feedback. Results showed subject’s to have improved positing, movement symmetry, joint range of motion, motivation, and overall an improved performance of the series of tasks tested. With the integration of the optimal model visualization, real-time visual feedback, and additional CAREN system capabilities, upper-extremity training and rehabilitation techniques were shown to enhance with the use of virtual reality, through improved task performance, and functional advances. The results of this dissertation introduce an alternative means for clinicians to consider for effectively rehabilitating and training upper-limb amputees.
Findings of this dissertation sought to provide useful guidelines and recommendation to aid in the development of a small-scale adaptable option for rehabilitation practitioners and at home use. The techniques investigated in this study could also be applicable for lower-limb amputee, post-stroke, traumatic brain injury, poly-trauma, and other patients with physically limiting disabilities. The techniques investigated in this study are expected to aid in the development of training and rehabilitation procedures for a variety of patient populations, to enhance the effectiveness and assist in improving the overall quality of life of others.
CHAPTER 1: INTRODUCTION

The objective of this dissertation was to investigate and develop an effective prosthetic training and rehabilitation platform, with the use of virtual reality, to return patients to the highest level of independence and functioning possible. This was done through the implementation of a real time model and the animation of an individualized optimal goal motion into the Computer Assisted Rehabilitation Environment (CAREN) system (Motek Medical, Amsterdam, Netherlands) to provide real-time visual feedback to the users while performing specified training and rehabilitating tasks. A Vicon optical motion captured system was used with the CAREN system capabilities to track body and upper extremity prosthetic segments during range of motion (ROM), activities of daily living (ADL), and return to duty (RTD) tasks with and without the use of the virtual reality visual feedback. The following list describes the specific aims of this research.

1. Provide a real-time model of the user’s motion to display real-time visual feedback to the users, and incorporate an individualized optimal motion model (optimized per capabilities of the subject) into a virtual reality system.

2. Determine the most effective way to display the visualization of the real-time and optimal model. Investigate and test the optimal animated model visualization at
various times (before and during task), and at various positions (in front, overlaid, and offset from real-time model).

3. Determine if the visual feedback using virtual reality is effective for training and rehabilitating upper-limb prosthesis users by testing with and without the use of virtual reality therapy.

4. Gain insight to provide useful guidelines and recommendations to aid in the development of small-scale adaptable options for rehabilitation practitioners and at home use.

It was hypothesized that gaining a better understanding of upper extremity prosthetic training and rehabilitation techniques would lead to a more effective procedure to increase independence and functionality of prosthetic users. Allowing a patient to view their motion in real-time along side an optimal motion, while providing quantitative measures with visual feedback, could significantly increase training and rehabilitation effectiveness for upper-limb prosthetic users.

A simulation tool consisting of a robotic human upper body model (RHBM) was incorporated into the virtual reality visualization. The RHBM was used to predict functional motions, and integrated modules for aid in prescription, training, comparative study, and determination of design parameters of upper extremity prostheses. The RHBM is a 25 DoF bilateral upper body model with subject specific kinematic and control parameters used to accurately predict the subjects’ motion during certain activities of daily living [1].
The overall idea of this project is to incorporate the RHBM predictive motions with the optimal model avatar, the real time model, a graphical user interface (GUI), and virtual reality visualization. This is to allow for the input of individualized parameters to aid in an effective process to prospectively determine patient outcomes while evaluating performance to better train and rehabilitate protheses users. Figure 1.1 describes the overall process of this project. Appendix G describes the overall project in further details.

![Flow Chart Describing the Overview of the Entire Project](image)

As shown, the operator, physician, or therapist would receive the patient specific parameters to input into the database to create the RHBM and then develop the optimal model avatar. The anatomical measurements of the patient would be entered into the system to create an accurate model of the patient’s motion in real-time. The real-time and optimal model avatar would then be fed into the virtual reality interface to allow for real time visual feedback to the patient and operator. The real-time visual feedback provided by the virtual reality visualization would then allow for the patient to adjust their positioning if needed, and improve their motions.
in real time to perform closer to the optimal motion. This also allows for the operator to see where adjustments need to be made and interpretation of the results can be given to the patient to encourage improvements to be made. The adjustments and improved motions are tracked by the real-time model and simultaneously shown through the virtual reality visual feedback. This process is thought to significantly improve patient performance to allow for enhanced training and rehabilitation results, specifically for upper-limb prosthetic users.

It has been noted that training with virtual reality is particularly valuable for upper-limb prosthetic users [2]. Motek Medical’s computer assisted rehabilitation environment (CAREN) system has been shown to be an effective prosthetic training and rehabilitation tool for patient assessment and improvements for a quick return to active duty or the civilian community [3]. CAREN is a multimodal system consisting of a 10-camera real time motion capture system (Vicon, Nexus, Englewood, CO), a 6 degree-of-freedom (DOF) hydraulic base, equipped with a double-belted instrumented treadmill, and a 180-degree cylindrical screen projection system to allow for a virtual reality immersive environment. It is thought that using the CAREN system capabilities, while providing a real-time model and optimal goal motion, will enhance training and rehabilitation for upper limb prosthetic users, through improved joint range of motion and movement symmetry. The objective of this research project is to investigate the advantages of using virtual reality visual feedback for upper limb prosthetic training and rehabilitation to eventually lead into the development of useful guidelines and recommendations to aid in the advancement of small-scale adaptable options for rehabilitation practitioners and at home use. This could be clinically significant by advancing knowledge and understanding within the field of upper limb prosthetic training and rehabilitation while introducing an adaptable way to increase effectiveness and greatly impact the future of prosthetic users.
1.1 Epidemiology and Need

Approximately one in every 160 Americans are currently living with an amputated limb, with that number predicted to double by 2025 [4]. There are nearly 2 million people with a limb loss in the United States, with around 50,000 new amputations occurring each year [5,6]. According to the National Center for Health Statistics, the ratio of upper limb to lower limb amputation is 1:4, with the most prominent causes of upper extremity amputation, in order of incidence being, trauma, including war related injuries, diseases, and congenital limb deficiencies [6,7]. Upper extremity amputation due to trauma and war related injuries make up 77% of the upper limb amputated population, making it the major cause of hand or arm loss [7]. Of the estimated 1.6 million persons with amputation in the United States in 2005, 35% are living with loss or deficiency of the upper extremity [5]. Although approximately 56,000 people live with the loss or deficiency of an upper limb in the United States, a large percentage are reported to abandon or reject prosthesis use [5,8]. Documented rejection and non-wear rates of prostheses vary from 44 to 75 percent for upper-limb amputees, with rejection rates of myoelectric devices to be the highest [9,10,11]. Rejection of prosthesis use was found mostly due to limited function and usability, as well as, lack of training and knowledge of the different devices, proving the rehabilitation and training to be extremely important for device success [10,11]. One study reported prosthesis rejection rates for upper extremity prostheses of up to 50% and that only about 25% would rate themselves as excellent prosthesis users due to lack of training and rehabilitation with the device [11]. Amputees often choose not to wear prostheses due to marginal performance or may settle for a prosthesis that offers only cosmetic improvement, but lacks function due to poor training and comfort with the device [11].
The sudden loss of a hand or arm causes the loss of fine, coordinated movements of the upper limb, reduced joint range of motion, tactile sensation, reduced proprioceptive feedback and aesthetic appearance, all which can be improved with the use of a prosthesis [12]. After proper postoperative therapy, wound healing, and pre-prosthetic therapy, a patient can be successfully fitted for a prosthesis. In order to maximize the functional potential of the prosthesis and support prosthetic control motions, it is essential for the patient to maintain scapular, glenohumeral, forearm, and elbow joint range of motion [12]. Maintenance of joint range of motion, increasing upper-limb muscle strength, and gaining maximal functional independence are all crucial elements to ensure patient success with the prosthesis, making the training and rehabilitation phase significantly important. A successful training and rehabilitation program allows the patient to return to their daily life duties at the most functional independence possible with the use of all prosthetic control capabilities. Since a successful training and rehabilitation program is essential, the demand for advanced rehabilitation techniques is substantially high, with a need for advanced rehabilitative interventions to optimize prosthetic training for amputees [13]. A significant need for more studies on military service members with amputations are in high demand in order to develop innovative training and therapeutic approaches to advance rehabilitation techniques, especially for higher functioning amputees with the goal of returning to duty (RTD) in the military or the civilian community [14,15].

1.2 Prosthetic Training and Rehabilitation Methods

Training and rehabilitation have shown to be significantly important and crucial to successful prosthetic function. Amputees with proper training have been shown to perform tasks with their prosthesis in a skillful, efficient manner, exceeding the performance of untrained amputees [16]. Current methods include patient education, evaluation, ROM assessment,
strength testing, ADL assessment, followed by specific ROM, ADL, and strengthening exercises [17]. The exercise program and specific tasks performed are designed according to the abilities and needs of the patient. The strengthening exercises focus on areas of weakness and especially muscle groups important to prosthetic harnessing and operation. Specific muscles deemed as potential myocytes for myoelectric prosthetic operation are also important to incorporate into strengthening exercises [17]. Current methods primarily focus on the initial evaluation and assessment with a brief demonstration of proper movement. In some cases users never receive any physical therapy where training of proper device use is often overlooked [18,19]. In some cases patients are even trained over the phone and learn how to use the device on their own with no real practice of proper movements and exercises. In addition to proper exercises, it is important to have a maintenance plan set in place where the user can continue to practice and improve movements [17]. In most cases this phase is left to the patient to perform on their own with no real direction or motivation to continue after the initial evaluation.

1.3 Previous Research

1.3.1 Upper Extremity Prosthetics

The importance of prosthetic training and rehabilitation has shown to be significant with great benefits for a person using an upper-extremity prosthesis. Training has a positive effect on the level of function and efficiency of prosthesis use by encouraging the patient to perform with the best, most optimal and ideal movement with appropriate position to complete a task [16]. Extensive knowledge of a prosthetic device, along with an effective training and rehabilitation method, significantly reduces the rate of prosthesis rejection and greatly improves the level of function [10,20]. Proper training and rehabilitation can greatly influence the level of function and independence a user may have. In a study involving 26 upper-limb amputees, 90 percent of the
subjects trained, used their prosthesis in a functional way; whereas only 50 percent of the subjects who were untrained used their prosthesis functionally [21,22]. These results along with others showed training to greatly impact the level of prosthetic function [6,16,21].

1.3.2 Training and Rehabilitation

In prosthetic training, it is especially important to maintain adequate range in joints of the upper limb. Maximum extension and flexion of the glenohumeral and elbow joints as well as supination and pronation of the forearm are crucial movements for subsequent function when using a prosthetic terminal device [12]. Training a prosthetic user to demonstrate proper movement and reduced compensatory body motions is essential in the training and rehabilitation process. Often amputees adjust their body in an awkward or compensatory body motion rather than repositioning a joint position [12]. It has been shown that using a mirror can be effective in assisting the amputee to see the way their body is positioned for prosthetic training or even to reduce phantom limb pain [12,23,24]. This has lead to the idea that virtual reality environment training, while showing the users their real time motion, could be advantageous in prosthetic training and rehabilitation.

1.3.3 Virtual Reality Training and Rehabilitation

The method of reducing phantom limb pain with a visual illusion of a second sound limb began with the use of mirrors and evolved into virtual reality therapy [24,25]. An immersive virtual reality system was successfully used to reduce phantom upper limb pain with the use of a data glove and motion tracking sensors attached to the wrist and elbow joints [25]. A full virtual body representation was provided for participants with the amputated limb being the transposed movement of the participant’s intact limb [25]. The amputee was able to virtually visualize on a screen or through a head mounted display, as if both limbs were moving simultaneously.
In recent studies, virtual reality has been used as an effective tool for a variety of upper limb rehabilitation and training applications including, phantom limb pain, rehabilitation following stroke, arm motor rehabilitation, DEKA Arm system training and optimization, designing and fitting prosthetic limbs, and prosthetic training and development with EMG or myoelectric control. Virtual reality has been shown to be an effective tool to improve training and rehabilitation for the military by reducing the errors and struggle to balance testing conditions that emulate the real world with the control and precision of a laboratory setting [26].

A variety of studies have shown great improvements in task performance with the use of virtual reality [8, 24-33]. A successful training program incorporates practice and feedback elements necessary for maximal motor recovery. Providing feedback on performance is an effective technique to enhance training and rehabilitation of upper limb movements [26-29].

One study in particular provided arm impaired, post stroke patients, with a virtual prerecorded trajectory of the proper movement and object placement while virtually performing motor tasks emulating the therapist’s prerecorded movement [29]. The trajectory of the prerecorded movement was displayed in the background of the virtual scene to allow the subject to perceive and adjust their movement accordingly. By providing a means of comparison to the user, adjustments and improvements in motor impairments were quickly and effectively made [29]. Improvements in movement could further be assessed through motion analysis and joint measurements to obtain accurate measurements of the differences between the proper prerecorded trajectory and the patient’s movement, as well as quantitative improvements made between each trial. The idea of providing a trajectory of proper movements could also be beneficial in other training and rehabilitation programs including prosthetics.
In a particular study, artificial neural networks and inferential command schemes were used with the position of the shoulder to predict the desired posture of the elbow and forearm joints during reaching and transporting movements for healthy able-bodied subjects [30]. This produced a predicted trajectory of proper movements successfully used to control a simulated unilateral transhumeral prosthesis in a virtual reality reach and grasp test. The subjects were able to view a virtual human model scaled to replicate their personal dimensions through stereoscopic goggles for a first-person view in the 3D virtual reality environment while successfully training to use a prostheses through predicted movements [30]. A noninvasive approach to providing a predicted trajectory would be to incorporate the visualization of an individualized optimal goal motion into the CAREN system. This would provide the user with a virtual visualization of their predicted movement of a specified task. Integrating the predicted model along with a virtual visualization and feedback of the subject’s real time motion would be especially advantageous to prosthetic training and rehabilitation programs. Displaying a real time realistic virtual model while giving visual feedback has been shown to be successful in prosthetic training.

Virtual reality has also shown to play an important role in training patients to operate myoelectric controls, such as with the DEKA Arm, or with electromyography (EMG) control. Resnik and others optimized the DEKA Arm system with a real-time 3-D avatar consisting of the subject’s full torso and head with both upper limbs intact [2,9]. Real time visual feedback was given of the prosthetic controls, providing user dynamics of movement of the arm for each command from the force-sensitive resistors (FSRs) or inertial measurement units (IMUs) foot controls [2]. The user was given a variety of perspectives to view the movement dynamics of their arm with the ability to zoom into particular joints to view where improvements were needed and to familiarize the subjects with motion trajectories of the DEKA Arm. The results showed
virtual reality training to be beneficial for the patients in creating a preexisting mental framework of proper arm movements required to operate a DEKA Arm system [2]. To assess the effectiveness or impact of a virtual reality environment for prosthetic training, results with and without the use of virtual reality should be compared. The speed of learning proper movements and measurements of joint positions can be used to assess the effectiveness of prosthetic training with and without virtual reality to further investigate the benefits.

A study using virtual reality was also developed for designing and fitting prosthetic limbs, where subjects operated a simulated limb to interact with virtual objects through a magnetic motion tracking system and EMG/EEG electrodes [31]. Stereoscopic goggles provided 3D visual feedback with head tracking sensors as part of the head mounted display. Subjects performed common activities of daily living by reaching, grasping, and interacting with virtual objects. The times to complete the tasks and successful/unsuccessful trials were recorded, with the results showing there to be improvements in performance when users were given realistic visual feedback provided by the virtual reality environment [31]. The use of virtual reality environments for prosthetic training and rehabilitation has shown to provide significant improvements to prosthetic users.

1.3.4 Computer Assisted Rehabilitation Environment (CAREN)

Most of the current research involving the CAREN system is related to evaluating balance and gait training with lower limb amputees and investigating rehabilitation interventions with post-stroke and traumatic brain injury (TBI) patients. Very few, if any, studies are being done strictly on upper limb amputees. Collins et al. completed a systematic literature review on the use of the CAREN system for wounded warrior rehabilitation and research, reporting no
studies on upper-limb amputees and concluding that more research needs to be performed to evaluate its effectiveness as a rehabilitation tool and method across all patient populations [34].

One paper discussing advanced rehabilitation techniques reported using the CAREN system to successfully return individuals to active duty by helping them obtain the highest level of independence and functioning possible through gait and motion analysis at the Walter Reed National Military Medical Center (WRNMMC) [13]. The CAREN system was reported to be an effective tool to work on multiple rehabilitation domains simultaneously, such as balance, ambulation, cognition, and falls recovery, all while providing visual feedback to the patients, therapists and prosthetists [13]. The CAREN system was described as a rehabilitation tool for upper, lower, and multi-limb amputees, but no results on the patients were reported.

Most studies involving upper-limb rehabilitation and training using the CAREN have been on post-stroke and TBI patients. The CAREN system platform integrated with a head mounted display, cyber glove, and a motion capture system was used to provide a real-time 3D hand, arm, and body position data used for post-stroke arm rehabilitation to incorporate practice and feedback elements necessary for maximal motor recovery [28]. Subjects were asked to point to specific points in the virtual environment. Movement time, precision, and trajectory smoothness were all shown to improve when the participant was given feedback on motor behavior and performance through the virtual environment, proving to enhance motor learning [18]. Other studies also looked at post-stroke patients were they pointed at specific points and were tracked using the CAREN virtual reality and motion analysis showing the CAREN to be an effective tool [29,35,36]. Another study using the CAREN system but involving TBI patients, looked at vestibular balance and cognitive performance during a variety of scenarios [37]. Results lead to the conclusions that users can benefit from using the CAREN system in addition
to or in place of traditional clinical therapies with the ability to simulate more dynamic environments and the ability to dual task, challenging the patient’s whole body physically and cognitively [37]. Most of the other studies found using the CAREN system focused on gait and balance with TBI patients and lower-limb amputees.

1.4 Gap in Knowledge

In summary, most of the prior work done using the CAREN system as a rehabilitation and training tool involved post-stroke, TBI, or lower-limb amputees focusing on gait and balance parameter, with no focus on upper-limb biomechanics. The only studies found involving upper-limb rehabilitation using the CAREN system was with post-stroke patients where they focused on speed, precision, and movement trajectory when reaching for a virtual point [28,29,35,36].

Previous work done on the CAREN system with lower and upper-limb amputees showed the CAREN system to be an effective tool to return patients to active duty [13]. Other studies not involving the CAREN system have shown virtual reality to be an effective tool in training and rehabilitating upper-limb amputees with using their prosthesis [24-33]. From the results and the previous work found, it is evident that more research needs to be performed to evaluate the effectiveness of virtual reality as a rehabilitation tool and method for upper-limb amputees.

This dissertation sought to fill some of these gaps in knowledge relating to upper-limb prosthetic training and rehabilitation. A biomechanical analysis was evaluated for amputees performing specific tasks with and without the use of virtual reality visualization. A new training platform was designed and developed to incorporate a real-time and optimal motion model for the amputee to visualize while performing the tasks with the use of virtual reality. Effectiveness of the use of virtual reality was evaluated and assessed. The findings provided guidelines and
recommendations to aid in the development of small-scale adaptable options for practitioners and at home use to positively impact upper-limb prosthetic training and rehabilitation procedures.
CHAPTER 2: DEVELOPMENT OF REAL-TIME KINEMATIC MODEL

For this study, motion analysis was used to track the subject’s movement and orientation of specific joints and body segments throughout the trials. Motion capture is a technique to gather precise, reliable data for any motion analysis application by recording the movement of objects or people. The motion analysis application used in this study captured and recorded the motion of body segments to evaluate joint angles through tracking software with infrared cameras and passive reflective markers. Ten Vicon (Oxford, UK) infrared cameras were used to track the positions of the passive reflective markers placed at specific locations on the subject’s body. Each of the ten infrared cameras captures the 2D position of each marker within the camera frame. With the use of the Vicon Nexus software, triangulation is used to determine the 3D marker position from the intersection of the camera frames into the lab frame. Each individual marker must be in the capture frame of two or more of the cameras in order to locate the 3D position. The local XYZ coordinates are captured for each marker throughout the recorded trial to create motion data. Motion analysis was chosen for this study to capture the movement of segments and joints of amputee patients who used a prosthetic device to perform specified tasks with and without the use of virtual reality. The motion analysis marker set used was the Plug-in-Gait full body model developed by Vicon.

2.1 Motion Analysis Model

The model was adapted from the pre-determined marker set developed for the Vicon Plug-in-Gait full body model. Markers and segments were determined to allow for the rotation and translation about all axes to be captured. The marker trajectories were captured in real-time
to generate virtual marker trajectories that represented kinematic and kinetic quantities, as well as representations of the modeled segments. The modeling stage of the full body model internally consisted of four interdependent models. The four models included; a kinematic lower body, a kinematic upper body, and kinetic lower and kinetic upper bodies. The lower bodies were from the pelvis to the feet, and the upper bodies were from the pelvis to the head and arms. The kinematic models were responsible for the definitions of the rigid body segments, and the calculations of joint angles between these segments. The two kinetic models then applied masses and moments of inertia to the segments to allow for calculations of segments reactions [38]. The markers were placed at specific points on the participant to properly define the segments and accurately model the joints in order to capture joint movements.

2.1.1 Full Body Marker Set

The marker set consisted of 39 passive reflective markers placed at specific points on the participant’s body. The full marker set was taking from the Vicon Nexus manual [38] and is depicted below in Figure 2.1. Proper placement of each marker, as demonstrated in Figure 2.1, was crucial for proper representation of the subject’s motion as the real-time model and correct joint angles measurements.

The Plug-in Gait full body marker set consisted of four head markers, five torso, four pelvis, twelve lower extremity, and fourteen upper extremity markers. Proper placements of the markers were crucial to accurately model the joints and segments of the participant. The description of the marker placement is shown below in Table 2.1.
Figure 2.1 Plug-in-Gait Full Body Marker Set (This image is from [38], public domain image)
## Table 2.1 Marker Placement Descriptions

<table>
<thead>
<tr>
<th>Label</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head Markers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LFHD</td>
<td>Left front head</td>
<td>Located approximately over the left temple</td>
</tr>
<tr>
<td>RFHD</td>
<td>Right front head</td>
<td>Located approximately over the right temple</td>
</tr>
<tr>
<td>LBHD</td>
<td>Left back head</td>
<td>Placed on the back of the head, in line with left front head marker</td>
</tr>
<tr>
<td>RBHD</td>
<td>Right back head</td>
<td>Placed on the back of the head, in line with right front head marker</td>
</tr>
<tr>
<td><strong>Torso Markers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>Spinous Process of the 7&lt;sup&gt;th&lt;/sup&gt; cervical vertebrae</td>
<td>Located approximately over the left temple</td>
</tr>
<tr>
<td>CLAV</td>
<td>Clavicle</td>
<td>Jugular Notch where the clavicle meets the sternum</td>
</tr>
<tr>
<td>STRN</td>
<td>Sternum</td>
<td>Xiphoid process of the Sternum</td>
</tr>
<tr>
<td><strong>Pelvis Markers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LASI</td>
<td>Left ASIS</td>
<td>Placed directly over the left anterior superior iliac spine</td>
</tr>
<tr>
<td>RASI</td>
<td>Right ASIS</td>
<td>Placed directly over the right anterior superior iliac spine</td>
</tr>
<tr>
<td>LPSI</td>
<td>Left PSIS</td>
<td>Placed directly over the left posterior superior iliac spine</td>
</tr>
<tr>
<td>RPSI</td>
<td>Right PSIS</td>
<td>Placed directly over the right posterior superior iliac spine</td>
</tr>
<tr>
<td><strong>Lower Extremities Markers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LKNE</td>
<td>Left knee</td>
<td>Placed on the lateral epicondyle of the left knee</td>
</tr>
<tr>
<td>LTHI</td>
<td>Left thigh</td>
<td>Placed on lower lateral surface of left thigh- lower than right side</td>
</tr>
<tr>
<td>LTHR</td>
<td>Left thigh</td>
<td>Placed on lower lateral surface of left thigh- higher than right side</td>
</tr>
<tr>
<td>LANK</td>
<td>Left ankle</td>
<td>Placed on left lateral malleolus in line with the transmalleolar axis</td>
</tr>
<tr>
<td>RTAE</td>
<td>Left toe</td>
<td>Placed on left second metatarsal head, mid-foot side of equinus break</td>
</tr>
<tr>
<td>LHEE</td>
<td>Left heel</td>
<td>Placed on left calcaneous at the same height as the toe marker</td>
</tr>
<tr>
<td>RKNE</td>
<td>Right knee</td>
<td>Placed on the lateral epicondyle of the right knee</td>
</tr>
<tr>
<td>RTHI</td>
<td>Right thigh</td>
<td>Placed on lateral surface of right thigh- higher than left side</td>
</tr>
<tr>
<td>RTOE</td>
<td>Right toe</td>
<td>Placed on right second metatarsal head, mid-foot side of equinus break</td>
</tr>
<tr>
<td>RHEE</td>
<td>Right heel</td>
<td>Placed on right calcaneous at the same height as the toe marker</td>
</tr>
<tr>
<td><strong>Upper Extremities Markers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSHO</td>
<td>Left shoulder</td>
<td>Placed on left Acromio-clavicular joint</td>
</tr>
<tr>
<td>LUPA</td>
<td>Left upper arm</td>
<td>Placed between left elbow and shoulder markers, higher than right side</td>
</tr>
<tr>
<td>LELB</td>
<td>Left elbow</td>
<td>Placed on left lateral epicondyle approximating elbow joint axis</td>
</tr>
<tr>
<td>LFRA</td>
<td>Left forearm</td>
<td>Placed between left wrist and elbow markers, lower than right side</td>
</tr>
<tr>
<td>LFIN</td>
<td>Left fingers</td>
<td>Placed on dorsum on left hand, just below head of second metacarpal</td>
</tr>
<tr>
<td>RSHO</td>
<td>Right shoulder</td>
<td>Placed on right Acromio-clavicular joint</td>
</tr>
<tr>
<td>RUPA</td>
<td>Right upper arm</td>
<td>Placed between right elbow and shoulder markers, lower than left side</td>
</tr>
<tr>
<td>RELB</td>
<td>Right elbow</td>
<td>Placed on right lateral epicondyle approximating elbow joint axis</td>
</tr>
<tr>
<td>RFRA</td>
<td>Right forearm</td>
<td>Placed between right wrist and elbow markers, higher than left side</td>
</tr>
<tr>
<td>RWRA</td>
<td>Right Wrist A</td>
<td>Placed on thumb side of right wrist</td>
</tr>
<tr>
<td>RWRB</td>
<td>Right Wrist B</td>
<td>Placed on pinkie side of right wrist</td>
</tr>
<tr>
<td>RFIN</td>
<td>Right fingers</td>
<td>Placed on dorsum on right hand, just below head of second metacarpal</td>
</tr>
</tbody>
</table>

### 2.2 Segment Definitions

The model used in this study consisted of seven body segments, which included, the head, torso, pelvis, right arm, left arm, right leg, and left leg. The segments were defined by the precise placement of the markers, as described above. The segments were created using an origin and two defining lines. Each segment was defined by an individual origin, where it was centered. The first defining line became the X-axis and the second defining line became the Y-axis. Lastly,
the cross product between the first and second defining lines became the Z-axis. In some cases, in order to satisfy the right hand rule, the direction of the Z axis was switched to the negative cross product of the X and Y axes. The orientations of the axes were used for post processing analysis to properly calculate joint angle measurements. The defined segments and axes are shown below in Figure 2.2.

![Figure 2.2 Full Body Kinematic Model Shown in Vicon Nexus](image)

### 2.2.1 Head

Four markers define the head segment; the left front (LFHD), right front (RFHD), left back (LBHD) and right back of head (RBHD). The front markers are approximately placed over the temples, directly in line and across from each other. The back head markers are placed on the left and right sides on the back of the head, level with the front markers, roughly in a horizontal
plane. The two front markers define the origin, and the scale of the head. The back markers define its orientation. The figure of the head with the axes is shown below in Figure 2.3.

![Figure 2.3 Head Segment](image)

### 2.2.2 Torso

The torso segment was created with five markers and was the base reference for the whole body. The torso is defined by a marker placed on the spinous process of the seventh cervical (C7), one on the spinous process of the tenth thoracic vertebrae (T10), one on the jugular notch where the clavicles meets the sternum (CLAV), one on the xiphoid process of the sternum (STRN), and one placed in the middle of the right scapula defined as the right back (RBAK) marker. The C7 and CLAV markers are laterally in line, and the T10 and STRN markers are in line. All four markers create a plane and the RBAK marker is used to make the model asymmetric to help with the auto-labeling process by distinguishing between the left and right side of the participant. The torso segment in shown in Figure 2.4.
2.2.3 Pelvis

Markers placed on the anterior and posterior superior iliac spine define the Pelvis. Markers are placed directly on the left (LASI) and right (RASI) anterior superior iliac spine, which can be found as the bony projection of the iliac bone as the anterior extremity of the iliac crest of the pelvis. Markers are also placed directly on the left (LPSI) and right (RPSI) posterior superior iliac spine, which are the slight bony prominences that can be felt immediately below the sacro-iliac joints, at the point where they define the pelvic axes. The pelvis segment is shown in Figure 2.5.
2.2.4 Upper Extremities

The upper extremity segments consist of the right and left shoulder, upper arm, forearm, and hand. The left (LSHO) and right (RSHO) shoulder markers are placed on the acromio-clavicular joints on either side. The upper arm markers are placed between the elbow and shoulder markers. The left upper arm (LUPA) marker is placed slightly higher than the right upper arm (RUPA) to again create an asymmetrical model to ensure accurate labeling. The left (LELB) and right (RELB) elbow markers are placed on the lateral epicondyle on both sides to approximate the elbow joint axis. The forearm markers are placed on the lower arm between the wrist and elbow markers. The left forearm (LFRA) marker is placed slightly lower than the right forearm (RFRA) marker. Two markers are placed on both wrists labeled as left wrist A (LWRA), B (LWRB), and right wrist A (LWRA), and B (RWRB). The A markers are placed on the thumb side, and the B markers are placed on the pinkie side. Lastly, the left (LFIN) and right (RFIN) fingers markers are placed on the dorsum of the hand, directly below the head of the second metacarpal. Together these markers create the right and left upper extremity segments, as shown in Figure 2.6.
2.2.5 Lower Extremities

The lower extremity segments consists of the right and left legs and feet. The leg segments are primarily made of three markers, one on the thigh, knee, and tibia. The left thigh (LTHI) marker was placed over the lower lateral surface of the thigh, just below the swing of the hand and the right thigh (RTHI) marker was placed directly in the middle lateral surface of the thigh to create an offset. The thigh markers are used to calculate the knee flexion axis location and orientation. The position of the marker is placed aligned in the plane that contains the hip and knee joint centers and the knee flexion/extension axis. The left (LKNE) and right (RKNE) knee markers are placed on the lateral epicondyle of the corresponding knee. The left tibia (LTIB) marker is placed over the lower lateral surface of the shank to determine the alignment of the ankle flexion axis. The right tibia (RTIB) is placed in the middle of the lateral surface of the shank-bone to once again create an offset from the left side. The tibia markers are placed aligned in the plane that contains the knee and ankle joint centers and the ankle flexion/extension axis. Figure 2.7 shows the marker and segment axes of the lower extremities.
2.3 Joint Angle Calculations

A joint angle is the relative orientation of the local coordinate system of one segment to another segment’s local coordinate system [39]. The unit vectors determined by the position and orientation of the segment defined the local coordinate system. Each segment’s local coordinate system was optimized to determine the joint translation. Segment optimization refers to each segment having six-DOF. Each segment had at least three tracking markers and all six variables that describe its pose; three variable that describe the position of the origin and three variables that describe the rotation about each of the principal axes of the segment local coordinate system. Tracking each segment separately allowed for each segment to be considered for six DOF, where the endpoint of the proximal and distal segments move relative to each other based directly on the recorded motion-captured data.

The position and orientation of each coordinate system was required to determine the relation to another coordinate system. The rotation of one segment to another was the derivation of a joint angle, where joint movement was defined as the orientation of a distal segment relative to a proximal segment to create a rotation matrix. All equations and matrices used in calculations described below were derived from the textbook, *Research Methods in Biomechanics* [39]. The rotation matrix (R) for an XYZ rotation sequence is defined by equation (1), where \( R_x \), \( R_y \), and \( R_z \) are defined below in equation (2).

\[
R = R_zR_yR_x
\]  

\[
R_x = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \alpha & \sin \alpha \\
0 & -\sin \alpha & \cos \alpha
\end{bmatrix},
R_y = \begin{bmatrix}
\cos \beta & 0 & -\sin \beta \\
0 & 1 & 0 \\
\sin \beta & 0 & \cos \beta
\end{bmatrix},
R_z = \begin{bmatrix}
\cos \gamma & \sin \gamma & 0 \\
-\sin \gamma & \cos \gamma & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(2)
The multiplication of these three matrices then results in the rotation matrix R, as shown below in equation (3).

\[
R = \begin{bmatrix}
\cos \gamma \cos \beta & \cos \gamma \sin \beta \sin \alpha + \sin \gamma \cos \alpha & \sin \gamma \sin \alpha - \cos \gamma \sin \beta \cos \alpha \\
-\sin \gamma \cos \beta & \cos \alpha \cos \gamma - \sin \gamma \sin \beta \sin \alpha & \sin \gamma \sin \beta \cos \alpha + \cos \gamma \sin \alpha \\
\sin \beta & -\cos \beta \sin \alpha & \cos \beta \cos \alpha
\end{bmatrix}
\] (3)

The rotation matrix of the XYZ sequence of one segment was used to then extract three angles. The joint angles were represented using Cardan-Euler angles by determining the rotation of one segment’s transformation matrix to another segment’s transformation matrix. The angles were calculated as a 3D rotation matrix representing three successive rotations about unique axes. Rotation about the X, Y, and Z axes were found. The rotation angles were represented by alpha (\(\alpha\)), beta (\(\beta\)), and gamma (\(\gamma\)). Where alpha was the rotation about the X-axis, beta was rotation about the Y-axis, and gamma was rotation about the Z-axis. The angles were computed from elements in the rotation matrix as shown below in equations 4-6.

\[
\alpha = \tan^{-1} \left( \frac{-R_{32}}{R_{33}} \right)
\] (4)

\[
\beta = \tan^{-1} \left( \frac{R_{31}}{\sqrt{R_{11}^2 + R_{21}^2}} \right)
\] (5)

\[
\gamma = \tan^{-1} \left( \frac{-R_{21}}{R_{11}} \right)
\] (6)
Euler angles of specified joints were computed for all trials and used for comparison to one another. All measurements were taken in relation to the lab coordinate frame. The lab coordinate frame was established during calibration of the Vicon motion analysis system with the calibration wand. The laboratory coordinate frame with the proper camera orientation was defined as the same position and orientation as shown below in Figure 2.8.

An accurate laboratory coordinate frame was critical to establish the local coordinate frames of each segment to ensure proper development of the real-time kinematic model.
CHAPTER 3: DEVELOPMENT OF OPTIMAL MODEL AVATAR

The optimal goal motion was visualized as a virtual character avatar animating the proper movements for each task. The character avatar and animations were developed using Autodesk Maya software (Autodesk, Inc., San Rafael, CA) and exported to the D-Flow (Motek Medical, Netherlands, Amsterdam) application using OgreMax Scene Converter (The OGRE Team) in order to display on the CAREN projection screen.

3.1 Avatar Character

The avatar character was created using Autodesk Character Generator where all characteristics were chosen and then exported into Maya to generate the three-dimensional model and define the assets of the avatar in a virtual scene. Maya is a 3D animation software that allow for computer animation, modeling, simulation, rendering, and compositing on a highly extensible production platform (Autodesk, Inc.).

3.1.1 Segment Definition

The first step of creating the character avatar was developing the skeleton of the character by first defining each segment. Each segment had to be properly named and oriented. To keep things consistent, the segments were named identical to the real-time model, as described in Chapter 2. The segments included the head, torso, pelvis, right upper arm, left upper arm, right forearm, left forearm, right hand, left hand, right thigh, left thigh, right tibia, left tibia, right foot, and left foot. Each segment was manually positioned and defined with proper orientation. Dimensions were input to relatively scale and size the individual segments and ensure all
segments were accurately proportional to one another. Once all segments were named, oriented, and sized, the joints and relationships to connect all segments were created.

3.1.2 Joint Definition and Attributes

A joint was defined as the joining of two segments to allow for various movement and specified degrees of freedom. The two joining segments were selected manually to create the joints used for this model. The pelvic joints defined for this model were the wrists, elbows, shoulders, neck, pelvis, hips, knees, and ankles. Once all joints were defined, the joint’s local axes were manually oriented.

The local rotation axes were oriented and transformed for each joint where the first defining line was X, the second defining line was Y, and the cross product of the two was Z. The local rotation axes for each joint in the model are shown below in Figure 3.1, as a straight and rotated view to better visualize the axes.

Figure 3.1 The Local Rotation Axes of Each Joint to Define the Optimal Model Avatar. A Straight View is Shown on the Left, and a Rotated View is on the Right.
The preferred angle for each joint was set as the rest pose. The rest pose was set to the static calibration positioning of a T-pose, where the feet were shoulder width apart and the arms were held straight out to the side to form a “T” with the body. Once the preferred angle was set, the XYZ translation and rotation limitations were set for all three directions. The joint limit specified the minimum and maximum translation and rotation values for each joint to ensure human-like behavior. For the purpose of this model the limits for all joints were set at -180 degrees to +180 degrees. The degrees of freedom (DOF) of each joint were also set in order to define the local axes the joints properly rotate around. For the purpose of this model, all joints were allowed three DOF; flexion/extension, abduction/adduction, and internal/external rotation. Dependent on how the X, Y, and Z axes were defined for each joint, determined the direction of the specific DOF. Joint damping and stiffness was all considered for this model. The joint damping affect was used to apply resistance to a joint as it approached its joint limits to avoid an abrupt stop. Joint stiffness was used to specify a joint’s resistance to rotation in each direction to define the joints that rotate less freely. All these attribute were set to allow the avatar to model human-like movements.

3.1.3 Segment and Joint Relationships

Prior to applying movement to the avatar, the proper relationship of the joints and segments had to be defined in a specific order to establish the parent-child relationship. The relationships of the segments and joints are defined as the skeleton hierarchy, where a parent segment or joint is higher in a skeleton’s hierarchy than any of the other segments or joints. Segments below a parent segment in the hierarchy are called child segments. Parent joints and segments drive the transformations of their respective child joints and segments. The corresponding parent segment influences each child segment in the specified sequence, thus
when a parent segment is translated or rotated, the child segments move accordingly. The primary parent segment, also known as the root segment, was defined as the pelvis, and all other segments were considered a child to the pelvis. All skeleton hierarchies of this model branched from the pelvis. The parent-child relationships for the entire avatar model are shown below in Figure 3.2.

![Figure 3.2 Skeleton Hierarchy of the Optimal Model Avatar. The Hierarchy Goes from Root Segment to Parent Segments to Child Segments. The Hierarchy is Represented by Colors in the Order of Orange to Yellow to Green to Light Blue to Dark Blue.](image)

The parent-child relationship order is represented by colors. The order and direction goes from the root segment to parent to child. The color order is orange to yellow to green to light
blue to dark blue. As shown, the primary parent segment is shown in orange as the pelvis. The hierarchy of the middle body was defined as:

\[ \text{Pelvis} \rightarrow \text{Torso} \rightarrow \text{Head} \]

The hierarchy of the lower extremities was defined as:

\[ \text{Pelvis} \rightarrow \text{Hips} \rightarrow \text{Knees} \rightarrow \text{Ankles} \]

The hierarchy of the upper extremities was defined as:

\[ \text{Pelvis} \rightarrow \text{Torso} \rightarrow \text{Shoulder} \rightarrow \text{Elbow} \rightarrow \text{Wrist} \]

Each child segment/joint transformed relative to the parent segments in their specified hierarchy. The parent-child relationship aligned each segment to the rotation of the relating segment so the movement remained constrained to the defined axes in the local space coordinate system.

### 3.1.4 Skin Weight and Appearance

Once the segment relationship and proper axes were defined, the weight of the skin was attached to the model. The skin weight had to be imported and blended properly, so when moving, the model would not look distorted and the segments would move proportional to one another. The skin was smoothed and weighted to follow the skeleton hierarchy so the proper joints and segments would move accordingly. The higher in the hierarchy, the greater the weight of the skin was over that specific segment. The skin weight of an area gradually decreased the lower the segment was in its specified skeleton hierarchy, as listed above. Once the skin weight was in place, images of the clothing and features that were previous selected from the Autodesk Character Generator® were imported onto the avatar to create a human-like appearance. This is shown below in Figure 3.3.
The platform was set up where the weight and height of the avatar could be scaled dependent on the user to individualize the model and make it patient specific.

### 3.1.5 Inverse Kinematics Joint Chain

In order to prepare for animations, the model was set up to perform inverse kinematic (IK) calculations to determine joint positioning. In addition to defining the skeleton hierarchy, local rotation axes, and applying proportional skin weights, an IK joint chain had to be established. The joint chain followed the same parent-child relationship order as the skeleton hierarchy. The defined joint chains allowed for the rotations of all the joints in a chain to be calculated with inverse kinematics by applying an IK handle. The IK handle incorporates mathematical algorithms to move and rotate all joints accordingly in its specified IK chain. When the XYZ positioning and orientation values were inputted for a joint, the values were considered and applied to the IK equations to determine the positioning and orientation of the
related joints in the specified IK chain. The end effector was the last joint in the chain related to the joint moved. The translation and rotation values are inputted into the equations to calculate how to move the position and orientation of the end effector to follow the IK handle to properly rotate and translate all related joints in the specified joint chain.

For example, when determining the elbow ($\theta_E$) and shoulder ($\theta_S$) angles from a given (X, Y) positioning of the wrist, inverse kinematics is used. The figure below illustrates the variables used, and positioning of the angles. By considering the new (X,Y) positioning of the wrist with the length of the upper arm (L1), and the length of the forearm (L2), the elbow and shoulder angles can be calculated. Equations 7-10 below describe the mathematic algorithm used to solve for the angles.

![Figure 3.4 Joint Angle Configurations for Inverse Kinematics Calculations. Elbow Angle ($\theta_E$), Shoulder Angle ($\theta_S$), Length of the Upper Arm (L1), and Length of the Forearm (L2).](image-url)
\[
\theta_E = \cos^{-1}\left(\frac{X^2 + Y^2 - L1^2 - L2^2}{2 \times L1 \times L2}\right) \tag{7}
\]

\[
(\theta_S + \theta_Q) = \tan^{-1}\left(\frac{Y}{X}\right) \tag{8}
\]

\[
\theta_Q = \cos^{-1}\left(\frac{X^2 + Y^2 + L1^2 - L2^2}{2 \times L1 \times \sqrt{X^2 + Y^2}}\right) \tag{9}
\]

\[
\theta_S = \tan^{-1}\left(\frac{Y}{X}\right) - \cos^{-1}\left(\frac{X^2 + Y^2 + L1^2 - L2^2}{2 \times L1 \times \sqrt{X^2 + Y^2}}\right) \tag{10}
\]

3.2 Avatar Animations

3.2.1 Joint Positions

The optimal motion animations were then developed by imported joint positions and range of motions throughout each task, for the virtual character to perform. The specific joint positions for each task were determined from average normal joint positions professionally reported [40,41] and by evaluating pre-collected motion captured data of able-bodied subjects performing the tasks. Average normal joint angle ranges are shown below in Table 3.1. Values were taken from references [40,41].

<table>
<thead>
<tr>
<th></th>
<th>FOREARM</th>
<th></th>
<th>ELBOW</th>
<th></th>
<th>SHOULDER</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pronation</td>
<td>Supination</td>
<td>Flexion</td>
<td>Extension</td>
<td>Flexion</td>
<td>Extension</td>
</tr>
<tr>
<td></td>
<td>80°-90°</td>
<td>80°-90°</td>
<td>150°-160°</td>
<td>0°</td>
<td>160°-180°</td>
<td>50°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Abduction</td>
<td>Adduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>150°</td>
<td>30°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>External Rotation</td>
<td>Internal Rotation</td>
<td>90°</td>
<td>70°-90°</td>
</tr>
</tbody>
</table>
Table 3.1 (Continued)

<table>
<thead>
<tr>
<th>TORSO</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexion</strong></td>
<td><strong>Extension</strong></td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td>25°</td>
<td></td>
</tr>
<tr>
<td><strong>Left Lateral Flexion</strong></td>
<td><strong>Right Lateral Flexion</strong></td>
<td></td>
</tr>
<tr>
<td>25°</td>
<td>25°</td>
<td></td>
</tr>
<tr>
<td><strong>Left Rotation</strong></td>
<td><strong>Right Rotation</strong></td>
<td></td>
</tr>
<tr>
<td>0°-30°</td>
<td>0°-30°</td>
<td></td>
</tr>
</tbody>
</table>

3.2.2 Real Human Body Model

In addition to normal and pre-collected joint values, the predictive joint positions determined by the Real Human Body Model (RHBM) were imported. The RHBM is a robotics based human body model for predictive simulation of upper-limb prostheses performance [1]. This model was used to predict the inverse kinematics of the upper body for those with a transradial or transhumeral amputation while performing specific ROM and ADL tasks. The joint positioning determined by this predictive model was also considered when creating the optimal motions.

3.2.3 Optimal Motions

Throughout a designated frame of time, keys were defined at specific points, where the positions of each corresponding segment were defined. The segments were developed to rotate in segment space coordinate system rotations on the segment itself, relative to its own space coordinate system. Therefore, once the position was defined, the segment moved along the average local reference frame, aligned to the world space axis. The movement of a segment was defined by the rotation around the pivot of the selected segment. For example, the pivot of the humerus segment was defined as the shoulder, and the pivot of the radius was defined as the elbow. The X, Y, and Z position of each segment was defined for each time key throughout a specified frame of time to properly animate the avatar to perform all range of motion (ROM),
activities of daily living (ADL), and return to duty (RTD) tasks. The Maya interface is shown below in Figure 3.5, where the character avatar was defined to perform a shoulder flexion motion and the proper rotation of the X,Y, and Z coordinate system of the humerus was defined about the shoulder pivot point.

![Figure 3.5 Maya Interface Showing Character Avatar Animating a Shoulder Flexion Movement](image)

As shown in the Figure, the keys on the time frame are shown as red tick marks. The tick marks represent a specified position on the current joint selected. The joint moves from position to position defined by the tick marks throughout the specified time frame. Text files containing proper joint positions to perform a specific task can be imported to animate the avatar throughout a designated time frame. The platform was developed to allow for the animation speed to be varied once exported in order to demonstrate motions based on the user’s abilities.
3.2.4 Exportation

Once all time frame positions of all related segments were properly defined to accurately animate the model, the mesh animations were exported using OgreMax Scene Converter (The OGRE Team). The mesh animations were exported by tracking the skin of the model throughout the defined frame of time by following the imported joint position. The character avatar model was then imported into D-Flow (Motek Medical, Amsterdam, Netherlands), with the animations attached to the model. The animations were then able to be selected from a dropdown box to apply to the avatar to perform alongside the real-time model.

The optimal model avatar was developed to accurately animate all ROM, ADL, and RTD tasks. The avatar could be shown in any position and any size on the virtual screen, and the selected animation could be performed at any time throughout the trial at various speeds through the developed D-Flow application.
CHAPTER 4: DEVELOPMENT OF D-FLOW PROGRAM INTERFACE

The D-Flow software is a visual programming tool designed for the immersive virtual reality applications developed specifically for the CAREN system (Motek Medical, Amsterdam, Netherlands). The D-Flow software allows for extensive programming of the virtual environment used on the CAREN system. The development of the D-Flow program interface was developed as an application incorporating the real-time and optimal model in an interactive virtual reality environment. The D-Flow application was designed to allow for various inputs and export features while providing useful visual feedback with the CAREN system.

4.1 Scene Development

The interactive virtual reality environment was first developed by the creation of the background or scene of the application. The scene was created using Google Sketchup®, by uploading images and blending them together to create a scene. The Images were exported through Ogre Max software (The OGRE Team) to convert them into a dot-scene file, to then upload into D-Flow. Once the background scene file was uploaded into D-Flow, additional scene images from Motek Medical’s pre-developed applications were inserted. The fully developed scene included an endless walking trail through a virtual forest. The developed scene was interactive and real looking to allow for users to be immersed in the virtual environment. The view the users were first immersed into is shown below in Figure 4.1.
4.2 Implementation of Real-Time Model

4.2.1 Visualization

The real-time model was implemented into the scene through the motion-capture (MoCap) module in D-Flow. The MoCap module allowed for D-Flow to communicate with Vicon-Nexus to incorporate the plug-in-gait model parameters and the real-time data. The MoCap module interface is shown below in Figure 4.2.
In order to visualize the model in D-Flow in real-time, the source must be selected in “Live Mode” and the marker mode must be in “Labeled.” The live mode allows for data to be obtained in D-Flow, from Vicon, using the labeled marker and segment data to create a real-time model. The virtual studio technology (VST) file created through Vicon-Nexus had to be uploaded for the proper configuration. This file contained the information on markers and segments to create the model. The VST file uploaded into D-Flow, had to be the same file
uploaded in Vicon when in live mode, in order to acquire real-time data. There were 39 markers and 19 segments that were defined to construct the real-time model. Next step was to define the display options under the “Display” tab as shown below in Figure 4.3.

Figure 4.3 MoCap Module Interface: Display Tab

For this real-time model, the segments were the only thing shown for the avatar visualization. Other visualization options were available where the markers could be shown, as
well as labels for the markers and segments. The forces produced by the user onto the instrumented treadmill could also be shown if needed. For the purpose of this model, the segments were the only thing shown at a selected diameter size of 0.1 meters for the joints and limbs. This module allowed for the joints and limbs to be sized differently, to closer resemble the user. The avatar was viewed as a white stick figure model implemented into the D-Flow scene, as shown below in Figure 4.4. The limb segments were shown as white cylinders connected by joints that were shown as white cubes. The model was chosen to remain as a white stick figure to easily visualize the model and distinguish the differences between both the real-time and optimal model. The white color allowed for the model to stand out compared to the background scene.

Figure 4.4 Real-Time Avatar Shown in the D-Flow Scene
4.2.2 Motion Capture

In order to accurately animate the real-time model with the movements of the user, the markers placed on the subject had to match the model created with the VST file, and Vicon-Nexus had to be properly configured. Once the ten cameras were calibrated, and motion was captured for the calibration file, the VST file was applied to virtually label the markers on the subject. Once the VST file was applied to the calibration data and the markers were properly labeled, the model would then be animated with the real-time motion of the user in both Vicon and D-Flow. The Vicon Nexus interface is shown below in Figure 4.5.

![Vicon Nexus Interface With Subject Calibration File](image)

Figure 4.5 Vicon Nexus Interface With Subject Calibration File

4.3 Implementation of Optimal Model Avatar

4.3.1 Visualization

The optimal model avatar was implemented into D-Flow as a dot-scene file. Exporting the Maya model through OgreMax software created the file. This was used to convert the file
from a Maya Binary file (dot-MB) to a dot-scene file, which could then be imported into the D-Flow application. The optimal model visualization was obtained by importing the scene file into the D-Flow application. An object module was then created with the file, which contained the avatar model along with the animation motions. The object module allowed for various settings to be manipulated. As shown in Figure 4.6, the model could be transformed into various sizes and set at various positions within the module.

Figure 4.6 Object Module Interface for the Optimal Model Avatar Showing the Shoulder Task Animations: Transformation Tab
When a scene file was applied to an object module, the translation, rotation and scaling of the avatar model could be altered within the transformation tab. The scene file contained the avatar model details, as well as, all the animations attached for the avatar to perform.

4.3.2 Animations

The animations were selected under the animation tab in the object module. For example, the object module for the shoulder is shown below in Figure 4.7, where the animation for the shoulder rotation ROM task is selected. The animation speed can be changed, dependent on the user. This allows for the optimal model to be animated at an individualized selected speed the user can follow according to their abilities.

Figure 4.7 Object Module Interface for the Optimal Model Avatar Showing the Shoulder Task Animations: Animation Tab
The animations were separated and grouped in different object modules according to the task. The desired motion for the model to animate is selected from the dropdown menu under the “Mesh / Skeleton animation” section. The model can continue to animate the selected motion as a loop or the motion can be chosen to animate one time through. The optimal model avatar can be transformed to view anywhere in the scene and shown at any point during the testing session. The D-Flow application interface allows for various options to be programmed for the interactive environment.

4.4 D-Flow Application Interface

Once the real-time and optimal models were implemented into the D-Flow application, they were visualized in the developed scene, as shown below in Figure 4.8. The display resource (DRS) window shown within D-Flow is what is then projected on the 180-degree projection screen of the CAREN system.

![Figure 4.8 Display Resource (DRS) Window Exhibiting the D-Flow Scene Visualization Showing the Real Time and Optimal Model Avatars. The Real-Time Model is Shown as the White Stick Figure and the Optimal Model Avatar is Shown as the Character Avatar.](image-url)
As shown, the optimal model is on the right, as the character avatar, and the real-time model is on the left, as the white stick figure. Various visualization options for the positioning of the models could be selected within the application. The programmable D-Flow interface is shown below in Figure 4.9.

![Figure 4.9 D-Flow Program Interface](image)

The scene files imported in the application are listed in the top left white box. Each file could be expanded to show the components of each root. All modules can be selected from the menu along the right side of the window, and the one used for the specific application are shown in the grey area. As shown, various modules were selected and programmed to develop the interactive scene used in this testing. To get a closer look at the modules used, Figure 4.10 shows a zoomed-in image of all programmed modules.
All options and features of the application are programmed and controlled through modules in the D-Flow application. The ROM, ADL, and RTD tasks are all grouped in separate sections containing object modules for the various tasks for the optimal model to animate. The real-time model is programmed with the MoCap module, which is connected to the valuater. The valuater module was programmed to allow for the scaling and positioning of the real-time model to be individualized to the user. An additional MoCap module and valuater was also programmed in the application to allow for any real-time data to be played back. Allow this feature was not used for the testing sessions; it was an added feature to allow for previously collected motion data to be replayed if needed. The background scene was developed with the object modules. All the features of the scene were programmed in the various object modules and blended together to create the interactive environment. The platform module allowed for the positioning and movement of the platform within the CAREN system to be changed. The platform had six-DOF.
movement variability. As shown in Figure 4.11, the platform could be translated in the X (sway), Y (Heave), and Z (surge) directions, and rotated about X (pitch), Y (yaw), and Z (roll).

![Platform Module Interface](image)

**Figure 4.11 Platform Module Interface.**

The treadmill module allowed for the speed to be adjusted. The treadmill on the CAREN platform consisted of two separate belts, allowing for differing speeds to be selected on either side. For the purpose of this study, the belts were linked to move at the same speed. The
treadmill speed could also be selected to a self-pace mode, where it would follow the movement of the user. A designated speed could also be selected to keep it consistent throughout the trial. The camera module was used to lock the view of the scene when the user was standing still and to change the view corresponding with the movement of the treadmill, to allow for a more virtual immersion into the scene. To allow for the scene to move during the walking tasks, the expression module was programmed to link the treadmill speed to the visualization, where the faster the subject was walking the faster they would move through the scene. As shown in Figure 4.12, the tiles of the road were programmed as separate object modules that were linked to the movement of the treadmill through the channels of the expression module. The equation programmed in the expression module allowed for the surrounding scene to move according to the movement of the subject.

Figure 4.12 Modules Programmed to Develop the Interactive Road
The D-Flow program interface allows for various features and options to be programmed in addition to what was described here. For the purpose of this study, the application was kept simple and only included features and capabilities needed during the testing sessions.
CHAPTER 5: STUDY PROCEDURES AND DATA ANALYSIS

All testing was done at the Interdisciplinary Research Building at the University of South Florida (USF), as part of the Center for Assistive Rehabilitation and Robotics Technology (CARRT) lab. All data were kept in the locked lab with limited allowable access, under password protection. The Institutional Review Board (IRB) at the University of South Florida approved the procedures for this study (Appendix A-B). Written informed consent was obtained from all participants prior to involvement in the study. All participants were given a detailed description of the study to ensure they completely understood all procedures prior to signing the informed consent. The signed consent forms were kept confidential and stored in a secured location, while any soft data collected were stored on a desktop computer in a USF laboratory with password protection. All subject names were kept anonymous and the data collected were not identifiable in any reports generated. All participants were assigned an identification code consisting of letters and numbers to ensure participant’s names were not attached to the data.

5.1 Subjects

Participants were recruited at the University of South Florida, as well as, at surrounding prosthetic and physical therapy clinics via IRB approved subject recruitment flyers (Appendix C.1). Collaborations with the James A. Haley Tampa VA Hospital and other professionals in the field also allowed for additional recruitment of subjects. The study was posted online and also registered with ClinicalTrials.gov under identified under #NCT02666859. The online post was shown in Appendix C.2.
Participants included veterans, active duty members, and civilians. The participants with a unilateral transradial amputation were all long-time daily users of a myoelectric prosthetic device. Amputee subjects were required to wear their same preferred prosthetic device for all sessions. All participants were between the ages of 18 and 65. Able-bodied subjects had to be free of any health ailment that would impair physical function, and amputee subjects had to be free of any injuries or surgeries on the affected limb within the past 90 days. Since upper limb amputee subjects were limited to recruit, able-bodied subjects with no amputation were also tested to obtain additional feedback and biomechanical data on human subjects to compare the VR and NOVR sessions.

5.2 Safety Procedures

This study intended to improve the prescription, design, training, and testing of upper limb prosthetic users. There were no major risks associated with the study. The only risks were minimal. This included the possibility of slight skin irritation due to the adhesive on the double-sided tape used to place the markers on the skin, and slight discomfort when removing the tape. All safety procedures developed with the CAREN system were followed to ensure a safe environment.

The CAREN system was equipped with a safety cage and all subjects wore a harness to prevent them from falling or injuring themselves. Emergency stop buttons were located in convenient locations for both the participants and operator in case a problem arose where the system needed to be shut down immediately. A study staff member also stood alongside the subject to guarantee safety while stepping onto the system, and to ensure the harness was attached correctly.
5.3 Equipment

A Computer Assisted Rehabilitation Environment (CAREN) system was used for the study. As stated in the introduction, CAREN (Motek Medical, Amsterdam, Netherlands) is a multimodal system consisting of ten motion-capture cameras (Vicon, Nexus, Englewood, CO), a six-DOF hydraulic base, a double-belted instrumented treadmill, and a 180-degree cylindrical screen with three projectors to allow for a virtual reality immersive environment. The system is depicted below in Figure 5.1.

![Figure 5.1 The CAREN System](image)

As shown, three computer monitors were used to control the CAREN system. The computer on the left was used to control the Vicon Nexus cameras and programming, the middle
computer was used for D-Flow programming, and the computer on the right displayed the image sent to the projectors that would be on the cylindrical screen. The ten Vicon motion capture cameras were installed on the scaffolds surrounding the platform. The cameras were used to track the motion of the participants while performing all the tasks while on the treadmill platform. The six-DOF motion platform included a double-belt instrumented treadmill and allowed for both translation and rotation in the X, Y, and Z directions. Three projectors were used to blend the images from the scene created in D-Flow to then project on the 180-degree screen to provide an immersive environment. All parts of the CAREN system communicated to one another to create a multimodal system with various capabilities.

5.4 Experimental Procedures

All data collection documents are shown in Appendix D. Once a subject agreed to participate and signed the consent form (Appendix D.2-D.3), a full set of thirty-nine passive reflective markers was attached to the subject’s body at specific points and joints with double-sided tape adhesive. The marker placement followed the full body marker set shown in Chapter 2. A few measurements including height, weight, and other anatomical measurements such as joint width and segment length were recorded to create the model, determine joint centers and to be used for post processing calculations. The anatomical measurement chart completed for each participant is shown below in Table 5.1.
Table 5.1 Anatomical Measurements Chart

<table>
<thead>
<tr>
<th>Anatomical Measurements</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Mass (kg):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (mm):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leg Length (mm):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Width (mm):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle Width (mm):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder Offset (mm):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elbow Width (mm):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrist Width (mm):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand Thickness (mm):</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The mass of the subject was measured in Kilograms (1lb=2.2kg), and all other measurements were in millimeters. The leg length was measured from the corresponding anterior superior iliac spine (ASIS), to the medial malleolus. The knee width was measured from the lateral to the medial epicondyle of the knee, about the flexion axis. The ankle width was measured from the lateral to the medial malleoli. The shoulder offset was measured as the vertical distance from the center of the glenohumeral joint to the corresponding acromioclavicular joint. The elbow width was measured from the lateral to medial epicondyles of the humerus. The wrist width was measured from the ulnocarpal joint to the radiocarpal joint. Lastly, the hand thickness was the distance measured between the dorsal and palmer surfaces of the hand.

Once all measurements were taken and entered into Vicon-Nexus, the subject put on the harness and was then asked to carefully step onto the platform with the guidance of a study staff member. A study staff member ensured the harness was adjusted correctly and attached to the
safety cage using a locking carabineer. The subject was notified before moving the motion platform and was given proper instructions throughout the entire study.

5.4.1 Animated Optimal Model Visualization Testing

The first step of the testing procedures was to test the various positions of the optimal model. Three different visualization options of the optimal model were shown to the participant. The optimal model was shown in front of the real time model (A), offset to the side (B), and overlaid on top (C).

Once the subject selected their preferred placement of the animated optimal model, the speed at which the motion was performed was matched to the user’s abilities. To do this, the subject was asked to perform a few simple ROM movements to evaluate the speed at which the subject performed the tasks. The animation speed of the optimal model was then aligned to match their individual speed. Subjects were also given the option of when the optimal model
movement was animated during the trials. The motion could be viewed before and/or while performing the specified task. The selections of each participant were recorded.

5.4.2 Virtual Reality and Non-Virtual Reality Sessions

Prior to beginning the virtual reality and non-virtual reality sessions, a random number generator created in Microsoft Excel was used to determine the order of testing. The VR session included visualization of the real-time model and the character avatar performing the optimal motions during all tasks, as demonstrated below in Figure 5.3. For the non-VR session, subjects only viewed the scene background on the screen with no visualization of the real-time or optimal models.

Figure 5.3 Amputee Subject Performing the Shoulder Rotation Task on the CAREN During the Virtual Reality Session, With the Optimal and Real-Time Model Shown
5.4.3 Series of Tasks

The subjects were asked to participate in a 2-hour data collection to test range of motion (ROM), activities of daily living (ADL), and return to duty (RTD) tasks with and without the use of virtual reality visualization. All tasks were completed three times for both the VR and non-VR session. Each movement was described and demonstrated by a study staff member.

5.4.3.1 Range of Motion Tasks

The ROM tasks included; elbow flexion / extension, forearm pronation / supination, shoulder flexion / extension, shoulder rotation, torso lateral bend, and torso rotation. The participants were instructed to perform each motion to the greatest range without causing any discomfort. The description given to each participant prior to starting the individual task is listed below in Table 5.2.

<table>
<thead>
<tr>
<th>Range of Motion</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow Flexion / Extension</td>
<td>Start facing forward with legs and arms straight, elbows extended towards the floors, and palms facing inward towards the body. Flex elbows, bringing forearms as close to the upper arms as possible (maximum elbow flexion). After a brief pause, follow the same path in the reverse direction extending elbows until the neutral starting position is reached.</td>
</tr>
<tr>
<td>Forearm Pronation / Supination</td>
<td>Start facing forward with legs straight and elbows flexed 90-degrees, with palms facing inward. Rotating only at the wrist, rotate upward to face palms up, pause, then rotate downward to face palm down to the floor. Note: depending on the prosthetic device used, some devices do not allow for wrist rotation, therefore only their sound arm would perform this motion.</td>
</tr>
<tr>
<td>Shoulder Flexion / Extension</td>
<td>Start facing forward with legs and arms straight, elbows extended towards the floors, and palms facing inward towards the body. Keeping arms straight, raise them forward then up overhead as far back as allowed (maximum shoulder flexion). After a brief pause, follow the same path in the reverse direction to bring arms back to the starting position then backwards behind the body as far as possible (maximum shoulder extension). Then return back to the neutral starting position following the same path in reverse.</td>
</tr>
</tbody>
</table>
Table 5.2 (Continued)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Rotation</td>
<td>Start facing forward with legs straight and arms abducted parallel to the ground, elbows flexed 90-degrees, and palms facing down, forming a box with arms. While keeping the upper-arms parallel to the ground and elbows at 90-degrees, rotate the arms upwards as far as possible, targeting for the palms to face towards the front of the room (maximum forward shoulder rotation). After a brief pause, follow the same path in the reverse direction bringing arms back to the starting position then continue to rotate the arms downwards as far as possible, targeting for the palms to face towards the back of the room (maximum backward shoulder rotation). After a brief pause, follow the same path to bring arms back to the neutral starting position.</td>
</tr>
<tr>
<td>Torso Lateral Bend</td>
<td>Start facing forward with legs and arms straight, elbows extended towards the floors, and palms facing inward towards the body. Keeping arms and legs straight, laterally bend at the torso to the right as if the arm or prosthesis is reaching down the corresponding leg, as far as possible. Pause briefly, then follow the same path to bend to the left side, pause, then return back to the starting position.</td>
</tr>
<tr>
<td>Torso Rotation</td>
<td>Start facing forward with legs straight, and elbows flexed 90-degrees, with palms facing inward. Keeping the legs and arms in the same position, and keeping hips facing forward, rotate at the torso to the right, pause, then to the left, as far as possible. After a brief pause, return to the starting position.</td>
</tr>
</tbody>
</table>

5.4.3.2 Activities of Daily Living Tasks

The ADL tasks included; a two-minute walk test, drinking from a cup, object transfer, bilateral and unilateral reach/grasp/lift tasks. The subjects were instructed to perform the tasks to their best ability without causing any discomfort. The ADL tasks were selected to include various movements one would perform on a daily basis. The description given to each participant prior to starting the individual task is listed below in Table 5.3.

Table 5.3 Activities of Daily Living Task Descriptions

<table>
<thead>
<tr>
<th>Activity of Daily Living</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Minute Walk Test</td>
<td>Starting the treadmill off slow and increasing the speed in small increments, select a comfortable walking speed. The treadmill belts will then be set to this speed to keep it consistent throughout the trial. Looking straight ahead at the screen, walk for two minutes. A one minute, 30 second, and times-up warning before stopping the treadmill, will be given.</td>
</tr>
<tr>
<td>Drinking from a Cup</td>
<td>Start with holding the cup with one hand or with the device (if using a prosthesis, subject was instructed to hold with their device), at a 90-degree angle. Imaging the cup is half-full, bring cup to mouth, as if taking a sip from it. Then return back to the starting position.</td>
</tr>
</tbody>
</table>
Object Transfer

Start with holding the cup with both hands (or with hand and prosthesis), at a 90-degree angle directly in front, center of body. Using only the right hand (or prosthesis), bring cup to the 40 inch high (1000mm) railing on the right, tap the cup on top of the railing, then bring back to center starting point. Transfer the cup to the left hand (or prosthesis) to then bring the cup to the 40 inch high (1000mm) railing on the left side. After tapping the cup on the railing, return back to the starting position.

Bilateral Lift

Start facing forward with legs and arms straight, elbows extended towards the floors, and palms facing inward towards the body. Bend down, grasp the handles on either side of the 26”x17.5”x10.5” (660x444.5x266.7mm) laundry basket with the 5lb (2.27kg) weight in it, placed on the floor directly in front of participant. Lift the weighted basket as high as possible without causing discomfort; imagining the basket is half full with laundry and needs to be set on a high shelf. Once the maximum possible height is reached, briefly pause, then set basket back down on the floor, release grip, and stand-up, returning to the neutral starting position.

Unilateral Lift

Start facing forward with legs and arms straight, elbows extended towards the floors, and palms facing inward towards the body. Using one hand or prosthesis (amputee subjects were instructed to use their prosthesis side), bend down and grasp the strap on the 5lb (2.27kg) weight, set on a platform 1 foot (304.8mm) above ground, and lift the weight straight up, as high as possible, overhead. Once maximum height is reached, briefly pause, then follow the same path to set the weight back down, release grip, and stand-up to return to the neutral starting position.

5.4.3.3 Return to Duty Tasks

The RTD tasks would include a series of tasks service members typically perform in their daily work routine [25,42,43] such as; holding and shooting a gun replica, packing/ unpacking a rucksack, walking with a weighted bag, and donning/doffing a helmet. The RTD tasks were intended to provide motivation to the subjects by having them perform interactive activities they were familiar with. The description given to each participant prior to starting the individual task is listed below in Table 5.4.
Table 5.4 Return Task Descriptions

<table>
<thead>
<tr>
<th>Return to Duty Task</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hold / Shoot Gun Replica</td>
<td>Start facing forward with legs and arms straight, elbows extended towards the floor, hold the gun replica with one hand or prosthesis (amputee subjects were instructed to use their prosthesis side). Lift the gun replica and grasp the barrel with other hand, aim directly at the front, center of the screen, cock the gun then pull the trigger. Once released, return to starting position with gun being held down on the one side.</td>
</tr>
<tr>
<td>Packing / Unpacking Rucksack</td>
<td>Start facing forward with legs and arms straight, elbows extended towards the floor, and palms facing inward towards the body. (A tote bag filled with four objects, including two 5.5”x3.5”x3.5” (140x90x90mm) wooden blocks, a metal bar, and a 57”x46” (1450x1170mm) cloth sheet, were set directly in front of participant) Bend down, unpack the bag involving both hands (or hand and prosthesis), one item at a time. Once all items are set out in a line on the ground, stand-up and return to the starting position. Then when told to do so bend down and pack the bag, once again involving both hands (or hand and prosthesis), one item at a time. Once all items are in the bag, stand-up and return to the starting position.</td>
</tr>
<tr>
<td>Weighted Bag Two-Minute Walk Test</td>
<td>Start with holding the 5lb (2.27kg) weighted bag in one hand (amputee subjects were instructed to use their prosthesis side). The treadmill belts will be set to the same speed that was previously selected as the comfortable walk speed for the first two-minute walk test. Looking straight ahead at the screen, walk for two minutes. A one minute, 30 second, and times-up warning before stopping the treadmill, will be given.</td>
</tr>
<tr>
<td>Donning / Doffing Helmet</td>
<td>Start facing forward with legs and arms straight, elbows extended towards the floors, holding the helmet with both hands (or hand and prosthesis), in front of body. When instructed to do so, lift the helmet up and put on top of head. Leaving the helmet on the head, return arms down by sides. After a brief pause, reach up to grasp the helmet with both hands (or hand and prosthesis), lift helmet off head and return to starting point.</td>
</tr>
</tbody>
</table>

5.5 Analytical Procedures

5.5.1 Joint Angle Calculations

The motion-captured data along with the joint center measurements of each subject were used to calculate the joint angles through Cardan-Euler angle transformation matrices, as previously described in Chapter 2. The joint angles found, were the transformation between two coordinate systems that were described by a rotation matrix, represented by a Cardan-Euler angle. The motion-captured data were post-processed in Vicon Nexus (Englewood, CO). The
parameters, kinematics, and kinetics were calculated using Polygon (Vicon, Englewood, CO.) and Visual 3D (C-Motion, Germantown, MD). The elbow, glenohumeral, torso, and pelvic angle range of motions were calculated for both the virtual reality and non-virtual reality groups. In order to calculate the joint angle using Visual 3D, a model was developed with the static calibration file (Figure 5.4). The segments and joints were defined to match the real-time kinematic model, as described in Chapter 2. For each segment coordinate system, the Y-axis was defined from anterior to posterior, the Z-axis was defined from the distal to proximal end, and the X-axis was the cross-product of the two. The sign convention for the joint angles followed the Right Hand Rule, where the direction of a positive angle was determined with respect to the segment coordinate system of the reference segment. For the purpose of this dissertation, only one trial for each subject is represented in the results. Due to some trials containing extreme gaps in the data from dropped markers, in order to stay consistent for all subjects, only one trial was used for each task under each condition. This avoided inconsistency in the data with some subjects having one trial and others having an average of three. In most cases, all three trials when performing the same task under the same condition were extremely similar, where averaging all three trials would not change the data. In the cases where there was noticeable variability, the middle trial was selected between the two extremes. The idea of selecting the middle trial to represent in the results was to provide a more accurate and better representation of the subject’s motion, without averaging the extremes. This also avoids averaging the averages when representing the data. As mentioned later in Chapter 8, future work should involve investigating the variability between the successive trials to further investigate the methods. Therefore to avoid gaps in the data and inconsistency, for the purpose of this dissertation of
comparing the VR trials with the NOVR trials, it was deemed best to represent one trial for each subject under both conditions for all tasks.

5.4 Visual 3D Model.

5.5.1.1 Elbow Joint Angles

The elbow joint angle was calculated by solving for the Cardan-Euler angle between the forearm and upper-arm segments. The upper-arm segments were defined as the reference segment, therefore the elbow angle was found by calculating the rotation matrix of the forearm in relation to the upper-arm. For the purpose of this study, the elbow flexion was the only elbow angle considered in this analysis, which was defined as the angle of the forearm in relation to the upper-arm, about the Y-axis. Therefore the Cardan sequence of rotation was defined as Y-Z-X.

5.5.1.2 Glenohumeral Joint Angles

The glenohumeral joint angle was calculated by solving for the Cardan-Euler angle between the upper-arm and torso segment. The torso segment was defined as the reference
segment, therefore the glenohumeral angles were found by calculating the rotation matrix of the upper-arms in relation to the torso. For the purpose of this study, the shoulder flexion was the only glenohumeral joint angle considered in this analysis, which was defined as the angle of the upper-arm in relation to the torso, about the X-axis. Therefore the Cardan sequence of rotation was defined as X-Y-Z.

The position offset between the shoulders was also measured during certain tasks. This was determined by solving for the difference between the shoulder positions in the Z-direction. For the shoulder offset during the bilateral lift task, the position in the Z-direction of each shoulder at the maximum height was found and then subtracted from one another to determine the offset. For the walking tasks, the shoulder offset was determined by tracking the position of both shoulders in the Z-direction throughout the entire task. The difference between the Z-positions of both shoulders were determined on a point-by-point basis, then the average of all differences were solved for to calculate the average shoulder offset.

5.5.1.3 Torso Joint Angles

The torso joint angles were calculated by solving for the Cardan-Euler angle between the torso and pelvis segment. The pelvis segment was defined as the reference segment, therefore the torso angles were found by calculating the rotation matrix of the torso segment in relation to the pelvis. Torso bend (X), tilt (Y), and rotation (Z) were all calculated. The Cadan sequence of rotation was defined as Y-Z-X.

5.5.1.4 Pelvic Joint Angles

The pelvic joint angles were calculated by solving for the Cardan-Euler angle between the pelvis segment in relation to the lab coordinate frame. The lab coordinate frame was defined as the reference segment where Y was defined as the direction of progression, Z was defined
vertically upward, and X was perpendicular to both Y and Z by the right-hand Cartesian coordinate system. The pelvic angles were found by calculating the rotation matrix of the pelvis segment in relation to the lab coordinate system. Pelvic tilt (X), obliquity (Y), and axial rotation (Z), were all found. The Cardan sequence of rotation was defined as Z-Y-X.

The joint angles of both conditions for all tasks were compared to one another to determine if there were differences in the movements and improvements using virtual reality. To easily compare the values, the joint angles calculated for each task, were normalized from 0% to 100% of task completion.

An emphasis was put on pelvic obliquity in the results of this dissertation. Pelvic obliquity is when the pelvis is out of alignment and is defined as an abnormal tilt of the pelvis with respect to the spine. Out of alignment could cause improper movements and result in supplemental joint injuries. Therefore, pelvic obliquity was determined to be an important measure. Results were presented for all tasks during both the VR and NOVR conditions.

5.5.2 Movement Symmetry

The movement symmetry was also evaluated by comparing the range of motion and movement of the right vs. left side for each subject throughout the various tasks. This was done to determine if the amputated arm was performing alike the sound arm and to ensure minimal compensation in movement was being made. Arm posture and symmetry greatly affects the performance during a variety of tasks [44,45] and compensation of supplemental joints was found directly correlated to functional imitations [46].

The typical measurements for movement symmetry in unilateral upper-extremity amputees start with observations, and advance to the elapsed time of both arms from a signal to move until movement begins (initiation time), and the time from the beginning of movement to
task completion (movement time) of each arm. [12,13] This is traditionally done using cross limb training with a simulator to enhance transfer of skill across limbs to improve movement symmetry while completing tasks [13]. This study took a more advance approach by evaluating the kinematics of each arm and comparing the two. The differences in the joint angles between the right and left sides were defined as the offset. For example, calculating the differences in the right and left shoulder angles and differences in positioning, determined the shoulder offset.

In addition to analyzing the motion-captured data and calculating joint angles, observations throughout the testing procedures were taken into consideration, as well as patient feedback obtained. The patient feedback verbalized, as well as, through a post-testing survey completed by each participant, was also used as an analytical measure to compare the virtual reality verses non-virtual reality sessions.

5.5.3 Survey Questionnaire

The survey questionnaire was given to each subject after completion of all trials. The survey consisted of five questions. The questions were:

1. Did you find it easier to complete the tasks with or without virtual reality?

2. Did you notice improvements in your motion when completing the tasks with and without virtual reality? Was it more noticeable in one form of training over the other?

3. Was it more enjoyable and/or motivational to complete the tasks with the use of the virtual reality? Briefly explain.
4. What do you believe is the best way to train/rehabilitate prosthetic users to effectively use their device with optimal movements and performance?

5. Any additional comments/ suggestions?

Each participant was given a few minutes at the end of the testing session to complete the survey and give any feedback they may have had. The answers to the questions along with any additional patient feedback, was considered when analyzing the results.

5.6 Statistical Analysis

Two types of analyses were performed on the data presented. The first type was a directional and non-directional two-sample T-test to investigate the differences in means of the maximum and ROM values. This was done using Microsoft Excel. The T-tests analyses were performed on the maximum lift heights for the bilateral and unilateral tasks, maximum and ROM values from the joint angle range of motion comparisons (between arms and NOVR vs. VR), average offset between shoulders during the NOVR and VR sessions for the movement symmetry comparisons, and the pelvic obliquity ROM values for NOVR vs. VR sessions.

The other analysis performed was using IBM SPSS software (Version 23, Chicago, IL), a repeated measure and one-way analysis of variance (ANOVA) was performed on the movement symmetry data. A multivariate general linear model was used to investigate the differences in joint angles between both shoulders of the subjects and between the NOVR and VR sessions, for both the able-bodied and amputee subjects.

For all statistical analyses, A p-value of less than 0.05 was considered significant with a level of significance of $\alpha = 0.05$. Further statistical analysis results are shown in Appendix E.
CHAPTER 6: RESULTS

6.1 Subjects

The patient population for this study included five healthy able-bodied individuals (n=5) and five individuals with a unilateral transradial amputation (n=5). Able-bodied subjects were named “AB” with a corresponding number and unilateral transradial amputee subjects were identified as “UTRA” with a corresponding number.

Subjects had a mean (SD) age of 31.4 years (±14.1), weight of 73.2 kg (±13.9), and height of 1704.2 mm (±85.9). Complete descriptions of the participants are shown below in Table 6.1 and 6.2.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>GENDER</th>
<th>AGE</th>
<th>WEIGHT (kg)</th>
<th>HEIGHT (mm)</th>
<th>Dominant Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB01</td>
<td>Female</td>
<td>22</td>
<td>53.5</td>
<td>1549.4</td>
<td>Right</td>
</tr>
<tr>
<td>AB02</td>
<td>Female</td>
<td>25</td>
<td>62.596</td>
<td>1701.8</td>
<td>Right</td>
</tr>
<tr>
<td>AB03</td>
<td>Male</td>
<td>21</td>
<td>94.347</td>
<td>1778</td>
<td>Right</td>
</tr>
<tr>
<td>AB04</td>
<td>Male</td>
<td>20</td>
<td>79.832</td>
<td>1803.4</td>
<td>Right</td>
</tr>
<tr>
<td>AB05</td>
<td>Female</td>
<td>22</td>
<td>70.31</td>
<td>1651</td>
<td>Left</td>
</tr>
<tr>
<td>UTRA01</td>
<td>Female</td>
<td>27</td>
<td>63.5</td>
<td>1650</td>
<td>Right</td>
</tr>
<tr>
<td>UTRA02</td>
<td>Male</td>
<td>54</td>
<td>74.843</td>
<td>1803.4</td>
<td>Right (prior to amputation)</td>
</tr>
<tr>
<td>UTRA03</td>
<td>Female</td>
<td>36</td>
<td>68.039</td>
<td>1625.6</td>
<td>Right</td>
</tr>
<tr>
<td>UTRA04</td>
<td>Male</td>
<td>59</td>
<td>97.52</td>
<td>1778</td>
<td>Right</td>
</tr>
<tr>
<td>UTRA05</td>
<td>Male</td>
<td>58</td>
<td>68</td>
<td>1701.8</td>
<td>Right</td>
</tr>
</tbody>
</table>
Table 6.2 Amputation and Prosthetic Device Information for Amputee Subjects

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>Affected Limb</th>
<th>Level of Amputation</th>
<th>Cause</th>
<th>Years of Prosthetic Use</th>
<th>Formal Prosthetic Training</th>
<th>Type of Prosthesis</th>
<th>Years with Current Device</th>
<th>Wrist Rotation</th>
<th>Level of Activity w/ device</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTRA01</td>
<td>Left</td>
<td>Transradial short</td>
<td>Congenital</td>
<td>25 years</td>
<td>1+ years</td>
<td>Myoelectric: BeBionic V3</td>
<td>3</td>
<td>Yes-Automatic</td>
<td>High</td>
</tr>
<tr>
<td>UTRA02</td>
<td>Right</td>
<td>Transradial short</td>
<td>Trauma</td>
<td>2 years</td>
<td>None</td>
<td>Myoelectric: Touch Bionics i-Limb Quantum</td>
<td>1</td>
<td>No</td>
<td>High</td>
</tr>
<tr>
<td>UTRA03</td>
<td>Left</td>
<td>Transradial short</td>
<td>Trauma</td>
<td>16 years</td>
<td>3 months 3x/week</td>
<td>Myoelectric: Touch Bionics i-Limb Quantum</td>
<td>2</td>
<td>Yes-Manual</td>
<td>High</td>
</tr>
<tr>
<td>UTRA04</td>
<td>Left</td>
<td>Transradial short</td>
<td>Trauma</td>
<td>18 years</td>
<td>1 hour</td>
<td>Myoelectric: Ottobock Michelangelo</td>
<td>6</td>
<td>No</td>
<td>50%</td>
</tr>
<tr>
<td>UTRA05</td>
<td>Left</td>
<td>Transradial short</td>
<td>Disease-Cancer</td>
<td>4 years</td>
<td>None</td>
<td>Body-Powered: pin-locking hook</td>
<td>4</td>
<td>No</td>
<td>25%</td>
</tr>
</tbody>
</table>

The order of the virtual reality (VR) and non-virtual reality (NOVR) sessions were kept at random and previously determined by a random number generator. The first session each subject was tested with is shown below in Table 6.3.

Table 6.3 Order of Testing Sessions for All Subjects

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>Order of Testing First Session:</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB01</td>
<td>With Virtual Reality</td>
</tr>
<tr>
<td>AB02</td>
<td>Without Virtual Reality</td>
</tr>
<tr>
<td>AB03</td>
<td>With Virtual Reality</td>
</tr>
<tr>
<td>AB04</td>
<td>Without Virtual Reality</td>
</tr>
<tr>
<td>AB05</td>
<td>With Virtual Reality</td>
</tr>
<tr>
<td>UTRA01</td>
<td>Without Virtual Reality</td>
</tr>
<tr>
<td>UTRA02</td>
<td>With Virtual Reality</td>
</tr>
<tr>
<td>UTRA03</td>
<td>With Virtual Reality</td>
</tr>
<tr>
<td>UTRA04</td>
<td>Without Virtual Reality</td>
</tr>
<tr>
<td>UTRA05</td>
<td>Without Virtual Reality</td>
</tr>
</tbody>
</table>
6.2 Optimal Model Visualization Testing

Prior to beginning the VR and NOVR testing sessions, each subject was shown the various optimal model visualization options for the VR testing session. As discussed in Chapter Five, each subject was shown the optimal model in front, to the side, and overlaid with the real-time model. After the preferred positioning was selected, the subject was asked to perform a few simple motions to match the animation to their individual speed. The optimal model animation was shown before and during the task. The subject could choose to have the optimal motion animation before and/or during the task. The preferred position and timing selections for each subject are shown below in Table 6.4.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>Preferred Visualization</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position</td>
<td>Timing</td>
<td></td>
</tr>
<tr>
<td>AB01</td>
<td>Overlaid</td>
<td>During</td>
<td></td>
</tr>
<tr>
<td>AB02</td>
<td>Offset</td>
<td>Before Task</td>
<td></td>
</tr>
<tr>
<td>AB03</td>
<td>Offset</td>
<td>Before Task</td>
<td></td>
</tr>
<tr>
<td>AB04</td>
<td>Overlaid</td>
<td>During</td>
<td></td>
</tr>
<tr>
<td>AB05</td>
<td>Offset</td>
<td>Before &amp; During</td>
<td></td>
</tr>
<tr>
<td>UTRA01</td>
<td>Offset</td>
<td>Before &amp; During</td>
<td></td>
</tr>
<tr>
<td>UTRA02</td>
<td>Offset</td>
<td>Before &amp; During</td>
<td></td>
</tr>
<tr>
<td>UTRA03</td>
<td>Offset</td>
<td>Before &amp; During</td>
<td></td>
</tr>
<tr>
<td>UTRA04</td>
<td>Offset</td>
<td>Before &amp; During</td>
<td></td>
</tr>
<tr>
<td>UTRA05</td>
<td>Offset</td>
<td>Before Task</td>
<td></td>
</tr>
</tbody>
</table>

As shown, majority of the subjects (8 out of 10) and all (5 out of 5) amputee subjects chose to have the model offset to the side of their personal real-time model. Three subjects chose to have the optimal model animation only shown before the task and two subjects chose to have the animation only shown during the task. Five subjects (4 out of the 5 amputees) chose to have the optimal model animation both before and during the task. Subjects who preferred the
animation only before the task, stated it was distracting to have the optimal motion animation playing while trying to perform the task themselves, but liked being able to see a proper demonstration of the motion they were expected to be performing.

6.3 Survey Questionnaire

After the completion of both testing sessions, each subject was given a survey questionnaire to complete. The survey questionnaire consisted of five questions, as listed in the Analytical Procedures in Chapter Five. The answers given were organized and shown below in Table 6.5. Since not all subjects answered question four, it was combined in the column with additional comments.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>Task Difficulty</th>
<th>Noticeable Improvements</th>
<th>Enjoyable/ Motivational</th>
<th>Additional Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB01</td>
<td>“Easier with VR. Better than mirror since distinct points on joints are emphasized.”</td>
<td>“Yes, greater noticeable improvements and more defined motions with VR.”</td>
<td>“VR made the task more fun to complete the tasks and was an enjoyable tool. More motivated to study body posture and motion.”</td>
<td>No response.</td>
</tr>
<tr>
<td>AB02</td>
<td>“Easier with VR. Helped to focus on motion on screen.”</td>
<td>“VR allowed for greater noticeable improvements, especially when arms were suppose to be straight during certain tasks.”</td>
<td>“VR made the tasks more enjoyable and motivational. Especially during the walking tasks.”</td>
<td>“The optimal model avatar was distracting when performing the tasks during trails. Was best to view from the side to see proper placement and shown before trail.”</td>
</tr>
<tr>
<td>AB03</td>
<td>“Easier without VR because then there’s no comparing movement to virtual model.”</td>
<td>“Better without comparing movement to virtual model.”</td>
<td>“VR made the tasks more enjoyable.”</td>
<td>No response.</td>
</tr>
</tbody>
</table>
Overall subjects expressed they had a greater desire and motivation to perform the tasks with correct positioning when they had the optimal model and real time visual feedback.

Majority of subjects thought it was easier to view where improvements needed to be made with the virtual reality visual feedback, allowing for quick adjustments in order to perform with a
more optimal motion. The patient feedback collected through the post-testing survey, revealed that subjects (n=10) enjoyed performing the tasks more with the use of the feedback provided by the VR visualization than without. Subjects stated they felt more motivated to perform the tasks with proper movement since they were able to visualize their motions in real-time along side the optimal model. With the VR visualization, subjects stated they were able to see when they did not have their joints positioned right, even when they thought they were performing the correct motion, allowing for them to quickly adjust their motions and perform the movements closer to the individualized optimal model. The patient feedback directly coincided with many of the observations noted throughout the study.

6.4 Observations of Biomechanics, Posture, and Positioning

Through observations, it was apparent that during the non-virtual reality sessions, majority of the subjects would look down at the ground or focus only on their hands while performing the tasks, rather than straight ahead. The VR visualization forced the subjects to look forward and perform the tasks with more confidence. It was also apparent that some subjects did not keep their arms straight during certain tasks when they were instructed to do so during the NOVR session, such as with many of the ROM tasks. Where as, when performing the same task with the VR visual feedback, the same subjects were able to quickly adjust their positioning and perform the task with both arms straight, like the optimal motion shown. During the drinking task, it was observed that majority of the subjects during the NOVR session would bring their head to the cup, straining their neck, rather than bringing the cup to their mouth with proper elbow and shoulder flexion movements. When subjects were able to see the optimal motion during the VR session they were able to better understand the proper motion and were able to adjust to perform more optimally. Looking at the gun shooting task, overall, during the NOVR
sessions, subjects did not hold the gun replica parallel to the ground but when able to see their motion in real-time with VR feedback, they were quickly able to adjust their positioning.

Through observations, it was apparent the subjects were able to execute the motions properly and overall closer to the optimal motion shown with the VR. Through observations, it was shown that without the visualization, subjects overall performed the tasks more unbalanced, and unsymmetrical. These observations were supported and further verified with the motion-captured data and kinematic calculations.

6.5 Bilateral and Unilateral Lift Heights

Specifically referring to the bilateral and unilateral lifting tasks, it was apparent that subjects were able to lift higher, with more optimal movements. It was observed that subjects overall lifted the objects unbalanced and unsymmetrical during the bilateral and unilateral lifting tasks when not provide the VR visualization. In some cases, subjects adjusted their movement during the VR session when they could see they were performing uneven; they reduced the height they lifted the object in order to perform with more optimal motion. In other cases, the VR feedback allowed for subjects to lift the objects higher. Tables 6.6, 6.7, and 6.8 below show the maximum heights the subjects lifted during the bilateral and unilateral lift tasks. In Tables 6.7 and 6.8, the greyed boxes indicate the greater height.

Looking specifically at the bilateral lifting task, Tables 6.6 and 6.7 below, demonstrate the maximum heights of the right and left sides, the offset between side, and the maximum height the object was lifted during the NOVR and VR sessions.
Table 6.6 Maximum Height and Offset of Right and Left Sides of Subjects While Performing the Bilateral List Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Subject</th>
<th>Height (mm)</th>
<th>NOVR</th>
<th>VR</th>
<th>Difference</th>
<th>NOVR</th>
<th>VR</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB01</td>
<td>1727</td>
<td>1725</td>
<td>2</td>
<td>1727</td>
<td>1727</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AB02</td>
<td>1887</td>
<td>1879</td>
<td>8</td>
<td>1928</td>
<td>1939</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>AB03</td>
<td>1921</td>
<td>1932</td>
<td>11</td>
<td>1957</td>
<td>1969</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>AB04</td>
<td>1960</td>
<td>1990</td>
<td>30</td>
<td>1992</td>
<td>1992</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>AB05</td>
<td>1833</td>
<td>1838</td>
<td>5</td>
<td>1868</td>
<td>1875</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>UTRA01</td>
<td>1215</td>
<td>1244</td>
<td>29</td>
<td>1129</td>
<td>1157</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>UTRA02</td>
<td>1478</td>
<td>1556</td>
<td>78</td>
<td>1365</td>
<td>1413</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>UTRA03</td>
<td>1340</td>
<td>1380</td>
<td>40</td>
<td>1478</td>
<td>1490</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>UTRA04</td>
<td>1565</td>
<td>1567</td>
<td>2</td>
<td>1683</td>
<td>1716</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>UTRA05</td>
<td>1797</td>
<td>1776</td>
<td>21</td>
<td>1840</td>
<td>1807</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Average:</td>
<td>1672.3</td>
<td>1688.7</td>
<td>22.6</td>
<td>1696.7</td>
<td>1708.5</td>
<td>18.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.7 Maximum Height Object was Lifted While Performing the Bilateral List Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Subject</th>
<th>Height (mm)</th>
<th>NOVR</th>
<th>VR</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB01</td>
<td>1726</td>
<td>1727</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AB02</td>
<td>1883</td>
<td>1933.5</td>
<td>50.5</td>
<td></td>
</tr>
<tr>
<td>AB03</td>
<td>1926.5</td>
<td>1963</td>
<td>36.5</td>
<td></td>
</tr>
<tr>
<td>AB04</td>
<td>1975</td>
<td>1992</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>AB05</td>
<td>1835.5</td>
<td>1871.5</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>UTRA01</td>
<td>1230.5</td>
<td>1143</td>
<td>87.5</td>
<td></td>
</tr>
<tr>
<td>UTRA02</td>
<td>1517</td>
<td>1389</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td>UTRA03</td>
<td>1360</td>
<td>1451.5</td>
<td>91.5</td>
<td></td>
</tr>
<tr>
<td>UTRA04</td>
<td>1566</td>
<td>1699.5</td>
<td>133.5</td>
<td></td>
</tr>
<tr>
<td>UTRA05</td>
<td>1786.5</td>
<td>1823.5</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Average:</td>
<td>1680.6</td>
<td>1699.35</td>
<td>61.85</td>
<td></td>
</tr>
</tbody>
</table>
As shown in Table 6.6, there was overall less offset between the right and left sides during the VR session versus the NOVR. On average subjects demonstrated an offset of 22.6 mm during the NOVR session and only 18.4 mm offset during the VR session (p=0.08). Table 6.7 (higher number is greyed) shows majority of the subjects (7 out of 10) to lift the object higher while performing the bilateral lift during the VR session. On average, subjects lifted the object 18.75 mm higher when shown the visual feedback the VR session provided (p=0.005). On average able-bodied subjects lifted the object 28.2 mm higher and amputee subjects lifted the object 9.3 mm higher. All three subjects that lifted the object higher during the NOVR session demonstrated a greater offset compared to the VR session. This indicates that although these subjects were able to lift higher during the non-virtual reality session, they performed with less arm symmetry (p=0.08). This shows when the subjects were able to see their motion in real time, they adjusted their arms to perform with less offset between their arms which in return did not allow them to lift the object as high. AB04 lifted the object 17 mm higher during the NOVR session with an offset of 30 mm, where as during the VR session, although a lower maximum height was reached, AB04 performed with an offset of zero. With the VR visual feedback, AB04 was able to perform with complete arm symmetry and overall a more optimal movement compared to the NOVR session. Both amputee subjects UTRA01 and UTRA02 also lifted the object higher during the NOVR session, yet demonstrated less of an offset during the VR session. Therefore even though these subjects lifted the object higher during the NOVR session, they performed with a more optimal position of greater symmetry during the VR session. Overall subjects lifted significantly higher (p=0.005) and with less of an offset during the virtual reality session while performing the bilateral lift.
Considering the unilateral lift, majority of the subjects (9 out of 10) lifted the object higher during the VR session, as shown in Table 6.8 below (higher number is greyed). All able-bodied subjects and all but one amputee subject demonstrated greater lifting heights during the unilateral lift. On average able-bodied subjects lifted 31.75 millimeters (mm) higher during the virtual reality session verses the non-virtual reality session. Amputee subjects lifted 80.25 mm higher on average during the virtual reality session, with one subject (UTRA03) lifting 27 mm higher during the NOVR session. Overall, on average subjects lifted significantly higher (47.7mm) during the VR verses the NOVR session (p=0.008).

Table 6.8 Maximum Height Object was Lifted While Performing the Unilateral Lift Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Subject</th>
<th>Height (mm)</th>
<th>NOVR</th>
<th>VR</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB01</td>
<td>1725</td>
<td>1727</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AB02</td>
<td>1887</td>
<td>1939</td>
<td></td>
<td>52</td>
</tr>
<tr>
<td>AB03</td>
<td>1887</td>
<td>1939</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>AB04</td>
<td>1932</td>
<td>1969</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AB05</td>
<td>1843</td>
<td>1879</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>UTRA01</td>
<td>1977</td>
<td>1982</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>UTRA02</td>
<td>1717</td>
<td>1920</td>
<td></td>
<td>203</td>
</tr>
<tr>
<td>UTRA03</td>
<td>1824</td>
<td>1797</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>UTRA04</td>
<td>2106</td>
<td>2126</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>UTRA05</td>
<td>2014</td>
<td>2107</td>
<td></td>
<td>93</td>
</tr>
<tr>
<td>Average:</td>
<td><strong>1891.2</strong></td>
<td><strong>1938.5</strong></td>
<td></td>
<td><strong>47.7</strong></td>
</tr>
</tbody>
</table>
6.6 Joint Angle Range of Motion Comparisons

The comparisons of joint angle range of motions were to investigate differences between the subject’s right and left sides and compare the biomechanical differences while performing the motion with and without the visual feedback provided by VR. Since not all tasks demonstrated differences, not all tasks were reported in the graphs below.

6.6.1 Elbow Flexion Range of Motion

As shown below in Figure 6.1, the left and right arms for the able-bodied subjects, and the sound arm and prosthetic side for the amputee subjects, had similar ranges of motion. Both the right arm and the prosthetic side demonstrated greater maximum and greater minimum elbow angles while performing the elbow flexion task compared to the left and sound arm, respectively. As shown in Table 6.9, amputee subjects demonstrated slightly greater maximum angles on both their sound arm and prosthetic side during the virtual reality session versus the non-virtual reality session, but differences were not large enough to show statistical significance.

Figure 6.1 Average Elbow Joint Angle Range Of Motion While Performing the Elbow Flexion Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
Table 6.9 Average Elbow Joint Angle Range of Motion and Standard Deviations (STDEV) While Performing the Elbow Flexion Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Elbow Flexion</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>MAX</td>
</tr>
<tr>
<td>Able-Bodied Subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>126.49</td>
<td>12.44</td>
</tr>
<tr>
<td>Right</td>
<td>123.67</td>
<td>18.26</td>
</tr>
<tr>
<td>Amputee Subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sound Arm</td>
<td>113.99</td>
<td>7.23</td>
</tr>
<tr>
<td>Prosthetic</td>
<td>121.23</td>
<td>10.74</td>
</tr>
</tbody>
</table>

6.6.2 Shoulder Flexion Range of Motion

Below, Figure 6.2 and Table 6.10 show there to be no significant differences between the arms, sessions, and subjects. All subjects demonstrated an average shoulder angle range around 50 degrees to 150 degrees during the shoulder flexion/extension task.
Table 6.10 Average Shoulder Joint Angle Range of Motion (Extension (-), Flexion (+)) and Standard Deviations (STDEV) While Performing the Shoulder Flexion / Extension Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Shoulder Flexion/Extension</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>MAX STDEV</td>
</tr>
<tr>
<td>Able-Bodied Subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>149.08</td>
<td>23.16</td>
</tr>
<tr>
<td>Amputee Subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sound Arm</td>
<td>149.48</td>
<td>18.91</td>
</tr>
<tr>
<td>Prosthetic</td>
<td>144.50</td>
<td>26.97</td>
</tr>
</tbody>
</table>

6.6.3 Shoulder Rotation Range of Motion

During the shoulder rotation task, both able-bodied and amputee subjects performed with greater arm symmetry during the virtual reality (VR) session verses the non-virtual reality (NOVR) session. For the able-bodied subjects, greater right shoulder ROM was demonstrated during the NOVR session, whereas greater left shoulder ROM was demonstrated during the VR session. Although the able-bodied subjects demonstrated greater ROM with the right shoulder during the NOVR session, there was a significantly greater offset between the arms (p=0.001). Therefore during the VR session, subjects were able to adjust by increasing the ROM with their left arm and decreasing the ROM with their right arm, to perform with greater arm symmetry to perform more optimally.

Similar results were shown with the amputee subjects. During the NOVR session, amputee subjects demonstrated a 116.6-degree shoulder ROM with their sound arm and an 86.9-degree shoulder ROM with their prosthetic side. Looking at the VR session, the amputee subjects demonstrated a 100.1-degree shoulder ROM on their sound arm side, and a 102.2-degree shoulder ROM with their prosthetic side. As described, greater shoulder ROM was performed on their sound arm during the NOVR session and significantly greater shoulder ROM was performed on their prosthetic side during the VR session. Comparing the average shoulder
rotation angles on the prosthetic side, amputee subjects demonstrated greater maximum values (p=0.065) and significantly greater ROM (p=0.031) with VR. During the VR session, amputee subjects only had a 2-degree difference in ROM, whereas during the NOVR session, subjects demonstrated a 30-degree difference in ROM between their sound arm and prosthetic side. This demonstrates that amputee subjects performed with a significantly greater offset during the NOVR session compared to the session with VR (p=0.001). This indicated that subjects were able to adjust and perform with greater symmetry during the VR session. This is shown below in Figure 6.3.

Figure 6.3 Average Shoulder Rotation Range of Motion (Internal (-), External (+)) While Performing the Shoulder Rotation Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
Table 6.11 Average Shoulder Rotation Range of Motion (Internal (-), External (+)) and Standard Deviations (STDEV) While Performing the Shoulder Rotation Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Shoulder Rotation</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>MIN</td>
</tr>
<tr>
<td></td>
<td>STDEV</td>
<td>STDEV</td>
</tr>
<tr>
<td>Able-Bodied Subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>31.95</td>
<td>-26.35</td>
</tr>
<tr>
<td>Right</td>
<td>62.30</td>
<td>-25.15</td>
</tr>
<tr>
<td>Amputee Subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sound Arm</td>
<td>83.75</td>
<td>-32.85</td>
</tr>
<tr>
<td>Prosthetic</td>
<td>61.60</td>
<td>-25.27</td>
</tr>
</tbody>
</table>

6.6.4 Torso Lateral Bend Range of Motion

Overall, during the torso lateral bend, subjects demonstrated greater torso range of motion during the VR session compared to the NOVR session. Able-bodied subjects had an average ROM 68.1-degrees during the NOVR session and 69.0-degrees during the VR session. Amputee subjects had an average ROM of 56.1-degrees during the NOVR session and 60.5-degrees during the VR session. Amputee subjects demonstrated greater torso angles on both their left and right sides during the VR session while performing the torso lateral bend task. This is shown below in Figure 6.4.
Figure 6.4 Average Torso Tilt Range of Motion (Left (-), Right (+)) While Performing the Torso Lateral Bend Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Table 6.12 Average Torso Tilt Range of Motion (Left (-), Right (+)) and Standard Deviations (STDEV) While Performing the Torso Lateral Bend Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Testing Sessions

<table>
<thead>
<tr>
<th>Torso Lateral Bend</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>MIN</td>
</tr>
<tr>
<td>Amputee Subjects</td>
<td>28.80</td>
<td>-27.26</td>
</tr>
</tbody>
</table>

6.6.5 Torso Rotation Range of Motion

During the Torso rotation task, there were no significant differences between the VR and NOVR sessions. Able-bodied subjects demonstrated slightly greater torso rotation ROM during the VR session, and amputee subjects demonstrated slighter greater ROM during the NOVR session. Differences in ROM were not shown to be statistically significant. This is shown below in Figure 6.5.
Table 6.13 Average Torso Rotation Range of Motion (Right (-), Left (+)) and Standard Deviations (STDEV) While Performing the Torso Rotation Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Testing Sessions

<table>
<thead>
<tr>
<th>Torso Rotation</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>MAX STDEV</td>
</tr>
<tr>
<td>Amputee Subjects</td>
<td>32.52</td>
<td>7.15</td>
</tr>
</tbody>
</table>

6.7 Movement Symmetry

The path of motion throughout the tasks that required symmetry between both sides were examined by calculating the shoulder angles of both the right and left arms for able-bodied subjects and sound arm and prosthetic side for amputee subjects. The shoulder angles were found for the non-virtual reality (NOVR) and virtual reality (VR) testing sessions. The shoulder angles calculated were normalized to show the average path of motion of all subjects from 0 to 100 percent task completion. The average path of motion of able-bodied and amputee subjects are
shown below for one ROM, ADL, and RTD task. Overall it was demonstrated that subjects performed tasks with greater arm symmetry during the VR verses NOVR session. In some cases subjects also exhibited greater joint angle ROM and greater maximum angles during the VR testing session.

6.7.1 Shoulder Flexion Task

The shoulder range of motion throughout the shoulder flexion / extension range of motion (ROM) task is shown below in Figure 6.6 for able-bodied subjects and Figure 6.7 for amputee subjects. The path of motion for the able-bodied subjects shows an overall less offset between arms throughout entire task during the VR session. Greater ROM with both arms during the VR session was also shown. Looking at Figure 6.7, amputee subjects also demonstrated greater ROM with both their sound arm and prosthetic side during the VR session, as well as a greater maximum value. Less offset between sides was also shown at the maximum shoulder flexion around 35% of task completion during the VR verses NOVR session. Overall greater symmetry between sides was also shown throughout the entire task with the VR feedback.
Figure 6.6 Shoulder Joint Angle Range of Motion (Extension (-), Flexion (+)) of Right (Solid Line) and Left (Dotted Line) Arms of Able-Bodied Subjects, While Performing the Shoulder Flexion / Extension Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions.

Figure 6.7 Shoulder Joint Angle Range Of Motion (Extension (-), Flexion (+)) of Sound Arm (Solid Line) and Prosthetic Device Side (Dotted Line) Of Amputee Subjects, While Performing the Shoulder Flexion / Extension Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions.
To get a closer look at the average offset between the sound arm and prosthetic side of the amputee subjects during the shoulder flexion / extension task, the difference in the shoulder angles were plotted in Figure 6.8. As shown below, during the NOVR session, amputee subjects had an overall greater difference between their shoulders, representing a significantly greater average offset between arms (p=0.001).

![Figure 6.8](image)

**Figure 6.8 Average Difference in Shoulder Flexion Angles Between the Sound Arm and Prosthetic Side of Amputee Subjects While Performing the Shoulder Flexion / Extension Task During the Virtual Reality (VR) and Non-Virtual Reality (NOVR) Sessions**

### 6.7.2 Bilateral Lift Task

The shoulder range of motion throughout the bilateral lift for the activities of daily living (ADL) task is shown below in Figure 6.9 for able-bodied subjects and Figure 6.10 for amputee subjects. Looking at Figure 6.9, although not a significant difference, able-bodied subjects demonstrated a greater maximum shoulder flexion and overall greater ROM during the VR session. Greater offset between the arms were also shown throughout majority of the task. Looking at the path of motion for the amputee subjects (Figure 6.10), overall less of an offset
between the sound arm and prosthetic side is shown throughout the task while performing the bilateral lift with the VR visual feedback.

Figure 6.9 Shoulder Joint Angle Range of Motion (Extension (-), Flexion (+)) of Right (Solid Line) and Left (Dotted Line) Arms of Able-Bodied Subjects, While Performing the Bilateral Lift Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Figure 6.10 Shoulder Joint Angle Range of Motion (Extension (-), Flexion (+)) of Sound Arm (Solid Line) and Prosthetic Device Side (Dotted Line) of Amputee Subjects, While Performing the Bilateral Lift Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
To get a closer look at the average offset between the sound arm and prosthetic side of the amputee subjects during the bilateral lift task, the differences in the shoulder angles were plotted in Figure 6.11. As shown below, during the NOVR session, amputee subjects had an overall greater difference between their shoulders, representing a significantly greater average offset between arms (p<0.001).

![Figure 6.11 Average Difference in Shoulder Flexion Between the Sound Arm and Prosthetic Side of Amputee Subjects While Performing the Bilateral Lift Task During the Virtual Reality (VR) and Non-Virtual Reality (NOVR) Sessions](image)

Although differences are still evident in Figure 6.10 and figure 6.11, there was great variability found between the five amputee subjects, causing the average curves to not be an accurate representation of all the subjects. To view the variability between the amputee subjects while performing the bilateral lift task, the average shoulder flexion with standard deviations (shown as the shaded area) of their prosthetic side during the VR session was plotted in Figure 6.12. As shown their were high standard deviations with shoulder angles ranging from 0° to 90°.
To view a better representation of the offset between the sound arm and prosthetic sides, and differences between the sessions, one individual amputee subject’s path of motion was displayed in Figure 6.13. Figure 6.13 below demonstrates the path of motion of both their shoulders during the NOVR and VR sessions, revealing greater differences. As shown, this subject demonstrated a significantly greater offset between their sound arm and prosthetic side during the session without virtual reality (NOVR). The subject was able to adjust their arm placement and movement to perform with greater arm symmetry during the bilateral lift task when provided the virtual reality visual feedback. As exhibited in Figure 6.13, although the subject reduced the shoulder flexion of their sound arm, this allow them to adjust their positioning of the sound arm to perform in line with their prosthetic side, and complete the bilateral lift with more optimal movement.
6.7.2.1 Percentage of Shoulder Range of Motion Used

Since subjects were instructed to lift the weighted basket as high as possible during the bilateral lift task, it was important to evaluate the maximum shoulder flexion used in comparison to the average maximum shoulder flexion obtainable by both able-bodied and amputee subjects. To further assess the bilateral lift task through investigation of the movement symmetry of the shoulders, the percentage of accessible shoulder range of motion used while completing the task was determined for all subjects. Tables 6.14 and 6.15 below compare the shoulder flexion range of motion during the bilateral lift task to the range of motion assessment task. Table 6.14 displays the average maximum shoulder flexion angle of both sides reached by able-bodied and amputee subjects during the ROM task and bilateral lift task. Table 6.15 presents the average percentage of shoulder flexion range of motion used during the bilateral lift. As shown,
during the VR session, on average all subjects were able to use a greater percentage of their accessible shoulder range of motion while completing the bilateral lift task.

Table 6.14 Average Maximum Shoulder Flexion Angles Obtained While Performing the Shoulder Range of Motion (ROM) and Bilateral Lift Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions.

<table>
<thead>
<tr>
<th>Maximum Shoulder Flexion Angle (°)</th>
<th>During Range of Motion</th>
<th>During Bilateral Lift</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NOVR</td>
<td>VR</td>
</tr>
<tr>
<td>Able-Bodied Subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>149.08</td>
<td>148.72</td>
</tr>
<tr>
<td>Right</td>
<td>151.55</td>
<td>148.38</td>
</tr>
<tr>
<td>Amputee Subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sound Arm</td>
<td>149.48</td>
<td>147.31</td>
</tr>
<tr>
<td>Prosthetic</td>
<td>144.50</td>
<td>144.41</td>
</tr>
</tbody>
</table>

Table 6.15 Average Percentage of Maximum Shoulder Flexion Used While Completing the Bilateral Lift Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions.

| Average Percentage of Maximum Shoulder Flexion Used During Bilateral Lift Task |
|---------------------------------|--------|------|
| Subjects                        | Side   | NOVR | VR  |
| Able-Bodied Subjects            |        |      |     |
| Left                            | 81%    | 87%  |
| Right                           | 79%    | 86%  |
| Amputee Subjects                |        |      |     |
| Sound Arm                       | 42%    | 45%  |
| Prosthetic                      | 42%    | 46%  |

6.7.3 Helmet Task

The shoulder range of motion throughout the helmet donning / doffing return to duty (RTD) task is shown below in Figure 6.14 for able-bodied subjects and Figure 6.15 for amputee subjects. Figure 6.14 shows able-bodied subjects to demonstrate significantly less of an offset
between arms, allowing for greater arm symmetry during the VR session. A greater maximum value was also reached during the VR session. Figure 6.15 also demonstrates an overall less offset and greater symmetry between the sound arm and prosthetic side during the VR session. Amputee subjects also exhibited greater maximum shoulder angles during the VR verses NOVR session.

To get a closer look at the average offset between the sound arm and prosthetic side of the amputee subjects during the helmet donning / doffing task, the differences in the shoulder angles were plotted in Figure 6.16. As shown below, during the NOVR session, amputee subjects had an overall greater difference between their shoulders, representing a significantly greater average offset between arms (p<0.001).
Figure 6.15 Shoulder Joint Angle Range Of Motion (Extension (-), Flexion (+)) of Sound Arm (Solid Line) and Prosthetic Device Side (Dotted Line) of Amputee Subjects, While Performing the Helmet Donning / Doffing Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Figure 6.16 Average Difference in Shoulder Flexion Angles Between the Sound Arm and Prosthetic Side of Amputee Subjects While Performing the Helmet Donning / Doffing Task During the Virtual Reality (VR) and Non-Virtual Reality (NOVR) Sessions
6.8 Pelvic Obliquity

Pelvic obliquity is when the pelvis is out of alignment and is defined as an abnormal tilt of the pelvis with respect to the spine. Pelvis Obliquity is the coronal-plane rotation of the pelvis, defined as the angle between the horizontal plane and the medial-lateral axis of the pelvis [47]. Positive pelvic obliquity was defined when the left anterior superior iliac spine was raised, and a negative value was when the right anterior superior iliac spine was raised. It is normal to have some degree of pelvic obliquity when standing with a mean of 1.18° [48]. Optimally subjects should demonstrate close to zero pelvic obliquity during stationary standing tasks and an even periodic cyclic curve on either size of zero when walking [47].

6.8.1 Range of Motion Tasks

The pelvic obliquity was investigated during the range of motion (ROM) tasks of able-bodied subjects (Figure 6.17) and amputee subjects (Figure 6.18) with (VR) and without (NOVR) the use of virtual reality. The values corresponding to each graph of pelvic obliquity during ROM tasks are depicted below in Tables 6.16 and 6.17 for able-bodied and amputee subjects, respectively.
Figure 6.17 Average Pelvic Obliquity (Right (-) / Left (+)) of Able-Bodied Subjects While Performing the Range Of Motion (ROM) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Table 6.16 Average Pelvic Obliquity (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able Bodied Subjects While Performing the Range of Motion Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Range of Motion Tasks</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV</td>
</tr>
<tr>
<td>Shoulder Flexion</td>
<td>-0.24</td>
<td>2.93</td>
</tr>
<tr>
<td>Shoulder Rotation</td>
<td>-0.52</td>
<td>2.79</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td>-0.62</td>
<td>2.75</td>
</tr>
<tr>
<td>Forearm Pronation</td>
<td>-0.64</td>
<td>2.68</td>
</tr>
<tr>
<td>Torso Rotation</td>
<td>1.05</td>
<td>3.29</td>
</tr>
<tr>
<td>Torso Lateral Bend</td>
<td>4.57</td>
<td>1.59</td>
</tr>
</tbody>
</table>
Figure 6.18 Average Pelvic Obliquity (Right (-) / Left (+)) of Amputee Subjects While Performing the Range Of Motion (ROM) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Table 6.17 Average Pelvic Obliquity (Right (-) / Left (+)) and Standard Deviations (STDEV) of Amputee Subjects While Performing the Range of Motion (ROM) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Range of Motion Tasks</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
</tr>
<tr>
<td>Shoulder Flexion</td>
<td>0.95</td>
<td>2.53</td>
</tr>
<tr>
<td>Shoulder Rotation</td>
<td>-0.52</td>
<td>1.58</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td>-0.63</td>
<td>2.81</td>
</tr>
<tr>
<td>Forearm Pronation</td>
<td>-1.31</td>
<td>2.03</td>
</tr>
<tr>
<td>Torso Rotation</td>
<td>1.52</td>
<td>1.87</td>
</tr>
<tr>
<td>Torso Lateral Bend</td>
<td>7.89</td>
<td>5.07</td>
</tr>
</tbody>
</table>

Overall subjects demonstrated less pelvic tilt during the VR session verses the NOVR session while performing majority of the tasks. Although subjects demonstrated less pelvic tilt
while performing the shoulder rotation, elbow flexion, forearm pronation, and the torso lateral bend, differences were not large enough to show statistical significance.

### 6.8.2 Activities of Daily Living Tasks

The pelvic obliquity was investigated during the activities of daily living (ADL) tasks of able-bodied subjects (Figure 6.19) and amputee subjects (Figure 6.20) with (VR) and without (NOVR) the use of virtual reality. The values corresponding to each graph of pelvic obliquity during ADL tasks are depicted below in Tables 6.18 and 6.19 for able-bodied and amputee subjects, respectively.

![Figure 6.19 Average Pelvic Obliquity (Right (-) / Left (+)) of Able-Bodied Subjects While Performing the Activities Of Daily Living (ADL) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions](image)
Table 6.18 Average Pelvic Obliquity (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able Bodied Subjects While Performing the Activities of Daily Living (ADL) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Activities of Daily Living Tasks</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
</tr>
<tr>
<td>Unilateral Lift</td>
<td>7.62</td>
<td>1.41</td>
</tr>
<tr>
<td>Object Transfer</td>
<td>-0.29</td>
<td>2.90</td>
</tr>
<tr>
<td>Drink</td>
<td>-0.09</td>
<td>2.88</td>
</tr>
<tr>
<td>Two Minute Walk</td>
<td>4.17</td>
<td>1.76</td>
</tr>
</tbody>
</table>

Figure 6.20 Average Pelvic Obliquity (Right (-) / Left (+)) of Amputee Subjects While Performing the Activities of Daily Living (ADL) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
Table 6.19 Average Pelvic Obliquity (Right (-) / Left (+)) and Standard Deviations (STDEV) of Amputee Subjects While Performing the Activities of Daily Living Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Activities of Daily Living Tasks</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
</tr>
<tr>
<td>Bilateral Lift</td>
<td>4.28</td>
<td>7.28</td>
</tr>
<tr>
<td>Unilateral Lift</td>
<td>3.39</td>
<td>6.36</td>
</tr>
<tr>
<td>Object Transfer</td>
<td>-0.47</td>
<td>1.50</td>
</tr>
<tr>
<td>Drink</td>
<td>-0.80</td>
<td>1.69</td>
</tr>
<tr>
<td>Two Minute Walk</td>
<td>4.36</td>
<td>2.64</td>
</tr>
</tbody>
</table>

As shown above, greater differences in pelvic obliquity between the NOVR and VR sessions were evident during the ADL tasks. Able-bodied subjects demonstrated greater pelvic obliquity while performing the bilateral lift during the NOVR verses VR session (p=0.082). Amputee subjects also demonstrated greater pelvic obliquity during the NOVR session, representing positioning significantly closer to the optimal motion during the VR session (p=0.033). Both able-bodied (p=0.019) and amputee subjects (p=0.183) also demonstrated greater pelvic tilt during the NOVR session while performing the unilateral lift task. Looking at the two-minute walking tasks able-bodied (p=0.037) and amputee subjects (p=0.111) had greater pelvic obliquity during the NOVR session, demonstrating less of a shift in their pelvis during the VR session. Although not shown to be statistically significant due to the high standard deviations, less pelvic obliquity was also demonstrated during the VR verses NOVR sessions while performing the object transfer and drinking tasks. To further investigate the differences in pelvic obliquity between NOVR and VR sessions, data from one amputee subject performing the bilateral lift, unilateral lift, and two minute walking task was considered.
6.8.2.1 Bilateral Lift

Looking specifically at one amputee subject performing the bilateral lift, significant differences between the NOVR and VR sessions were apparent. Figure 6.21 below demonstrates that during the NOVR session, the amputee subject performed the task with much greater pelvic tilt compared to the VR session. There was a $16.7^\circ$ difference between maximum pelvic obliquity reached during both sessions and a $9.18^\circ$ difference between the average angle demonstrated while performing the bilateral lift. This illustrates that this subject performed the bilateral lift task with less pelvic obliquity when provided the VR visual feedback, allowing for more optimal movements.

![Pelvic Obliquity During Bilateral Lift Task](image)

**Figure 6.21** Average Pelvic Obliquity (Right (-) / Left (+)) of One Amputee Subject While Performing the Bilateral Lift Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
6.8.2.2 Unilateral Lift

Looking specifically at one amputee subject performing the unilateral lift, a significant difference between the NOVR and VR sessions was apparent. Figure 6.22 below demonstrates that during the NOVR session, the amputee subject performed the task with greater pelvic tilt compared to the VR session. There was a 9.01° difference between the ranges of pelvic obliquity demonstrated during the VR verses NOVR sessions while performing the unilateral lift. The graph indicates that less pelvic obliquity was demonstrated while performing the unilateral lift task during the VR session.

![Figure 6.22 Average Pelvic Obliquity (Right (-) / Left (+)) of One Amputee Subject While Performing the Unilateral Lift Task During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions](image)

6.8.2.3 Two Minute Walk

Examining data from one amputee subject performing the two-minute walk test, the differences between the NOVR and VR sessions were evident. The subject demonstrated a
greater maximum degree of pelvic obliquity (4.43°) and greater range of pelvic obliquity (0.56° greater range) when performing the task during the NOVR session. Although differences in the range were minimal, noticeable differences in the average positions were greater. During the NOVR session the subject had an average position of 3.53°, oscillating approximately 3-degrees greater and less than this position. Since the subject only had positive pelvic obliquity during the NOVR session, this indicates that the subject’s pelvis was raised only on the left side, never raising to the right side or reaching the optimal neutral position of zero. Where as, during the VR session, the subject was able to adjust their average neutral position to 0.02° and had even pelvic obliquity on both the right and left sides, demonstrating a more optimal curve of pelvic obliquity.

It has been reported that on average a person without an amputation, walking at an individualized selected comfortable speed, typically exhibits -5° to 5° of pelvic obliquity, demonstrating a neutral position at zero. This shows the pelvis to rise evenly on either side when a step is taken with the corresponding leg, creating a cyclic periodic curve with each stride. [47] As shown in Figure 6.23, this is demonstrated more so by the subject during the VR session than during the session without the virtual reality visual feedback (NOVR).
Looking further into the differences between the NOVR and VR sessions, on average, subjects demonstrated a greater offset between shoulders during the session without the virtual reality visual feedback, as shown in Table 6.20. During the VR session, able-bodied (p=0.111) and amputee (p=0.118) subjects demonstrated less of an offset between shoulders, performing closer to the optimal motion.

Table 6.20 Average Shoulder Offset While Performing the Two-Minute Walking Task During the Non-Virtual Reality (NOVR) and Virtual-Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Average Offset Between Right and Left Shoulders (mm)</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Minute Walking Task</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Able-Bodied Subjects</td>
<td>11.00</td>
<td>9.49</td>
</tr>
<tr>
<td>Amputee Subjects</td>
<td>17.00</td>
<td>14.95</td>
</tr>
</tbody>
</table>
6.8.3 Return to Duty Tasks

The pelvic obliquity was investigated during the return to duty (RTD) tasks of able-bodied subjects (Figure 6.24) and amputee subjects (Figure 6.25) with (VR) and without (NOVR) the use of virtual reality. The values corresponding to each graph of pelvic obliquity during RTD tasks are depicted below in Tables 6.21 and 6.22 for able-bodied and amputee subjects, respectively. The only RTD task not reported here was the packing / unpacking of the rucksack. This was because no valuable biomechanical data were collected for this task. Since the subjects bent down to perform this task, all frontal markers were lost throughout portions of the trial, resulting in unusable data.

![Average Pelvic Obliquity Dring Return to Duty Tasks](image)

Figure 6.24 Average Pelvic Obliquity (Right (-) / Left (+)) of Able-Bodied Subjects While Performing the Return to Duty (RTD) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
Table 6.21 Average Pelvic Obliquity (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able Bodied Subjects While Performing the Return to Duty Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Return to Duty Tasks</th>
<th>NOVR MAX</th>
<th>STDEV MAX</th>
<th>MIN</th>
<th>STDEV MIN</th>
<th>VR MAX</th>
<th>STDEV MAX</th>
<th>MIN</th>
<th>STDEV MIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helmet</td>
<td>-0.99</td>
<td>2.41</td>
<td>-1.54</td>
<td>2.50</td>
<td>0.14</td>
<td>1.84</td>
<td>-0.24</td>
<td>1.86</td>
</tr>
<tr>
<td>Gun</td>
<td>-0.30</td>
<td>2.42</td>
<td>-1.79</td>
<td>2.44</td>
<td>0.41</td>
<td>1.97</td>
<td>-0.73</td>
<td>2.08</td>
</tr>
<tr>
<td>Two Minute Walk with Weighted Bag</td>
<td>4.77</td>
<td>1.57</td>
<td>-4.65</td>
<td>1.98</td>
<td>1.87</td>
<td>1.72</td>
<td>-5.57</td>
<td>3.05</td>
</tr>
</tbody>
</table>

Figure 6.25 Average Pelvic Obliquity (Right (-) / Left (+)) of Amputee Subjects While Performing the Return to Duty (RTD) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
Table 6.22 Average Pelvic Obliquity (Right (-) / Left (+)) and Standard Deviations (STDEV) of Amputee Subjects While Performing the Return to Duty Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Return to Duty Tasks</th>
<th>NOVR</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
</tr>
<tr>
<td>Helmet</td>
<td>-1.28</td>
<td>2.12</td>
</tr>
<tr>
<td>Gun</td>
<td>0.39</td>
<td>2.64</td>
</tr>
<tr>
<td>Two Minute Walk with Weighted Bag</td>
<td>3.90</td>
<td>1.73</td>
</tr>
</tbody>
</table>

As shown, overall less pelvic obliquity was demonstrated when performing the RTD tasks with the virtual reality visual feedback. Although differences were minimal, they were still evident across all tasks. Looking at the two-minute walk task carrying the weighted bag, both able-bodied (p=0.059) and amputee (p=0.095) subjects demonstrated less pelvic obliquity during the VR session.

6.8.3.1 Two Minute Walk Carrying Weighted Bag

Looking at the same individual amputee subject now performing the two-minute walking task carrying a weighted bag on their right side (Figure 6.26), it was evident that a shift in the degree of pelvic obliquity was made. As shown, during the NOVR session, the subject still performed the task with their pelvic obliquity mostly to the left with less than a one degree shift towards the right but a 3.7° decrease in the maximum. During the VR session, the subject still demonstrated a cyclic periodic pelvic obliquity curve on either side. Now with the weighted bag being carried while completing the walking task, the subject demonstrated slightly greater obliquity on the left side. This could be because the weight the subject was carrying with the bag on their right side, causing them to adjust their positioning.
Looking further into the differences between the NOVR and VR sessions in Table 6.23, once again subjects demonstrated a greater offset between shoulders during the session without the virtual reality visual feedback. On average able-bodied (p=0.238) and amputee (p=0.014) subjects demonstrated less of an offset between shoulders, performing closer to the optimal motion while performing the task during the VR session. Amputee subjects demonstrated an offset of 5.75-degrees less during the VR session compared to the NOVR session, showing statistical significant difference between the sessions (p=0.014).
Table 6.23 Average Shoulder Offset While Performing the Two Minute Walking Task Carrying a Weighted Bag During the Non-Virtual Reality (NOVR) and Virtual-Reality (VR) Sessions

<table>
<thead>
<tr>
<th>Average Offset Between Right and Left Shoulders (mm)</th>
<th>Two Minute Walking Task Carrying Weighted Bag</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Session: NOVR</td>
</tr>
<tr>
<td>Able-Bodied Subjects</td>
<td>12.50</td>
</tr>
<tr>
<td>Amputee Subjects</td>
<td>17.99</td>
</tr>
</tbody>
</table>

6.9 Torso Rotation

A direct correlation between pelvic obliquity and torso rotation has been reported with the idea that compensatory motions are demonstrated with the torso when greater pelvic obliquity occurs [48-50]. When analyzing the torso rotation for all subjects across all tasks for both sessions, no correlations were found with the significant abnormal pelvic obliquity values found. The only significant differences found, was with the amputee subjects performing the unilateral lift task. On average, amputee subjects had a 10.5° greater torso rotation while completing the task during the NOVR verses VR session. This directly correlates to the previous findings of greater pelvic obliquity when the subjects performed the unilateral lift during the NOVR session. When further investigating this correlation by comparing individual subject data, there were no direct correlations found between pelvic obliquity and torso rotation in the tasks tested. The complete torso rotation results can be found in Appendix F.
CHAPTER 7: DISCUSSION AND LIMITATIONS

This dissertation sought to advance knowledge and understanding within the field of upper-limb prosthetics. The impacts of the results could be highly advantageous to clinicians and prosthetic users by providing a platform for a controlled, individualized training regime. The enhancement of upper-limb prosthetic training and rehabilitation would be especially beneficial to improve user’s movement and functionality with their device. Using this developed virtual reality platform, patients were immersed into a virtual environment while provided real-time visual feedback of their instantaneous motion, along side an individualized predictive optimal goal motion.

The objective of this research project was to investigate the advantages of using virtual reality visual feedback for upper limb prosthetic training and rehabilitation. This idea was to eventually lead into the development of useful guidelines and recommendations to aid in the advancement of small-scale adaptable options for rehabilitation practitioners and at home use. This could be clinically significant by advancing knowledge and understanding within the field of upper limb prosthetic training and rehabilitation, while introducing an adaptable way to increase effectiveness, and greatly impact the future of prosthetic users.

7.1 Review of Hypotheses

It was hypothesized, that gaining a better understanding of upper extremity prosthetic training and rehabilitation techniques could lead to a more effective procedure to increase independence and functionality of prosthetic users. Allowing a patient to view their motion in
real-time along side an optimal motion, while providing quantitative measures with visual feedback, was hypothesized to significantly increase training and rehabilitation effectiveness for upper-limb prosthetic users. It was also hypothesized that greater improvements in movement symmetry and range of motion would be evident in subjects when using the virtual reality system versus non virtual reality training. It was thought that displaying an optimal target motion would encourage the subject to work towards completing the tasks in the most efficient and proper way. Integrating optimal model visualization and real time feedback with the CAREN system capabilities, upper extremity prosthetic training and rehabilitation was thought to enhance through improved movement symmetry, task performance and functional advances.

Although results did not reveal as many significant improvements in movement symmetry and range of motion as expected with the use of virtual reality, it is projected, when further analyzing data from additional amputee subjects, greater differences will be evident with greater beneficial results when using virtual reality therapy. From the results and the previous work found, it is evident that more research needs to be performed to evaluate the effectiveness of virtual reality as a rehabilitation tool and method for upper-limb amputees.

7.2 Review of Results

The motion-captured data along with the observations and patient feedback revealed that virtual reality could be effective for training and rehabilitating upper-extremity prosthetic users. The developed platform interface introduced a way to accurately model a full-body representation of the user’s motion in real time, along with a model animating the predicted and optimal motions of specified tasks. Various visualization options were provided to the participants to determine their preferred positioning of the models. The visualization options included the optimal model shown in front of the real time model, offset to the side, and overlaid
on top. Subjects were also given the option to have the optimal model animations displayed before and/or during the specified task. Out of the subjects tested, the most preferred visualization option was shown to be with the optimal model offset to the side of their personal real-time model, with the animation shown before and during the task. This visualization option was shown to be effective by displaying a demonstration of the motion prior to the start of the task and then again simultaneously while the subject was performing the task to give them an optimal goal motion to follow. This allowed users to judge where improvements needed to be made and allowed them to quickly adjust and perform more alike the optimal motion shown.

This interface was set up where the real-time and optimal model could be individualized to each user to make for a more accurate, patient specific regime. The developed interface also allowed for a playback of the real-time and optimal motions either individually or simultaneously, in any position desired by the user. This allows for both the patient and the practitioner or operator to assess movements to determine where improvements need to be made.

The patient feedback collected through the post-testing survey revealed that subjects (n=10) enjoyed performing the tasks more with the use of the feedback provided by the VR visualization than without. Subjects stated they felt more motivated to perform the tasks with proper movement since they were able to visualize their motions in real-time along side the optimal model. Overall subjects expressed they had a greater desire and motivation to perform the tasks with correct positioning when they had the optimal model and real time visual feedback. Majority of the subjects thought it was easier to view where improvements needed to be made with the virtual reality visual feedback, allowing for quick adjustments in order to perform with a more optimal motion. The patient feedback directly coincided with many of the observations noticed throughout the study.
7.2.1 Observations of Biomechanics, Posture, and Positioning

Observations revealed that subjects were able to execute the motions properly and overall closer to the optimal motions shown with the VR. The VR visualization forced the subjects to look forward and perform the tasks with more confidence. It was apparent that, when performing the tasks with the VR visual feedback, subjects were able to quickly adjust their positioning and perform the task with proper movements, closer to the optimal motion shown. This was specifically apparent during the drinking and gun shooting tasks where subjects were able to perform more alike the optimal model avatar when shown the VR visualization.

Overall through observations, it was noticed that without the visualization, subjects generally performed the tasks less balanced, and less symmetrical. These observations were supported and further verified with the motion-captured data and kinematic calculations.

7.2.2 Bilateral and Unilateral Lift Heights

Considering the lifting tasks, it was determined that overall subjects reached greater maximum heights and performed with greater symmetry during the VR sessions compared to the NOVR sessions. It was observed that subjects overall lifted the objects unbalanced and unsymmetrical during the bilateral and unilateral lifting tasks when not provided the VR visualization. In some cases, subjects adjusted their movement during the VR session when they could see they were performing uneven; they reduced the height they lifted the object in order to perform with more optimal motion. In other cases, the VR feedback allowed for subjects to lift the objects higher.

7.2.3 Joint Angle Range of Motion Comparisons

Although not all joint angle comparisons showed significant differences between sessions, overall greater maximum range of motion values were reached and tasks were
performed with greater symmetry during the VR sessions. With the virtual reality visual feedback, subjects were able to view their motions in comparison to the optimal motion, allowing for adjustments to be made. In some cases during the VR sessions, subjects were able to adjust by increasing the ROM on one side while decreasing the ROM of their other side, to perform with greater arm symmetry and perform the tasks with more optimal motions.

7.2.4 Movement Symmetry

Overall it was demonstrated that subjects performed tasks with greater arm symmetry during the VR verses NOVR sessions. In some cases subjects also exhibited greater joint angle ROM and greater maximum angles during the VR testing sessions. The path of motion performed by subjects revealed that greater movement symmetry was obtained with the virtual reality visual feedback. Less offset between right and left sides were evident throughout most tasks when performing with the VR visualization. Considering all the tasks analyzed for the movement symmetry, on average, amputee subjects all performed with less offset between their sound arm and prosthetic side during the VR session, demonstrating greater optimal performance.

Looking specifically at the bilateral lift task, overall users demonstrated more symmetrical movements and reached greater maximum heights while performing the tasks with the VR visualization. It was also examined that during the VR session, on average, all subjects were able to use a greater percentage of their accessible shoulder range of motion while completing the bilateral lift task. This validates that subjects completed the task with more optimal movements and greater function with the assistance of the visual feedback provided by the VR.
7.2.5 Pelvic Obliquity

In summary, pelvic obliquity is when the pelvis is out of alignment and is defined as an abnormal tilt of the pelvis with respect to the spine. Pelvis Obliquity is the coronal-plane rotation of the pelvis, defined as the angle between the horizontal plane and the medial-lateral axis of the pelvis [47]. Optimally subjects should demonstrate close to zero pelvic obliquity during stationary standing tasks and an even, periodic cyclic curve, on either side of zero when walking [47]. Overall subjects demonstrated less pelvic obliquity during the VR session verses the NOVR session while performing majority of the ROM, ADL, and RTD tasks. Although differences were not always shown to be statistically significant due to the high standard deviations, less pelvic obliquity was evident across most tasks while performing with the VR visualization.

Looking specifically at the bilateral and unilateral lift tasks, on average, all subjects performed the tasks with less pelvic obliquity throughout the entire duration of the task during the VR sessions. This confirms that subjects were able to monitor their motions and make adjustments to perform more optimally when provided the VR visual feedback.

Considering the two-minute walking with and without carrying the weighted bag, subjects also demonstrated less pelvic obliquity during the VR sessions. On average, subjects were able to perform the tasks more optimally by having less pelvic obliquity and demonstrating the same degree of obliquity to the right and left sides during the VR sessions. During the NOVR session it was evident that subjects had greater pelvic obliquity shifted to one side over the other, leading to an unsymmetrical and less optimal performance.

7.2.6 Conclusions and Comparison to Other Studies

In summary, overall subjects demonstrated improved movements and positions closer to the optimal model while performing the tasks with the virtual reality visual feedback. Although
not all differences were shown to be statistically significant, it is thought with the testing of additional subjects, greater differences will be evident. Exhibiting joint angle ROMs closer to the optimal motion shows reduced compensation for lack of movement or function, and therefore demonstrating reduced compensatory motion [51]. Reduced compensatory motion lessens the risk of misuse and injuries leading to overall a more advanced and functional performance of daily tasks. It had been reported that a successful training and rehabilitation program, significantly decreases the use of compensatory motion when completing daily tasks [51].

The anecdotal and quantitative results suggest that the use of virtual reality enhances the performance of subjects with a unilateral transradial amputation using a prosthesis. The visual feedback of the real-time and optimal models provided by the virtual reality, allowed for the subjects to adjust and correct their motion to perform tasks with more optimal motion and without compensating with other joint movements. Performing the task with less pelvic obliquity, greater arm symmetry, and overall closer to the optimal model, demonstrated reduced compensation for lack of movement or function, and therefore performance with greater optimal motion.

The visual feedback, along with the quantitative data collected, allowed for the patient and operator to know where improvements had to be made while providing an accurate assessment of the patient’s developments. A variety of studies have shown great improvements in task performance with the use of virtual reality [8, 25-37]. A successful training program incorporates practice and feedback elements necessary for maximal motor recovery. Providing virtual feedback on performance is an effective technique to enhance training and rehabilitation of upper limb amputees [2, 30-34]. Although not many advanced studies have been performed on upper-limb prosthetic users, virtual reality has been shown to be an effective tool for a variety of
other patient populations. Specifically, virtual reality has been shown to significantly enhance training and rehabilitation in patients following a stroke, exclusively in upper-limb movements [52-58]. The few studies found using VR to train amputees who use an upper-limb prosthesis were training with the DEKA arm to specifically practice operating the foot controls [2], to program and practice using EMG controlled devices [30,31], and reaching for a virtual image or following a prerecorded trajectory of motion [29]. All were shown to be an effective use of virtual reality to enhance training and improve movements of users. In all of these cases virtual reality was used to provide visual feedback of the patient’s hand, arm, or just the upper-body. None of the studies found for upper-limb prosthetic training demonstrated a full body representation of the user in a virtual environment. The only case found using a full-body representation of the user was used for treating phantom-limb pain and did not directly correspond to the user’s motion in real-time [25]. Therefore the platform interface developed in this study greatly advances current virtual reality training programs while aiming to enhance training and rehabilitation procedures for upper-limb prosthetic users. Most of the studies testing the effectiveness of virtual reality were through observations and completeness of task, whereas this dissertation investigated the biomechanical differences to quantify the improvements.

For instance, Crosbie’s study looking at virtual reality for upper-limb rehabilitation following a stroke, concluded that using virtual reality would lead to improved rehabilitation outcomes [27]. This was evaluated and reported through several questionnaires that revealed VR to be associated with better task performance. Although the questionnaires were on a scoring system to quantify the differences, a biomechanical analysis was not performed to quantify the improvements in joint positioning, posture, or movements. This was the same for Piron’s study where significant improvements in upper-limb movements were reported with the use of VR,
where it was quantified through patient feedback from a questionnaire and through a measurement scale assessment taken by the physical therapist [29]. Resnik’s studies investigating the use of virtual reality to facilitate training with advanced upper-limb prosthesis, stated that improvements were evident with the use of VR [2,8]. The results revealed that subjects were able to perform more of functional controls of the myoelectric prosthesis when training with VR, indicating VR to be a valuable tool for prosthetic training.

Instead of solving for joint angle range of motions throughout tasks like performed in this dissertation, Kaliki’s study evaluated the total workspace covered during certain tasks [30]. Looking at an XZ plot of the workspace, the total area covered by the user’s arms during tasks with and without virtual reality was evaluated. It was demonstrated that greater workspace was covered when performing the tasks with VR, which directly correlates to the findings in this dissertation, where overall greater joint angle range of motions were evaluated when performing the tasks with VR.

Although differences between virtual reality and non-virtual reality training for upper-limb rehabilitation have been assessed, complete biomechanical evaluations of subjects’ joint angles have not been reported. This dissertation filled the gap and further verified the findings by quantifying the demonstrated improvements in upper-limb training and rehabilitation with the use of VR.

The use of virtual reality to display the real-time and optimal models, were shown to overall improve the performance of the subjects tested. Effectiveness of the use of virtual reality was evaluated and assessed. The findings provided guidelines and recommendations to aid in the development of small-scale adaptable options for practitioners and at home use to positively impact upper-limb prosthetic training and rehabilitation procedures.
7.3 Guidelines and Recommendations for Adaptable System

The idea of this study was to evolve the developed program interface into an adaptable system to be used by clinicians and for at-home use. From testing the virtual reality program interface, guidelines and recommendations for an adaptable system can be extracted by evaluating the successes of the regime. For an adaptable system, it is thought that it would be beneficial to incorporate the individualized real-time and optimal models, with the various visualization options available. The real-time model would directly correspond to the user’s motion in real-time. The optimal model would predict and demonstrate the goal motion for the user to follow while incorporating patient-specific parameters. The adaptable system should allow for the patient parameters to be entered into the system databases to individualize the program, and allow for several selections to be made. The models should be able to be visualized in various positions and at various times. This would allow the user to individualize the training regime and both models to their specific parameters, skills, and desires. The option to choose the size, positioning, and speed would be enabled. It would also allow for the selection of patient-specific parameters such as individual goals and what type of device is being used, with the optimal model reflecting the proper limitations from the results of the predictive model. The adaptable system would also allow for playback of the real-time model demonstrating the motions previously performed by the user. The playback could be viewed in any desired position, along with visualization of the optimal model. This would allow the user to assess their movements in various positions and fully analyze their performance.

The adaptable system should be allowed to be taken home for continual training and should be set up where the patient data collected during at-home sessions would be sent to their therapist or clinician. This would allow for the progress to be assessed in order to determine
where improvements needed to be made and to tailor the training regime to the individual. The system would be adaptable where it could be used at home and/or in the clinic. In either circumstance, the operator would be able to individualize and tailor the training regime to the patient based on their parameters and improvements assessed. This would allow for continual improvement since the tasks could be increased in difficulty based on performance. This would also allow for a consistent training regime for prosthesis users, giving them access to expertise care, no matter their location.

The adaptable at home system should be set up like a gaming system for a user-friendly environment. Commercial gaming systems, such as the Xbox Kinect or Wii Fit, have been shown to be effective for virtual reality training systems in a variety of studies [59-64]. It is thought that incorporating the developed platform interface from this dissertation into a gaming system, would allow for an effective adaptable system to be used in various clinics and for at-home use. This would present a tool to assist in training while introducing an alternative procedure for clinicians to consider for rehabilitating upper-limb amputees. This would advance the field of prosthetics by introducing a way to standardize care and expand the expertise in the field. An adaptable system for upper-extremity prosthetic users could be clinically significant to introduce a way to effectively train and rehabilitate procedures to assist in returning amputees to the highest level of function and independence possible. The same idea and procedure could be addressed for any rehabilitation regime requiring training to perform certain tasks with proper movement and joint positioning. This could be transitioned to other patient populations with limiting physical disabilities requiring training, assistive device training, as well as training for athletes to perfect a certain movement (i.e. golf swing or baseball swing). The guidelines and
recommendations for an adaptable system provided in this dissertation could be beneficial to consider for various training and rehabilitating procedures.

The developed platform interface presented in this dissertation could easily be transitioned into an adaptable training system by purchasing a small-scale system that allowed D-Flow programming to run. Another, more affordable option, would be to transition the D-Flow programming script to a gaming system’s specific programming platform. This could be done using the program Unity-3D (Unity Technologies, San Francisco, CA), which is a licensed game engine using JavaScript and/or C++ language. Unity is often used to program 3D video/virtual games and can be used with a variety of current gaming and computer systems. Further information on coding software and possible implementation methods should be investigated.

7.4 Clinical Impact

Despite all the technological advancements in the field, upper-extremity prosthetics accounts for a small fraction of the prosthetics field. It has been reported that an average of 132,198 new amputations occur each year in the United States, where as only 18,496 of those are upper-extremity amputations, and of those, only 1,900 are above the wrist [65]. It is reported that upper-limb amputee patients are outnumbered 30:1 by lower-limb amputee patients, causing a significantly low number of specialists in the field. Although there is no official designation or criteria to distinguish upper-limb specialists in the field, a list of the practitioners that are known to be leaders and experts in the U.S. have been reported [66]. Hess reported that only four multi-state facilities are designated as specialists in upper-limb prosthetics, with each facility only being represented in a few states. Only 16 out of the 50 states in the U.S. were reported to have an expert in upper-limb prosthetics, with most states only having one location. Out of the 16 states, only four were reported to have more than one expert in the field [66]. This limits the
available care for upper-limb amputees, resulting in patients having to travel to the specified locations if they wish to receive quality, expertise care. Many practitioners are unfamiliar with the new, advanced technology resulting in providing little to no training with the devices, and sometimes even resulting in prescribing a lower level prosthesis [66]. This typically results in a high number of unsatisfied patients making the prosthesis rejection and abandonment rate significantly high at 45-75% [9,10,11]. With a lack of expertise in the field, upper-limb amputees are typically left with the lack of functionality, usability and knowledge the device. This results in improper movements, causing compensatory motions leading to injuries of other joints, and / or abandonment of the device all together, which in return causes overuse injuries of their sound arm [51,67,68]. With the advanced technology and high functioning devices available for those with an amputated upper-limb, there should be no reason for abandonment or miss-use of the devices. Therefore, the need for successful training procedures for upper-extremity amputees is substantially high. A successful training and rehabilitation program would allow the patient to return to their daily life duties at the most functional level of independence possible with the use of all prosthetic control capabilities [13]. Amputees with proper training have been shown to perform tasks with more optimal movements, greater usability, functionality, and overall results in reduced rejection rates. [10,16]. An advanced regime to improve all these parameters, would be significantly impactful for prosthesis users.

This dissertation aimed to advance the knowledge and provide evidence of an effective training regime to enhance upper-limb prosthetic use and performance. A successful training and rehabilitation process could greatly impact the use of prosthetics and aid in improving the overall quality of life for upper-limb amputees. The results from this study are clinically significant by
introducing a way to effectively train upper-limb amputees with sufficient expertise and knowledge to allow the user to obtain advanced use and function with their personal device.

The impact of these results lead into guidelines and recommendations for adaptable systems for clinics and at home use. This greatly impacts the future of upper-extremity prosthetics by introducing a consistent, controlled, and reliable process to train users. A small-scale adaptable system for clinics and at-home use would be beneficial by proving an individualized, patient and device specific, training regime to assist users in reaching the highest level of function and independence possible with their device. The idea of the adaptable system would allow for amputees to train with their device and master optimal motions individualized to their skills and needs. It would then allow for a playback of the motions performed for the user to assess and to be sent to the therapist or clinician for proper monitoring of the patient’s progress. This would eventually permit assess to expertise training in the field to any user, at any location, using any device, greatly impacting the future of upper-extremity prosthetics.

7.5 Limitations

The major limitation of this study is the amount of subjects tested. The small sample size limits the power and impact of the results. Although the sample size of five unilateral transradial amputees is greater than most in upper limb prosthetics, it is still a limitation that should be addressed in future studies. Since a convenience sample of test subjects was recruited, not all subjects had received that same amount of training and were performing at the same functional level with their prosthetic device, causing variations to the data. Testing of other amputation levels and prosthetic systems will be needed to further validate the procedures.

Another limitation is the use of the CAREN system. Using the CAREN system limits the type of tasks that could be tested. There are some tasks and movements the subjects were not
able to perform on the CAREN system due to the space and restrictions of the safety rails and harness. This potentially could have limited the movements and full range of motions they performed with. However, the intention of this work was not to eliminate traditional modes of training and rehabilitation, but to complement existing procedures by providing a tool to enhance results. The CAREN system setup and operation is also very expensive, making it difficult to implement into a typical clinical settings and impossible for at home use. However, there are currently four different military treatment facilities with the CAREN system in the U.S. that patients could be referred to if necessary. Although the expenses may limit the use of the CAREN system, the idea of this study is to use the results for a valuable database of knowledge and set of recommendations for developing an affordable and adaptable virtual reality training procedure for clinicians and at home use to enhance current training and rehabilitation methods.

Another limitation when using virtual reality is the patient’s aversion to the technology. Some people may have sensitivity to certain virtual environment that could cause adjustments in performance. Also this study did not consider the eyesight of the participants. Since the virtual reality sessions required visualization of the models, it may have been important to consider the eyesight of all participants.

As expected, another limitation of the study was human error. When using passive reflective markers in motion-capture studies, proper placement of the markers is crucial. Although the same marker set was used for all participants, the placement could be slightly off due to human error. Even though a standardized placement procedure was in place and great care was taken when placing the markers, shift in the placement could have occurred causing variations in the data collected.
Overall a relatively small sample size was collected, and therefore more data would be needed before further conclusions can be made.
CHAPTER 8: CONTRIBUTIONS AND FUTURE WORK

A new training platform was designed and developed to incorporate a real-time and optimal motion model for the amputee to visualize while performing the tasks with the use of virtual reality. Effectiveness of the use of virtual reality was evaluated and assessed. The findings provided guidelines and recommendations to aid in the development of small-scale adaptable options for practitioners and at home use to positively impact upper-limb prosthetic training and rehabilitation procedures. The work from this dissertation has provided many contributions to the areas of biomechanics, prosthetics and physical medicine fields. This work has documented biomechanics and kinematic data of upper-extremity prosthetic users performing range of motion, activities of daily living, and return to duty tasks. The data collected on five transradial amputees represents one of the larger sample sizes in the field of upper-extremity prosthetics and especially in virtual reality training, currently reported in the literature. Although, additional participants are needed in order to increase the power of the study and impact of the results. This dissertation introduced a complete biomechanical analysis on upper-limb training using virtual reality, which has not yet been reported in the literature. Also, reports of testing upper-limb amputees performing return to duty tasks are limited. This dissertation introduced additional, unique tasks, and provided a biomechanical analysis of the subject’s performance with and without the use of virtual reality visual feedback.
Although this dissertation advanced knowledge and understanding within the field, providing various contributions to state of science, future work should involve investigating these findings further with additional test subjects and data analyses.

8.1 Contributions

The work in this dissertation has made several contributions to the areas of basic and applied research in upper-extremity prosthetics. The main contributions are:

1. A full-body real-time motion capture model was developed and incorporated into a virtual reality system to provide the user with instant visual feedback of their motion.

2. An individualized full-body character avatar was developed to animate optimal motions for the user to follow and allow for the input of individualized optimal or predictive motions optimized per capabilities of the user. This could be based on the Robotics Based Human Upper Body Model (RHBM) or other desired joint angle values entered into the system.

3. Ways to effectively visualize the real-time and optimal models were discovered based on the preference of the subject’s tested.
   i. The models can be overlaid on top of one another, offset in any direction, or placed side-by-side.
   ii. The optimal model can be animated before and/or during the task.
   iii. The models can also be played back to demonstrate the user’s motion in comparison to the optimal model.
4. Expands and improves the database in the field of upper-extremity amputees.
   
i. Unilateral transradial amputees’ biomechanics and kinematic data during range of motion, activities of daily living, and return to duty tasks has been documented. This can be used for additional comparative studies in upper-extremity prosthetics, or for clinicians when assessing patient data and training procedures.

   ii. Motion-captured data was collected on upper-limb amputees performing unique activities of daily living and return to duty tasks.

   iii. Expands the knowledge in the field of upper extremity prosthetics and provides additional data to help quantify disability.

   iv. Differences were found between the amputee and able-bodied subjects, between the amputee’s sound arm and prosthetic side, and between movements with and without the virtual reality visual feedback. This contributes to the general knowledge of the impact of using a prosthesis for everyday activities, as well as, increases the awareness of the advantages of virtual reality training.

5. Evidence was provided that visual feedback using virtual reality is effective for training and rehabilitating upper-limb prosthetic users.

   i. Advances the knowledge of using virtual reality for training and rehabilitation to increase the chance of being accepted by clinicians for therapy and training techniques.
6. Provides useful guidelines and recommendations to aid in the development of small-scale adaptable options for rehabilitation practitioners and at home use.

7. A consistent, efficient, safe, and controlled protocol was presented to increase the effectiveness of training and rehabilitation regimes for users.

The methods investigated and developed in this dissertation are beneficial to researchers, practitioners, clinicians, and prosthetic users. This dissertation advanced discovery and understanding while promoting teaching, training, and learning in the field of upper-extremity prosthetics. An effective prosthetic training and rehabilitation regime is advantageous in returning the patient to the highest level of independence and functioning possible. This project sought to enhance the overall infrastructure of research in training and rehabilitation. The results from this study introduced a way to significantly improve upper-limb prosthetic training and rehabilitation while providing useful guidelines and recommendations for an adaptable system for clinics and at home use to assist in the training process for prosthetic users. An adaptable system that a prosthetic user could use to enrich the training and rehabilitation process, would significantly impact and improve their overall quality of life while greatly contributing to the state of science. These advancements could be used to integrate civilians back into the community or return patients to active duty after an amputation. These results can also be implemented into other centers with a CAREN system or be used to implement into a small-scale adaptable system. The techniques investigated in this study can also be useful for lower-limb amputee, post-stroke, traumatic brain injury, and poly-trauma patients.
8.2 Future Work

Continued research investigating the use of virtual reality for upper-extremity prosthetic training and rehabilitation is needed. Through the work and findings investigated throughout this study, factors were discovered that could be investigated further to contribute to the field. Testing of additional subjects, at various amputation levels, using various prosthetic device systems, will be needed to further validate these methods. A larger sample size will allow for greater outcome measures and additional validation of the findings.

In addition to more subjects tested, other tasks such as occupational therapy tasks requiring small motor skills should be included. Since it is important to be able to perform small, fine motor skills with upper-limb prosthetic devices in order to complete daily occupational tasks, it may be beneficial to assess the effectiveness of training for these tasks with the virtual reality feedback. It would be beneficial to also include additional ADL and RTD tasks to expand the biomechanical database of upper-limb prosthetic users performing various tasks. Additional measures would also be important, such as considering the subject’s vision and eye movement. Since training with the use of VR required visualization of the virtual screen, it would be important to assess the subject’s ability to see. Since not all humans have the same level of vision, it may be important to consider this when further evaluating the effectiveness of VR training. The subject’s eye movement may be another important outcome measure to consider when evaluating VR training to assess where the subject’s focus mostly on when performing the task in the virtual environment. This measure could help to better develop an effective virtual reality training platform demonstrating both the real-time and optimal models in the best positioning with the best visualization option.
Additional survey questions should also be included when further testing subjects. An expansion of survey question can help to get a better idea of the patient’s health or well-being and also in obtaining valuable user feedback. A survey questionnaire with a scale portion would also be useful to quantify the feedback and to provide a questionnaire score for the analysis.

A future study could further evaluate the pelvic obliquity of upper-limb amputees, especially in gait analysis studies. With additional subjects tested, with various amputation sides’ levels, and devices used, further analyses could be investigated. There aren’t many studies looking at the changes in gait for upper-limb prosthetic users and the affect on the pelvic obliquity. This study did not look at the gait and force feedback of the users when walking with and without the use of the virtual reality visual feedback, but this would be an important measure to consider. From the data collected, it was evident that differences may exists in the gait and further analysis should be done on the pelvic obliquity in relation to the side amputated. It would be interesting to see how the gait and pelvic obliquity is affected in relation to the side amputated and type of device used, with and without the virtual reality feedback. Arm and shoulder postures are additional measures that should be considered when assessing the gait and pelvic obliquity of upper-limb prosthetic users.

Additional work should also involve testing subjects performing tasks with the virtual reality for several successive trials. Just looking at the data from the virtual reality training, it is indicative that greater noticeable improvements could be shown after consecutively performing the tasks with the virtual reality visualization of their real time and individualized optimal model. This suggested study would compare the data to a control group of amputee patients performing the tasks without the use of any virtual reality feedback to assess the improvements made between successive trials.
Physicians, physical therapists, prosthetists, amputees, and other specialists in the field, should also continue to be consulted. This will allow for additional valuable feedback to be obtained on the findings and help to validate results to continue to develop useful guidelines and recommendations. This could also add to aiding in the development of small-scale adaptable options for rehabilitation practitioners and at home use.

The methods used in this study were only tested on unilateral transradial amputees but should be expanded to patients with other levels of amputation, as well as other patient populations with physical limitations who are in need of training and rehabilitation. Additional outcome measures and collected data would further validate and emphasize the importance of the findings.

The investigative and developmental methods presented in this study offer a well-designed, effective approach to upper-extremity prosthetic training and rehabilitation. The results from this study and related future work, hope to enhance prosthetic training and rehabilitation methods to assist in returning patients to the highest level of independence and functioning possible. The findings intend to help improve the overall quality of life of amputees and greatly impact the future of prosthetic users.
REFERENCES


68. Jones LE, Davidson JH. *Save that Arm: A study of problems in the remaining arm of unilateral upper limb amputees.* Prosthetics Orthotics International 1999; 23; 55-58
APPENDICES
Appendix A: IRB Approved Study Protocol

IRB Study Protocol

The Use of a Virtual Reality System to Enhance Upper Extremity Prosthetic Training and Rehabilitation

PI: Ashley Knight

Rationale for the Study
The proposed project will greatly contribute to the state of science and patient care. This study will create an effective training and rehabilitation regime for upper limb prosthetic users to improve the amputee’s ability to integrate back into their daily routine. This regime will develop a way for users to visualize the best, most optimal movement to complete a task, while viewing their real time motion for comparison for superb results. This system will also be used for prescription to determine the most valid prosthetic design and training program for an individual. This training and rehabilitation regime will be designed to become adaptable for clinicians and at home therapy through an affordable virtual reality system. This proposed project will benefit prosthesis users, including veterans and the active military who are trying to return to duty. An effective training and rehabilitation program will greatly impact amputees by improving their quality of life through enhanced training and rehabilitation therapy.

Background
Approximately one in every 160 Americans are currently living with an amputated limb. There are nearly 2 million people with a limb loss in the United States, with around 50,000 new amputations occurring each year. According to the National Center for Health Statistics, the ratio of upper limb to lower limb amputation is 1:4, with the most prominent causes of upper extremity amputation, in order of incidence being, trauma, including war related injuries, diseases, and congenital limb deficiencies. Upper extremity amputation due to trauma and war related injuries make up 77% of the upper limb amputated population, making it the major cause of hand or arm loss.

The sudden loss of a hand or arm causes the loss of fine, coordinated movements of the upper limb, reduced joint range of motion, tactile sensation, reduced proprioceptive feedback and aesthetic appearance, all which can be improved with the use of a prosthesis. After proper postoperative therapy, wound healing, and pre-prosthetic therapy, a patient can be successfully fitted for a prosthesis. In order to maximize the functional potential of the prosthesis and support prosthetic control motions, it is essential for the patient to maintain scapular, glenohumeral, forearm, and elbow joint range of motion. Maintenance of joint range of motion, increasing upper-limb muscle strength, and gaining maximal functional independence are all crucial elements to ensure patient success with the prosthesis, making the training and rehabilitation phase significantly important. A successful training and rehabilitation program allows the patient to return to their daily life duties at the most functional independence possible with the use of all prosthetic control capabilities. Since a successful training and rehabilitation program is
essential, the need for advanced rehabilitation techniques is substantially high. A significant need for more studies on military service members with amputations are in high demand in order to develop innovative training and therapeutic approaches to advance rehabilitation techniques, especially for higher functioning amputees with the goal of returning to duty (RTD) in the military or the civilian community. It has been noted that training with virtual reality is particularly valuable for upper-limb prosthetic users since it provides immediate feedback to the patient.  

Virtual reality training allows the user to view their motion in real time and simultaneously make improvements. Motek Medical’s Computer Assisted Rehabilitation Environment (CAREN) system has been shown to be an effective prosthetic training and rehabilitation tool for patient assessment and improvements for a quick return to active duty or the civilian community. CAREN is a multimodal system consisting of a 10 camera real time motion capture system (Vicon, Nexus, Englewood, CO), with a 6 degree of freedom hydraulic base with a double-belted instrumented treadmill and a 180 degree cylindrical screen projection system to allow for a virtual reality immersive environment. It is thought that using the CAREN system while providing an optimal goal motion will enhance training and rehabilitation for upper limb prosthetic users through improved joint range of motion and movement symmetry. The objective of this research project is to investigate the advantages of using virtual reality for upper limb prosthetic training and rehabilitation while providing the patient with an optimal goal motion.

Objectives/ Research Questions

The proposed project is to develop an effective prosthetic training and rehabilitation regimen, with the use of virtual reality, to return patients to the highest level of independence and functioning possible. The Computer Assisted Rehabilitation Environment (CAREN) system (Motek Medical, Netherlands) will be used to immerse patients into real life situations while providing real time visual feedback of their motion to improve the training and rehabilitation of upper limb prosthetic users. The specific aims include;

**Aim 1:** Provide a real time avatar of the user’s motion to display real time visual feedback to the users. Determine the most effective way to display this visualization.

**Aim 2:** Create and incorporate individualized optimal motion models (optimized per capabilities of the subject) into a virtual reality system. Determine the most effective way to display the visualization of the optimal model.

**Aim 3:** Determine if the visual feedback using virtual reality is effective for training and rehabilitating upper-limb prosthetic users.

**Aim 4:** Determine if virtual reality is an effective rehabilitation and training method for upper extremity prosthetic users and rehabilitation practitioners while providing useful information and developing a small-scale adaptable option for at home use.

Figure A.2 IRB Approved Study Protocol, Page Two
**Study Design**
Prior to participation, all subjects will sign an informed consent. Each subject will participate in two sessions, one with the use of virtual reality and one without. The order each subject completes the sessions will be predetermined by a random generator. Each session will last 1-2 hours, consisting of a series of range of motion (ROM) tasks, activities of daily living (ADL), and return to duty (RTD) tasks.

**Participants and Sample Size**
The patient population for this study will be healthy individuals (n=10) and individuals with a unilateral upper limb amputation who uses a prosthesis (n=20). The upper limb prosthesis users will consist of transhumeral or transtential amputations with the use of body powered or myoelectric devices. A total of thirty subjects will be tested in this study.

**Inclusion and Exclusion Criteria**
Participants will be between the ages of 18-65. Healthy subjects must be free of any health ailment that would impair physical function, and amputee subjects must not have any injuries or surgeries on the affected limb within the past 90 days.

**Expected Results**
It is expected that the use of virtual reality will enhance upper limb prosthetic training and rehabilitation. Virtual reality training will provide users with a safe and interactive environment to master range of motion movements essential to complete activities of daily living, all while providing visualization of the real time motion along with an individualized projected optimal goal motion. This system will provide accurate and advance analysis of the subject and provide real time visual feedback to both the operator and subject. This could be especially beneficial to improve and increase the effectiveness of upper limb prosthetic training and rehabilitation. It is thought that displaying an optimal target motion will encourage the subject to work towards completing the tasks in the most efficient and proper way. The visual feedback, along with the quantitative data collected, will allow for the patient and operator to know where improvements must be made while providing an accurate assessment of the patient’s developments. The use of virtual reality for upper limb prosthetic training has been shown to be highly advantageous and effective for upper limb prosthetic training. Therefore, it is expected that adding the features of the CAREN system, while providing the optimized goal motion along side the real time motion, will provide greater improvements. This will be clinically significant to upper limb prosthetic training and rehabilitation programs by introducing an adaptable way to increase effectiveness and greatly impact the future of prosthetic users.

**Description of the Roles of Study Staff**
The study is being conducted at the Center for Assistive Rehabilitation and Robotics Technology Lab at the University of South Florida. The Principal Investigator/Student Investigator is Ashley Knight. The Co-Investigators/ Faculty Advisors involved in this study are Dr. Stephanie Carey, and Dr. Rajiv Dubey.
Risk to Subjects
This study intends to improve the prescription, design, training, and testing of upper limb prosthetic users. There are no major risks associated with this study. The risks are minimal and may include slight skin irritation due to the adhesive on the double-sided tape used to place the markers on the skin, and slight discomfort when removing the tape. All safety procedures developed with the CAREN system will be followed to ensure a safe environment. The CAREN system is equipped with a safety cage and all subjects will wear a harness that prevents them from falling or injuring themselves. The operator or participant can shut down the complete system immediately if anything goes wrong. A study staff member will be standing alongside the subject to guarantee safety while stepping onto the system and to ensure the harness is attached correctly. The CAREN system is used in several locations in the United States for performing similar methods as proposed here, and it has been used for rehabilitation on individuals with amputations. The system is depicted below in Figure 1.

![Figure 1. The CAREN system](image)

Experimental Procedures
Once a subject agrees to participate and sign the consent form, a few measurements including height, weight and anatomical measurements such as arm length and width, will be recorded and 40 reflective markers will be attached to the subject’s body with double-sided tape adhesive. The subject will then be asked to carefully step onto the platform with the guidance of a study staff member and the safety harness will be put on the subject. A study staff member will ensure that the harness is adjusted correctly and will catch them in case they fall. The staff member attaches the harness to the safety cage using a locking carabiner. The subject will be notified before moving the motion platform and will be given proper instructions throughout the entire study.
The subjects will be asked to participate in two 1-2 hour sessions to test the ROM, ADL and RTD tasks with and without the use of virtual reality. All amputee subjects will be required to wear their same preferred prosthetic device for all sessions. The ROM tasks include, elbow flexion/extension, forearm pronation/supination, shoulder flexion/extension, shoulder abduction/adduction, shoulder rotation, torso flexion/extension, torso lateral flexion, and torso rotation. The ADL tasks would include a series of tasks to encompass typical active one would encounter on a daily basis such as, drinking from a cup, bilateral and unilateral lift tasks, and a reach and grasp test. Subjects will also be asked to perform a two-minute walk test at a self-selected speed. The RTD tasks would include a series of tasks service members typically perform in their daily work routine such as donning and doffing a jacket and helmet, packing and unpacking a rucksack, and carrying a weapon.

The subjects will be asked to complete each task three times. Prior to performing a task, when participating in the virtual reality session, the task will be demonstrated on the virtual screen with an animated model. The motion of the animated model will be determined by previously collected data to accurately predict the correct motion for each individual. An avatar of the subject will then be shown on the screen through a program in DFlow (Motek Medical, Netherlands). The animated model and avatar will be created in Maya 3D modeling software (Autodesk Inc., U.S.) and exported to DFlow (Motek Medical, Netherlands) on the CAREN system through an Ogre 3D exporter (OgreMax, Inc.). The reflective markers that were strategically placed on the subject will be connected to the corresponding joint on the virtual avatar to accurately animate the real-time motion of the subject on the virtual screen using the Vicon Nexus (Englewood, CO) motion capture system in conjunction with DFlow (Motek Medical, Netherlands). The demonstrated model will be shown simultaneously with the real-time avatar to show the accuracy of the subject’s performance in relation to the individualized predicted optimized motion. This will provide instant visual feedback to the subject.

The motion captured data along with the joint center measurements of each subject will be imported into Visual 3D (C-Motion, Georgetown, MD) software to calculate the joint angles through Euler angle transformation matrices. The elbow, glenohumeral, and torso angle range of motions will all be found for both the virtual reality and non-virtual reality groups. The ROM of the elbow, glenohumeral, and torso will all be calculated from optimal motion analysis data for a measure of comparison. The joint angle ROMs of both groups, for all tasks, will be compared to one another, and to the optimal motion data, to determine if there are improvements in the movements using virtual reality training. It is thought when doing the tasks on the CAREN system, with an optimized goal motion shown, the subjects will have improved movement symmetry and demonstrate joint angle ROMs closer to the optimal motion.

Exhibiting joint angle ROMs closer to the optimal motion shows reduced compensation for lack of movement or function, and therefore demonstrating reduced compensatory motion. The movement symmetry of each trial will be compared to the predicted model to determine how close the subject’s movement is to the optimized goal motion. Since
Appendix B: IRB Approval Letters

B.1 IRB Initial Review Study Approval Letter

Figure B.1 IRB Initial Review Study Approval Letter, Page One
(4) Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing.

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

As the principal investigator of this study, it is your responsibility to conduct this study in accordance with IRB policies and procedures and as approved by the IRB. Any changes to the approved research must be submitted to the IRB for review and approval via an amendment. Additionally, all unanticipated problems must be reported to the USF IRB within five (5) calendar days.

We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

[Signature]

E. Verena Jorgensen, M.D., Chairperson
USF Institutional Review Board
B.2 IRB Continuing Review Study Approval Letter

10/3/2016

Ashley Knight
Chemical and Biomedical Engineering
4202 East Fowler Ave
Tampa, FL 33620

RE: Expedited Approval for Continuing Review
IRB#: CR1_Pro00016934
Title: The Use of a Virtual Reality System to Enhance Upper Extremity Prosthetic Training and Rehabilitation

Study Approval Period: 10/29/2016 to 10/29/2017

Dear Dr. Knight:

On 10/3/2016, the Institutional Review Board (IRB) reviewed and APPROVED the above application and all documents contained within including those outlined below.

Approved Item(s):
Protocol Document(s):
The Use of a Virtual Reality System to Enhance Upper Extremity Prosthetic Training and Rehabilitation Protocol

Consent/Assent Document(s)*:
Consent Form.pdf

*Please use only the official IRB stamped informed consent/assent document(s) found under the "Attachments" tab on the main study's workspace. Please note, these consent/assent document(s) are only valid during the approval period indicated at the top of the form(s) and replace the previously approved versions.

Please Note: USF HRPP policy 11.1 states "The original signed hardcopy of the entire informed consent document must be maintained in the PI’s research records and available to the IRB upon request."

Figure B.3 IRB Continuing Review Study Approval Letter, Page Three
The IRB determined that your study qualified for expedited review based on federal expedited category number(s):

(4) Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing.

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

As the principal investigator of this study, it is your responsibility to conduct this study in accordance with USF HRPP policies and procedures and as approved by the USF IRB. Any changes to the approved research must be submitted to the IRB for review and approval by an amendment. Additionally, all unanticipated problems must be reported to the USF IRB within five (5) calendar days.

We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

E. Verena Jorgensen, M.D., Chairperson
USF Institutional Review Board
Appendix C: Amputee Subject Recruitment

C.1 IRB Approved Amputee Subject Recruitment Flyer

![RESEARCH PARTICIPANTS NEEDED](image)

Researchers from the University of South Florida are recruiting healthy adult unilateral (or bilateral) upper limb (transradial or transhumeral) amputee volunteers to participate in a research study investigating upper limb prosthetic training and rehabilitation using a virtual reality system with a motion capture system, treadmill, moving platform, and a 180°cylindrical screen for an immersive real time experience. The purpose of this study is to develop a more advanced and effective training and rehabilitation regime for upper limb prosthetic users.

**Participant requirements:**
- Have a transradial or transhumeral amputation (unilateral or bilateral)
- Must use a body powered or myoelectric prosthetic device
- Must have the ability to perform simple activities of daily living and range of motion movements without assistance
- Must be over the age of 18
- Need to participate in one 2hr session at the Computer Assisted Rehabilitation Environment (CAREN) laboratory located at:

  **University of South Florida**
  **Interdisciplinary Research Building; IDR 114**
  **3720 Spectrum Blvd, Tampa, FL**
- Must not be allergic to adhesive that will be used to place markers on skin.
- Must wear a dark, tight fitting shirt and tight pants or shorts.
- Sign an informed consent form.

**Participants will be compensated with a Visa gift card after session.**

Participation in this study is entirely voluntary. If you are interested in participating in this study or have questions about the study, please contact:

  **Ashley Knight**
  **adknight@mail.usf.edu**
  **607-743-8555**

Figure C.1 IRB Approved Amputee Subject Recruitment Flyer
C.2 Subject Recruitment Online Posting

Researchers from the University of South Florida as part of the Center for Assistive Rehabilitation and Robotics Technology (CARRT) Lab are recruiting healthy adult unilateral or bilateral upper limb (transradial or transhumeral) amputee volunteers to participate in a research study investigating upper limb prosthetic training and rehabilitation using a virtual reality system. The purpose of this study is to compare user’s performance with and without the use of virtual reality to develop an effective prosthetic training and rehabilitation program to improve the amputee’s ability to integrate back into their daily routine. This regime will develop a way for users to visualize the best, most optimal movement to complete a task, while viewing their real time motion for comparison for superb results. This system will also be used for prescription to determine the most valid prosthetic design and training program for an individual. This study will be conducted on the Computer Assisted Rehabilitation Environment (CAREN) system, which is a multimodal virtual reality system consisting of a 10 camera real time motion capture system so the environment can respond to the user's motion, a 6 degree of freedom movable base, with an instrumented split-belt treadmill, and a 180 degree cylindrical screen projection system to allow for a virtual reality immersive environment. The CAREN system is designed for rehabilitation and training and has safety incorporated in many ways. The purpose of this study is to develop a more advanced and effective training and rehabilitation routine for upper limb prosthetic users. This training and rehabilitation regime will be designed to become adaptable for clinicians and at home therapy through an affordable virtual reality system. The study will consist of one session lasting approximately 2 hours and will take place at the Center for Assistive Rehabilitation and Robotics Technology Lab located in Tampa, Florida. Participants will be compensated for time involved in study.

If interested in becoming involved or for any further information please contact: Ashley Knight at adknight@mail.usf.edu or at 607-743-8555.

Thank you!

Figure C.2 Subject Recruitment Information Posted on the TRS Prosthetics Inc. and Clinical Trials .Gov Websites
Appendix D: Data Collection Documents

D.1 Random Order Generator

Table D.1 Random Number Generator From Excel Used to Determine the Order of Testing Sessions. First Session Tested With Virtual Reality is 1 and Without Virtual Reality is 2

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D.2 IRB Approved Informed Consent 2015-2016 Version

Informed Consent to Participate in Research and Authorization to Collect, Use, and Share your Health Information

Pro # 00016934

You are being asked to take part in a research study. Research studies include only people who choose to take part. This document is called an informed consent form. Please read this information carefully and take your time making your decision. Ask the researcher or study staff to discuss this consent form with you, please ask him/her to explain any words or information you do not clearly understand. We encourage you to talk with your family and friends before you decide to take part in this research study. The nature of the study, risks, inconveniences, discomforts, and other important information about the study are listed below.

We are asking you to take part in a research study called:

The Use of a Virtual Reality System to Enhance Upper Extremity Prosthetic Training and Rehabilitation.

The person who is in charge of this research study is Ashley Knight. This person is called the Principal Investigator. However, other research staff may be involved and can act on behalf of the person in charge. She is being guided in this research by Dr. Stephanie Carey and Dr. Rajiv Dubey.

The research will be conducted at the Center for Assistive Rehabilitation and Robotics Technology Lab in the Interdisciplinary Research Building (IDRB 114) at the University of South Florida.

This research is being sponsored by the U.S. Department of Defense.

Purpose of the study

The purpose of this study is to compare user’s performance with and without the use of virtual reality to develop an effective prosthetic training and rehabilitation program to improve the amputee’s ability to integrate back into their daily routine. This regime will develop a way for users to visualize the best, most optimal movement to complete a task, while viewing their real time motion for comparison for superb results. This system will also be used for prescription to determine the most valid prosthetic design and training program for an individual. This study will be conducted on the Computer Assisted Rehabilitation Environment (CAREN) system, which is a multimodal virtual reality system consisting of
a 10 camera real time motion capture system so the environment can respond to the user’s motion, a 6 degree of freedom movable base with an instrumented split-belt treadmill, and a 180 degree cylindrical screen projection system to allow for a virtual reality immersive environment. The CAREN system is designed for rehabilitation and training and has safety incorporated in many ways. This training and rehabilitation regime will be designed to become adaptable for clinicians and at home therapy through an affordable virtual reality system.

Why are you being asked to take part?

We are asking you to take part in this research study because you are able-bodied with no physical impairments. Or you are an upper limb prosthetic user with a unilateral, transradial or transhumeral amputation. We want to determine if this procedure would be effective to improve the training and rehabilitation processes for upper limb prosthetic users.

Study Procedures: What will happen during this study?

If you take part in this study, you will be asked to:

- Wear tight fitting clothing.
- Answer some general questions such as your age, occupation, level of activity, and hobbies practiced.
- Answer some health related questions. For amputees only: questions such as date of injury, cause of injury, years of prosthetic use, type of prosthesis, level of amputation, and skin tissue type.
- Forty small (approximately 0.5 inch in diameter) spherical markers will be taped to specific points on your body, including you arms, hands, torso, and legs. These markers reflect infrared rays that are detected by the cameras in order to record your motion throughout the study.
- Wear a safety harness that will be attached to the safety cage while on the CAREN system.
- Follow instructions given by the study staff to perform simple range of motion tasks, activities of daily living, and return to duty tasks. Each task will be explained in detail and repeated three times. These tasks will be used to assess your performance ability, improvements made throughout the study, and to compare performance between study visits.

A study visit is one you will have with the person in charge of the study or study staff. You will need to come for 2 study visits. Most study visits will take about 2 hours.

Total Number of Participants

About 30 individuals will take part in this study at USF.

Alternatives / Voluntary Participation / Withdrawal

You do not have to participate in this research study.
You should only take part in this study if you want to volunteer. You should not feel that there is any pressure to take part in the study. You are free to participate in this research or withdraw at any time. There will be no penalty or loss of benefits you are entitled to receive if you stop taking part in this study.

You can decide after signing this informed consent document that you no longer want to take part in this study for any reason at any time. If you decide you want to stop taking part in the study, tell the study staff as soon as you can.

Please note, even if you want to stay in the study, there may be reasons we will need to withdraw you from the study. You may be taken out of this study if we find out it is not safe for you to stay in the study or if you are not coming for the study visits when scheduled. We will let you know the reason for withdrawing you from this study.

**Benefits**

You will receive no direct benefit(s) by participating in this research study, but it may be beneficial to the development of upper limb prosthetic training and rehabilitation.

**Risks or Discomfort**

This research is considered to be minimal risk. That means that the risks associated with this study are the same as what you face every day. There are no known additional risks to those who take part in this study.

**Compensation**

We will pay you $15/hour in the form of a gift card for the time you volunteer to participate in this study. Transportation to the study site will not be provided but parking will be free.

**Costs**

It will not cost you anything to take part in the study.

**Privacy and Confidentiality**

We will keep your study records private and confidential. Certain people may need to see your study records. Anyone who looks at your records must keep them completely confidential. These individuals include:

- The research team, including the Principal Investigator, study coordinator, research nurses, and all other research staff.
- Certain government and university people who need to know more about the study. For example, individuals who provide oversight on this study may need to look at your records. This is done to make sure that we are doing the study in the right way. They also need to make sure that we are protecting your rights and your safety.
- Any agency of the federal, state, or local government that regulates this research. This includes the Department of Health and Human Services (DHHS) and the Office for Human Research Protection (OHRP)
The USF Institutional Review Board (IRB) and its related staff who have oversight responsibilities for this study, and staff in USF Research Integrity and Compliance.

We may publish what we learn from this study. If we do, we will not include your name. We will not publish anything that would let people know who you are.

What if new information becomes available about the study?
During the course of this study, we may find more information that could be important to you. This includes information that, once learned, might cause you to change your mind about being in this study. We will notify you as soon as possible if such information becomes available.

You can get the answers to your questions, concerns, or complaints.
If you have any questions, concerns or complaints about this study, call Dr. Stephanie Carey at 813-974-5765. If you have questions about your rights, complaints, or issues as a person taking part in this study, call the USF IRB at (813) 974-5638.

By signing this form, you are giving your permission to use and/or share your health information as described in this document. As part of this research, USF may collect, use, and share the following information:

- Your research record
- Your anthropometric measurements (height, weight, limb lengths) collected during this study.
- Personal information asked during this study (date of birth, age, level of activity, general health).
- For amputees only: questions asked during this study such as date of injury, cause of injury, years of prosthetic use, type of prosthesis, level of amputation, and skin tissue type.
- Motion-capture video recordings of completion of tasks during this study.

You can refuse to sign this form. If you do not sign this form you will not be able to take part in this research study. However, your care outside of this study and benefits will not change. Your authorization to use your health information will not expire unless you revoke (withdraw) it in writing. You can revoke this form at any time by sending a letter clearly stating that you wish to withdraw your authorization to use your health information in the research. If you revoke your permission:

- You will no longer be a participant in this research study;
- We will stop collecting new information about you;
- We will use the information collected prior to the revocation of your authorization. This information may already have been used or shared with others, or we may need it to complete and protect the validity of the research; and
- Staff may need to follow-up with you if there is a medical reason to do so.

To revoke this form, please write to:
Stephanie Carey, Ph.D.
For IRB Study # Pro00016934
University of South Florida
Mechanical Engineering Dept.
4202 E. Fowler Ave. ENB 118
Tampa, FL 33612
While we are conducting the research study, we cannot let you see or copy the research information we have about you. After the research is completed, you have a right to see the information about you, as allowed by USF policies.

Consent to Take Part in Research

I freely give my consent to take part in this study and authorize the use of my health information as outlined above. I understand that by signing this form I am agreeing to take part in research. I have received a signed copy of this form to take with me.

______________________________
Signature of Person Taking Part in Study
______________________________
Printed Name of Person Taking Part in Study

______________________________
Signature of Person Obtaining Informed Consent
______________________________
Printed Name of Person Obtaining Informed Consent
D.3 IRB Approved Informed Consent 2016-2017 Version

Informed Consent to Participate in Research and Authorization to Collect, Use, and Share your Health Information

Pro # 00016934

You are being asked to take part in a research study. Research studies include only people who choose to take part. This document is called an informed consent form. Please read this information carefully and take your time making your decision. Ask the researcher or study staff to discuss this consent form with you, please ask him/her to explain any words or information you do not clearly understand. We encourage you to talk with your family and friends before you decide to take part in this research study. The nature of the study, risks, inconveniences, discomforts, and other important information about the study are listed below.

We are asking you to take part in a research study called:

The Use of a Virtual Reality System to Enhance Upper Extremity Prosthetic Training and Rehabilitation.

The person who is in charge of this research study is Ashley Knight. This person is called the Principal Investigator. However, other research staff may be involved and can act on behalf of the person in charge. She is being guided in this research by Dr. Stephanie Carey and Dr. Rajiv Dubey.

The research will be conducted at the Center for Assistive Rehabilitation and Robotics Technology Lab in the Interdisciplinary Research Building (IDRB 114) at the University of South Florida.

This research is being sponsored by the U.S. Department of Defense.

Purpose of the study

The purpose of this study is to compare user’s performance with and without the use of virtual reality to develop an effective prosthetic training and rehabilitation program to improve the amputee’s ability to integrate back into their daily routine. This regime will develop a way for users to visualize the best, most optimal movement to complete a task, while viewing their real time motion for comparison for superb results. This system will also be used for prescription to determine the most valid prosthetic design and training program for an individual. This study will be conducted on the Computer Assisted Rehabilitation Environment (CAREN) system, which is a multimodal virtual reality system consisting of...
a 10 camera real time motion capture system so the environment can respond to the user’s motion, a 6 degree of freedom movable base with an instrumented split-belt treadmill, and a 180 degree cylindrical screen projection system to allow for a virtual reality immersive environment. The CAREN system is designed for rehabilitation and training and has safety incorporated in many ways. This training and rehabilitation regime will be designed to become adaptable for clinicians and at home therapy through an affordable virtual reality system.

**Why are you being asked to take part?**

We are asking you to take part in this research study because you are able-bodied with no physical impairments. Or you are an upper limb prosthetic user with a unilateral, transradial or transhumeral, amputation. We want to determine if this procedure would be effective to improve the training and rehabilitation processes for upper limb prosthetic users.

**Study Procedures: What will happen during this study?**

If you take part in this study, you will be asked to:

- Wear tight fitting clothing.
- Answer some general questions such as your age, occupation, level of activity, and hobbies practiced.
- Answer some health related questions. For amputees only: questions such as date of injury, cause of injury, years of prosthetic use, type of prosthesis, level of amputation, and skin tissue type.
- Forty small (approximately 0.5 inch in diameter) spherical markers will be taped to specific points on your body, including you arms, hands, torso, and legs. These markers reflect infrared rays that are detected by the cameras in order to record your motion throughout the study.
- Wear a safety harness that will be attached to the safety cage while on the CAREN system.
- Follow instructions given by the study staff to perform simple range of motion tasks, activities of daily living, and return to duty tasks. Each task will be explained in detail and repeated three times. These tasks will be used to assess your performance ability, improvements made throughout the study, and to compare performance between study visits.

A study visit is one you will have with the person in charge of the study or study staff. You will need to come for 2 study visits. Most study visits will take about 2 hours.

**Total Number of Participants**

About 30 individuals will take part in this study at USF.

**Alternatives / Voluntary Participation / Withdrawal**

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Benefits
You will receive no direct benefit(s) by participating in this research study, but it may be beneficial to the development of upper limb prosthetic training and rehabilitation.

Risks or Discomfort
This research is considered to be minimal risk. That means that the risks associated with this study are the same as what you face every day. There are no known additional risks to those who take part in this study.

Compensation
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We will keep your study records private and confidential. Certain people may need to see your study records. Anyone who looks at your records must keep them completely confidential. These individuals include:

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- Certain government and university people who need to know more about the study. For example, individuals who provide oversight on this study may need to look at your records. This is done to make sure that we are doing the study in the right way. They also need to make sure that we are protecting your rights and your safety.
- Any agency of the federal, state, or local government that regulates this research. This includes the Department of Health and Human Services (DHHS) and the Office for Human Research Protection (OHRP)
The USF Institutional Review Board (IRB) and its related staff who has oversight responsibilities for this study, and staff in USF Research Integrity and Compliance.

The sponsor of this study: U.S. Department of Defense

We may publish what we learn from this study. If we do, we will not include your name. We will not publish anything that would let people know who you are.

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- Your anthropometric measurements (height, weight, limb lengths) collected during this study.
- Personal information asked during this study (date of birth, age, level of activity, general health).
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- Motion-capture video recordings of completion of tasks during this study.

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- We will stop collecting new information about you;
- We will use the information collected prior to the revocation of your authorization. This information may already have been used or shared with others, or we may need it to complete and protect the validity of the research; and
- Staff may need to follow-up with you if there is a medical reason to do so.

To revoke this form, please write to:
Stephanie Carey, Ph.D.
For IRB Study # Pro00016934
University of South Florida
Mechanical Engineering Dept.
4202 E. Fowler Ave. ENB 118
Tampa, FL 33612

Figure D.9 IRB Approved Informed Consent, 2016-2017 Version, Page Four
While we are conducting the research study, we cannot let you see or copy the research information we have about you. After the research is completed, you have a right to see the information about you, as allowed by USF policies.

Consent to Take Part in Research
I freely give my consent to take part in this study and authorize the use of my health information as outlined above. I understand that by signing this form I am agreeing to take part in research. I have received a signed copy of this form to take with me.

Signature of Person Taking Part in Study

Date

Printed Name of Person Taking Part in Study

Statement of Person Obtaining Informed Consent and Research Authorization
I have carefully explained to the person taking part in the study what he or she can expect from their participation. I confirm that this research subject speaks the language that was used to explain this research and is receiving an informed consent form in their primary language. This research subject has provided legally effective informed consent.

Signature of Person Obtaining Informed Consent

Date

Printed Name of Person Obtaining Informed Consent

Figure D.10 IRB Approved Informed Consent, 2016-2017 Version, Page Five
D.4 Picture Release Form

Adult Release Form

I do hereby grant to Photographer, ____________________________, and to his/her employees or assigns, permission to photograph and/or capture video of me, and use such images in any manner consistent with the promotion of The University of South Florida, and it’s affiliated agencies. Such use to include, but is not limited to: publication, display, advertising, editorial illustration, web use, broadcast, etc. I hereby swear that I am an adult of sound mind and body, and agree to all terms stated above.

Description of Shoot:

____________________________________

Subject’s Name (Printed):

____________________________________

Subject’s Name (Signature):

____________________________________

Date:

____________________________________

Witness:

____________________________________

Figure D.11 Picture Release Form for Data Collections
### D.5 Protocol Testing Checklist

<table>
<thead>
<tr>
<th>Subject:</th>
<th>Date:</th>
</tr>
</thead>
</table>

- [ ] Calibrate System - cameras and force plates
- [ ] Random generator in Excel to determine order of testing
- [ ] Brief explanation of testing, give subject protocol document to review
- [ ] Informed Consent signed
- [ ] Picture Release Form signed
- [ ] Attach 39 reflective markers to subject
- [ ] Take anatomical measurements - fill out subject form
- [ ] Put subject on system - Attach harness
- [ ] Ensure all markers appear in Vicon
- [ ] Display force feedback in real-time
- [ ] Calibrate subject - record T-pose & Dynamic calibration (~20 Seconds)
- [ ] Run core processing and Label markers
- [ ] Run Static and functional subject calibration, dynamic gait model & Save.
- [ ] Go Live - ensure segments and forces are displayed in D-Flow
- [ ] Static Trial - Record T-pose for 5 seconds
- [ ] Test for preferred avatar visualization option: OFFSET OVERLAID IN FRONT
- [ ] Match optimal motion animation speed to patient

- [ ] Model visualization: SHOW or HIDE

---

- [ ] Range of Motion (ROM) Tasks (x3)
  - [ ] Elbow Flexion/Extension
  - [ ] Shoulder Rotation
  - [ ] Forearm Pro/Supination
  - [ ] Torso Right/Left Lateral Bend
  - [ ] Shoulder Flexion/Extension
  - [ ] Torso Right/Left Rotation

---

Figure D.12 Protocol Testing Checklist for Data Collections, Page One
- Activities of Daily Living (ADL) Tasks (x3)
  - Two-minute walk test (x1)
  - Drink from a cup
  - Cup transfer
  - Bilateral reach/grasp lift - laundry basket w/ 5lbs lift as high as possible
  - Unilateral reach/grasp lift – brace weight lift with one hand-curl
- Return to Duty (RTD) Tasks (x3)
  - Hold and shoot weapon replica-start at side, raise, cock and shoot
  - Pack/unpack rucksack- sheet, brace weight, stick, & two blocks into bag (x2)
  - Two minute walk with packed bag (carrying at side) (x1)
  - Donning/Doffing helmet

- Model visualization: SHOW or HIDE

- Range of Motion (ROM) Tasks (x3)
  - Elbow Flexion/Extension
  - Forearm Pro/Supination
  - Shoulder Flexion/Extension
  - Shoulder Rotation
  - Torso Right/Left Lateral Bend
  - Torso Right/Left Rotation

- Activities of Daily Living (ADL) Tasks (x3)
  - Two-minute walk test (x1)
  - Drink from a cup
  - Cup transfer
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  - Hold and shoot weapon replica-start at side, raise, cock and shoot
  - Pack/unpack rucksack- sheet, brace weight, stick, & two blocks into bag (x2)
  - Two minute walk with packed bag (carrying at side) (x1)
  - Donning/Doffing helmet

- Subject survey
D.6 Subject Information Form

<table>
<thead>
<tr>
<th>Name:</th>
<th>Subject ID:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age:</td>
<td></td>
</tr>
<tr>
<td>Occupation:</td>
<td></td>
</tr>
<tr>
<td>Hobbies:</td>
<td></td>
</tr>
<tr>
<td>Dominant side:</td>
<td></td>
</tr>
<tr>
<td>Affected Limb:</td>
<td></td>
</tr>
<tr>
<td>Level of Amputation:</td>
<td></td>
</tr>
<tr>
<td>Level of Activity:</td>
<td></td>
</tr>
<tr>
<td>Type of Prosthesis:</td>
<td></td>
</tr>
<tr>
<td>Order of Testing:</td>
<td></td>
</tr>
<tr>
<td>Avatar Visualization:</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anatomical Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Mass (kg):</td>
</tr>
<tr>
<td>Height (mm):</td>
</tr>
<tr>
<td>Leg Length:</td>
</tr>
<tr>
<td>Knee Width:</td>
</tr>
<tr>
<td>Ankle Width:</td>
</tr>
<tr>
<td>Shoulder Offset:</td>
</tr>
<tr>
<td>Elbow Width:</td>
</tr>
<tr>
<td>Wrist Width:</td>
</tr>
<tr>
<td>Hand Thickness:</td>
</tr>
</tbody>
</table>

Notes/Observations:

Figure D.14 Subject Information Form to be Completed Prior to Testing
D.7 Post-Testing Survey Questionnaire

Prosthetic Training and Rehabilitation Questionnaire

Did you find it easier to complete the tasks with or without virtual reality?

Did you notice improvements in your motion when completing the tasks with and without virtual reality? Was it more noticeable in one form of training over the other?

Was it more enjoyable and/or motivational to complete the tasks with the use of the virtual reality? Briefly explain.

What do you believe is the best way to train/rehabilitate prosthetic users to effectively use their device with optimal movements and performance?

Any additional comments/ suggestions:

Figure D.15 Survey Questionnaire for Subjects to Complete After Testing Sessions
### Appendix E: Statistical Analysis Results

#### Table E.1 Statistical Analysis Results

<table>
<thead>
<tr>
<th>Table/Figure</th>
<th>Task</th>
<th>Subjects</th>
<th>Samples</th>
<th>Two-Tailed Test (Non-Directional)</th>
<th>One-Tailed Test (Directional)</th>
</tr>
</thead>
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<tr>
<td>Table 6.6</td>
<td>Bilateral Lift</td>
<td>All</td>
<td>NOVR Difference vs. VR Difference</td>
<td>p = 0.160 (83.98%)</td>
<td>p = 0.080 (91.99%)</td>
</tr>
<tr>
<td>Table 6.7</td>
<td>Bilateral Lift</td>
<td>All</td>
<td>NOVR Height vs. VR Height</td>
<td>p = 0.011 (98.92%)</td>
<td>p = 0.005 (99.46%)</td>
</tr>
<tr>
<td>Table 6.8</td>
<td>Unilateral Lift</td>
<td>All</td>
<td>NOVR Height vs. VR Height</td>
<td>p = 0.017 (98.34%)</td>
<td>p = 0.008 (99.17%)</td>
</tr>
<tr>
<td>Figure 6.3</td>
<td>Shoulder Rotation</td>
<td>Amputee</td>
<td>Prosthetic: NOVR Max vs. VR Max</td>
<td>p = 0.130 (87.02%)</td>
<td>p = 0.065 (93.51%)</td>
</tr>
<tr>
<td>Figure 6.3</td>
<td>Shoulder Rotation</td>
<td>Amputee</td>
<td>Prosthetic: NOVR ROM vs. VR ROM</td>
<td>p = 0.062 (93.81%)</td>
<td>p = 0.031 (96.91%)</td>
</tr>
<tr>
<td>Figure 6.3</td>
<td>Shoulder Rotation</td>
<td>Amputee</td>
<td>ROM Offset NOVR vs. VR</td>
<td>p = 0.003 (99.73%)</td>
<td>p = 0.001 (99.866%)</td>
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<tr>
<td>Figure 6.8</td>
<td>Shoulder Flexion/Extension</td>
<td>Amputee</td>
<td>Avg. Difference NOVR vs. VR</td>
<td>p = 0.003 (99.70%)</td>
<td>p = 0.001 (99.85%)</td>
</tr>
<tr>
<td>Figure 6.11</td>
<td>Bilateral Lift</td>
<td>Amputee</td>
<td>Avg. Difference NOVR vs. VR</td>
<td>p = 0.001 (99.91%)</td>
<td>p = 0.000 (99.95%)</td>
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<tr>
<td>Table 6.16</td>
<td>Helmet</td>
<td>Amputee</td>
<td>Avg. Difference NOVR vs. VR</td>
<td>p = 0.000 (99.98%)</td>
<td>p = 0.000 (99.99%)</td>
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<tr>
<td>Figure</td>
<td>Lift Type</td>
<td>Group Type</td>
<td>Pelvic Obliquity</td>
<td>NOVR vs. VR</td>
<td>p Value</td>
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<td>----------------</td>
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<td>------------------</td>
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<tr>
<td>6.19</td>
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<tr>
<td></td>
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<td>Amputee</td>
<td>Pelvic</td>
<td>NOVR vs. VR</td>
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<tr>
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<td>0.365</td>
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<td></td>
<td>Two-Minute</td>
<td>Amputee</td>
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<td>NOVR vs. VR</td>
<td>0.223</td>
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<td>Able-Bodied</td>
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<td>Amputee</td>
<td>Avg. Offset</td>
<td>NOVR vs. VR</td>
<td>0.235</td>
</tr>
<tr>
<td>6.24</td>
<td>Two-Minute</td>
<td>Able-Bodied</td>
<td>Pelvic</td>
<td>NOVR vs. VR</td>
<td>0.119</td>
</tr>
<tr>
<td></td>
<td>Walk w/ Bag</td>
<td>Amputee</td>
<td>Pelvic</td>
<td>NOVR vs. VR</td>
<td>0.189</td>
</tr>
<tr>
<td></td>
<td>Two-Minute</td>
<td>Able-Bodied</td>
<td>Avg. Offset</td>
<td>NOVR vs. VR</td>
<td>0.476</td>
</tr>
<tr>
<td></td>
<td>Walk w/ Bag</td>
<td>Amputee</td>
<td>Avg. Offset</td>
<td>NOVR vs. VR</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>Walk w/ Bag</td>
<td>Amputee</td>
<td>Avg. Offset</td>
<td>NOVR vs. VR</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Table E.1 (Continued)
Appendix F: Additional Results- Torso Rotation Data

F.1 Range of Motion Tasks

Figure F.1 Average Torso Rotation of Able-Bodied Subjects While Performing the Range of Motion (ROM) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Figure F.2 Average Torso Rotation of Amputee Subjects While Performing the Range of Motion (ROM) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Table F.1 Average Torso Rotation (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able-Bodied and Amputee Subjects While Performing the Range of Motion (ROM) Tasks During the Non-Virtual Reality (NOVR) Session
Table F.1 Average Torso Rotation (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able-Bodied and Amputee Subjects While Performing the Range of Motion (ROM) Tasks During the Non-Virtual Reality (NOVR) Session

<table>
<thead>
<tr>
<th>Range of Motion Tasks</th>
<th>NOVR</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Able-Bodied Subjects</td>
<td>Amputee Subjects</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
<td>MIN</td>
</tr>
<tr>
<td>Shoulder Flexion</td>
<td>0.62</td>
<td>3.19</td>
<td>-4.04</td>
</tr>
<tr>
<td>Shoulder Rotation</td>
<td>-0.14</td>
<td>3.54</td>
<td>-2.53</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td>-0.75</td>
<td>3.73</td>
<td>-1.99</td>
</tr>
<tr>
<td>Forearm Pronation</td>
<td>-0.71</td>
<td>3.93</td>
<td>-1.99</td>
</tr>
<tr>
<td>Torso Rotation</td>
<td>27.95</td>
<td>6.32</td>
<td>-29.03</td>
</tr>
<tr>
<td>Torso Lateral Bend</td>
<td>3.49</td>
<td>3.61</td>
<td>-8.71</td>
</tr>
</tbody>
</table>

Table F.2 Average Torso Rotation (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able-Bodied and Amputee Subjects While Performing the Range of Motion (ROM) Tasks During the Virtual Reality (VR) Session

<table>
<thead>
<tr>
<th>Range of Motion Tasks</th>
<th>VR</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Able-Bodied Subjects</td>
<td>Amputee Subjects</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
<td>MIN</td>
</tr>
<tr>
<td>Shoulder Flexion</td>
<td>1.77</td>
<td>3.15</td>
<td>-3.84</td>
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<tr>
<td>Shoulder Rotation</td>
<td>0.36</td>
<td>3.49</td>
<td>-1.86</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td>-1.20</td>
<td>3.71</td>
<td>-1.98</td>
</tr>
<tr>
<td>Forearm Pronation</td>
<td>-1.00</td>
<td>3.50</td>
<td>-1.47</td>
</tr>
<tr>
<td>Torso Rotation</td>
<td>28.49</td>
<td>4.80</td>
<td>-30.43</td>
</tr>
<tr>
<td>Torso Lateral Bend</td>
<td>5.61</td>
<td>0.92</td>
<td>-8.87</td>
</tr>
</tbody>
</table>
F.2 Activities of Daily Living Tasks

Figure F.3 Average Torso Rotation of Able-Bodied Subjects While Performing the Activities of Daily Living (ADL) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Figure F.4 Average Torso Rotation of Amputee Subjects While Performing the Activities of Daily Living (ADL) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
Table F.3 Average Torso Rotation (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able-Bodied and Amputee Subjects While Performing the Activities of Daily Living (ADL) Tasks During the Non-Virtual Reality (NOVR) Session

<table>
<thead>
<tr>
<th>Activities of Daily Living Tasks</th>
<th>NOVR</th>
<th>Able-Bodied Subjects</th>
<th>Amputee Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
<td>MIN</td>
</tr>
<tr>
<td>Bilateral Lift</td>
<td>3.52</td>
<td>2.46</td>
<td>-10.16</td>
</tr>
<tr>
<td>Unilateral Lift</td>
<td>10.91</td>
<td>4.43</td>
<td>0.56</td>
</tr>
<tr>
<td>Object Transfer</td>
<td>-0.96</td>
<td>2.32</td>
<td>-4.58</td>
</tr>
<tr>
<td>Drink</td>
<td>-0.79</td>
<td>3.32</td>
<td>-3.69</td>
</tr>
<tr>
<td>Two Minute Walk</td>
<td>3.51</td>
<td>2.39</td>
<td>-8.34</td>
</tr>
</tbody>
</table>

Table F.4 Average Torso Rotation (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able-Bodied and Amputee Subjects While Performing the Activities of Daily Living (ADL) Tasks During the Virtual Reality (VR) Session

<table>
<thead>
<tr>
<th>Activities of Daily Living Tasks</th>
<th>VR</th>
<th>Able-Bodied Subjects</th>
<th>Amputee Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
<td>MIN</td>
</tr>
<tr>
<td>Bilateral Lift</td>
<td>6.16</td>
<td>5.85</td>
<td>-11.25</td>
</tr>
<tr>
<td>Unilateral Lift</td>
<td>10.88</td>
<td>3.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Object Transfer</td>
<td>-0.13</td>
<td>2.99</td>
<td>-4.37</td>
</tr>
<tr>
<td>Drink</td>
<td>0.73</td>
<td>3.18</td>
<td>-1.92</td>
</tr>
<tr>
<td>Two Minute Walk</td>
<td>4.00</td>
<td>3.14</td>
<td>-8.34</td>
</tr>
</tbody>
</table>
F.3 Return to Duty Tasks

Figure F.5 Average Torso Rotation of Able-Bodied Subjects While Performing the Return to Duty (RTD) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions

Figure F.6 Average Torso Rotation of Amputee Subjects While Performing the Return to Duty (RTD) Tasks During the Non-Virtual Reality (NOVR) and Virtual Reality (VR) Sessions
Table F.5 Average Torso Rotation (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able-Bodied and Amputee Subjects While Performing the Return to Duty (RTD) Tasks During the Non-Virtual Reality (NOVR) Session

<table>
<thead>
<tr>
<th>Return to Duty Tasks</th>
<th>Able-Bodied Subjects</th>
<th>Amputee Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
</tr>
<tr>
<td>Helmet</td>
<td>0.63</td>
<td>3.80</td>
</tr>
<tr>
<td>Gun</td>
<td>-3.11</td>
<td>4.44</td>
</tr>
<tr>
<td>Two Minute Walk with Weighted Bag</td>
<td>3.71</td>
<td>2.06</td>
</tr>
</tbody>
</table>

Table F.6 Average Torso Rotation (Right (-) / Left (+)) and Standard Deviations (STDEV) of Able-Bodied and Amputee Subjects While Performing the Return to Duty (RTD) Tasks During the Virtual Reality (VR) Session

<table>
<thead>
<tr>
<th>Return to Duty Tasks</th>
<th>Able-Bodied Subjects</th>
<th>Amputee Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX</td>
<td>STDEV MAX</td>
</tr>
<tr>
<td>Helmet</td>
<td>0.68</td>
<td>4.48</td>
</tr>
<tr>
<td>Gun</td>
<td>-0.87</td>
<td>4.36</td>
</tr>
<tr>
<td>Two Minute Walk with Weighted Bag</td>
<td>2.39</td>
<td>3.39</td>
</tr>
</tbody>
</table>
Appendix G: TATRC Grant Project Narrative

Development of a Simulation Tool for Upper Extremity Prostheses
PI: Rajiv V. Dubey
University of South Florida

Project Narrative

Statement of Work (SOW):

The current award (W81XWH1010601) titled “Development of Simulation Tool for Upper Extremity Prostheses” has led to the development of a novel tool for simulating the compensatory motion of prostheses users that has applications in rehabilitation, design, and evaluation of prosthetic devices. Additionally, the Robotic Human Body Model (RHBM) and the slip detection sensor developed in conjunction with the simulation tool have potential to positively impact a broad variety of clinical and research activities. The RHBM will be expanded with a kinetic component, an added pseudo-joint and updated visualization using solid modeling animation. The RHBM will be combined with a state of the art virtual reality rehabilitation system, the CAREN (Computer Assisted Rehabilitation ENVironment) system, for improved rehabilitation and training. For the proposed study, the following tasks will be completed:

1) Robotics Based Human Upper Body Model (RHBM) Expansion

- Expand the RHBM to include kinetic component
- Expand the RHBM to include a pseudo-joint between the socket and residual limb with use of data from the slip detection sensor and motion data
- Collect motion analysis, EMG and force data for additional upper limb tasks including warfighter specific tasks such as loading/carrying a weapon, donning/doffing a helmet or a pack for return to duty (RTD) activities
- Validate and optimize RHBM based on collected data and expanded tasks

2) Simulation Tool Enhancement

- Enhance the visualization of the RHBM using solid modeling animation
- Provide a capability to overlay RHBM’s visualization onto user’s avatar
- Enhance the graphical user interface (GUI) to allow for intuitive and expanded clinical use

3) Rehabilitation and Training Applications using the CAREN System

- Incorporate the RHBM’s visualization into the CAREN system’s virtual environment and real time avatar of user’s motions
- Determine rehabilitation and training options for upper extremity prosthetic users and rehabilitation practitioners

Figure G.1 TATRC Grant Project Narrative, Page One. Highlighted Items Outline Points Accomplished by this Dissertation
Project Narrative

Technical Objectives:

The technical objectives and the questions to be answered by each objective are described below:

1) Robotics Based Human Upper Body Model (RHBM) Expansion

   - *Will expanding the RHBM to include a kinetic component improve the prediction of functional motions of upper limb prosthesis users?* The current RHBM simplifies human motion by ignoring kinetic data and relying only on kinematic data. Many activities of daily living (ADL) and return to duty (RTD) tasks include physical interaction with the environment, and various carrying loads on the arm and body. Motion prediction can significantly improve if acting forces and weights are included in the RHBM.

   - *Is adding warfighter tasks in the RHBM-based simulator helpful in RTD for prosthesis users?* The current RHBM includes ADL tasks that may not be enough for RTD amputees. Adding warfighter specific tasks to RHBM such as loading/carrying a weapon, donning/doffing a helmet or a pack can help in utilizing the simulation tool for efficacy, prescription, training, and designs of upper prostheses for RTD amputees.

   - *Can RHBM motion prediction capabilities be improved if a pseudo-joint is added to the model to account for socket slippage?* The current RHBM ignores socket slippage, which is acceptable if kinetic data is not included. Once forces are introduced to the model, socket fit will carry a major impact on the functionality and motion prediction of prostheses users. A pseudo-joint will be added to the RHBM to improve the prediction capabilities of the model when reaction forces and various weights during ADL and RTD activities are introduced. Data from the slip detection sensor and motion data will be used to validate and optimize RHBM.

2) Simulation Tool Enhancement

   - *Would an enhanced visualization using solid model animation help in training of prosthesis users?* The stick-figure currently used in RHBM is useful in providing visual feedback to trainees for comparing how they use their prosthesis versus how it should be used. Enhancing the visualization by including the animated solid body segments will make it easier for the user to relate to the visual segments on RHBM. This will also be useful in overlaying the predicted body segments motion onto the user’s avatar or real time motion.
Development of a Simulation Tool for Upper Extremity Prostheses  
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University of South Florida

Project Narrative

- **Can RHBM visualized solid model animation overlaid onto real-time avatar of the user help in training of prosthesis users?** At its current stage, RHBM cannot be overlaid onto any other graphical representation of the user’s actual motions. Adding this capability to RHBM makes it easier for trainees to correct their motion based on the overlaid visualization.

- **Will enhancing the graphical user interface (GUI) make it easier for clinicians to expand the use of RHBM?** The primary user interface for clinicians will include only the information needed for their clinical use. All the technical data and kinematic/kinetic data will be used in the background to make the interface user-friendly for clinicians. This will allow for intuitive and expanded clinical use, which will result in enhanced efficacy, prescription, training, and designs of upper prostheses.

3) Rehabilitation and training applications using the CAREN system

- **Can CAREN Virtual Reality (VR) system be used with RHBM to improve rehabilitation and training and rehabilitation?** The existing CAREN VR is very useful in providing immersive environment for trainees and rehabilitation practitioners. CAREN system will include VR environment of various settings for ADL and RTD activities, and the user’s avatar will be shown in the environment. During rehabilitation and training, predicted motion from RHBM will be overlaid onto real-time motion of trainee’s avatar. The users will be able to correct their motions based on the overlaid visualization that uses solid modeling animation and complete the task in the most efficient and safe way. This will also allow for a variety of environments, rehabilitation and training options for both upper extremity prosthetic users and for rehabilitation practitioners to choose from.

Methods:

Robotic Human Body Model (RHBM) Expansion:

The RHBM will be expanded to include kinetic data that includes acting forces on the limb due to weights and interaction with objects. Motion analysis data, kinetic forces, and electromyography of prosthetic users will be collected in order to optimize and validate the prediction capabilities of the RHBM. This data will be used to generate the optimization weights for the diagonal matrix used in the control algorithm. A current IRB approved testing protocol for the upper limb RHBM requires participants to complete eight ranges of motion tasks and five activity of daily living: brushing hair, drinking from a cup, eating with a knife and fork, lifting a laundry basket and opening a door. More tasks related to RTD activities such as loading/carrying a weapon, donning/doffing a helmet or a pack will be added. Thirty one reflective markers are placed on boney landmarks of the subjects and Vicon motion analysis.

Figure G.3 TATRC Grant Project Narrative, Page Three. Highlighted Items Outline Points Accomplished by this Dissertation.
Development of a Simulation Tool for Upper Extremity Prostheses
PI: Rajiv V. Dubey
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Project Narrative

system (Vicon, Oxford, UK) is used to capture the motion data. A wireless Biopac EMG system
(Biopac Systems, Inc., Atlanta, GA) will be used to collect EMG data during assigned activities,
and ground reaction forces will be recorded using two AMTI force plates (Advanced Mechanical
Technology, Inc., Watertown, MA). An ATI 6-axes force transducer (ATI Industrial
Automation, Apex, NC) will be placed at the points of interaction to measure reaction forces and
moments. Various weights acting on the prosthesis will be measures, including prosthesis weight
as well as any additional weight needed for the activity at hand. This testing protocol will be
expanded to allow for the testing of more prosthesis users during more ADL and RTD activities
as well as during sport and recreation activities. The large range of variability of amputee
motions and compensations makes additional data very valuable for both general knowledge of
compensatory motion and for validating the simulation.

During the current work, a sensor that measures socket slippage has been developed. This
sensor will be used in the proposed work to measure slippage for various users wearing different
prostheses to provide a quantified measure of slippage during ADL and RTD activities. A
pseudo-joint will be modeled and added to the RHBM to account for socket slippage. Data
gathered from the slip sensor will be used to validate and optimize the design of the pseudo-joint
and predict slippage using RHBM. During ADL and RTD activities, reaction forces, prosthesis
loads and EMG data will be used in the RHBM model with the added pseudo-joint to predict the
motion and socket slippage. This will be used to adjust the design of the socket to avoid slippage
and to improve the prosthesis motion configuration during the activity. Motion data from various
ADL and RTD tasks performed by a variety of human subjects will be used to optimize the
expanded RHBM. Validation of the expanded RHBM will be conducted by comparing the
predicted motion of RHBM and the actual motion data gathered during a new activity (not
included in the optimization process).

Simulation Tool Enhancement:

The statement of work of the current funding award (W81XWH1010601) includes the
development of a simulation tool consisting of a robotics-based human body model (RHBM) to
predict functional motions, and integrated modules for aid in prescription, training, comparative
study, and determination of design parameters of upper extremity prostheses will be developed.

For this proposal, the simulation tool will be enhanced by improving the predication
capabilities of the RHBM, enhancing the visualization of the RHBM using solid modeling
animation, and enhancing the clinical usability of the GUI. Currently visualization of the RHBM
is completed using the Robotics Toolbox in Matlab as shown in Figure 10 (left). A more human
like visualization will be created using a 3D virtual reality gaming or animation software such as
Unity, Autodesk Maya, SolidWorks (Figure 10 righ) to display the results of the RHBM in a
solid visualization appropriate for clinical use. The simulation tool will also be expanded to
allow for a simple real time tracking system such as a Kinect to track the real time upper limb
motions of amputees creating an avatar that can be overlaid on the animation of the RHBM

Figure G.4 TATRC Grant Project Narrative, Page Four.
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PI: Rajiv V. Dubey  
University of South Florida

Project Narrative

predicted motion. The GUI of the simulation tool will be improved to become more clinically applicable. Clinicians will easily be able to choose subject (amputee) parameters, tasks, and prosthetic components and then run an executable of the RHBM to display motions as well as joint angle graphs and limb trajectories. The simulation tool will be vetted by a panel of expert clinicians to determine its assets in prosthetic prescription, training, design and efficacy.

Figure 10: The current RHBM visualization (left) and the proposed visualization enhancement (right)

Rehabilitation and Training Applications

The simulation tool will be geared toward clinical use. It may also have applications for research in developing new rehabilitation and training techniques. The RHBM visualization portion of the tool will be integrated with the newly acquired CAREN system. This will encourage amputee users to match their motions displayed with an avatar representing their real time motions with the RHBM’s optimized motions in the virtual environments displayed on the CAREN system. The CAREN software suite the includes a D-Flow Main Feedback Loop Control Software, the CAREN application editor, 3D Interactive Viewer and the CAREN module suite will be used in to integrate the RHBM into the CAREN system (Figure 11).

Figure 11: Rehabilitation and training using the CAREN system, courtesy of torontosun

Figure G.5 TATRC Grant Project Narrative, Page Five.
Development of a Simulation Tool for Upper Extremity Prostheses
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University of South Florida

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This immersive environment and coordination between the human motion and the desired robotic model pose through visual feedback for the whole upper body will be developed to improve the effectiveness of the rehabilitation programs and increase motivation of patients. Additionally, the enhancement will allow clinicians to track the progress of the user and allow for the adjustment of therapy difficulty to maximize patient outcomes. Testing the proposed system with human subjects to determine the effectiveness of the real-time visual feedback for coordination with the optimized robotic model will be conducted, and the results will be reported.

Robotic Human Lower Body Model (RLBM) Development (Future Phases)

For a follow up phase, RLBM will be developed and optimized based on human kinematics and kinetics. Motion capture data on healthy subjects’ lower limb motion during RTD activities will be used to optimize the model. Similar to RHBM, RLBM will be utilized to aid in enhanced efficacy, prescription, training, and designs of lower limb prostheses. This will provide a baseline for a robotic full human body model that can be developed by integrating RHBM and RLBM for full human body motion prediction in active ADL and RTD tasks.

Project Milestones:

Figure 12 shows the timeline with SOW milestones to be met for this project.

![Project Milestones and Timeline](image_url)

Figure 12: Project milestones and timeline