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Quantification of Transhumeral Prosthetic Socket Residual Limb Interface Movement Using Motion Capture and a Slip Detection Sensor

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Quantification of Transhumeral Prosthetic Socket Residual Limb Interface Movement Using Motion Capture and a Slip Detection Sensor

by

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DEDICATION

I dedicate this dissertation to my parents, Michael and Debbie, and my sisters, Stephanie and Rachel. Without their constant love and support, I would not have been able to finish this dissertation.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Current literature focusing on the prosthetic socket is limited by measurement techniques and modeling assumptions, leading to a limited understanding of the forces and motions occurring between the residual limb and prosthesis and how they can be used to influence socket design and fitting. Prosthetic socket fitting and prescription would benefit from an elegant method for comparing socket designs. This dissertation focuses on the development and implementation of a 3D motion capture model and a Slip Detection Sensor to quantify rotations and translations at the prosthetic socket-residual limb interface. The 3D motion capture model defines the residual limb bone position inside the prosthetic socket which allows for measurement of the movement occurring at the prosthetic socket interface. The Slip Detection Sensor is an optoelectronic sensor embedded into the prosthetic socket wall to measure the amount of socket slip occurring between the socket wall and the residual limb skin surface. The motion capture model and Slip Detection Sensor were used to measure motion at the socket interface of transhumeral amputees during activities of daily living. Data were collected on six transhumeral amputees in the University of South Florida's (USF) motion analysis laboratory. One of the participants completed the collection procedures twice using two different suspension systems (pin locking versus no pin locking) within the same socket.

An eight camera Vicon (Oxord, UK) motion capture system was used to collect kinematic data for each participant during the repetition of a series of range of motion (RoM) and activities of daily living (ADL). The RoM tasks included shoulder flexion/extension, shoulder abduction/adduction, shoulder rotation, and elbow flexion. The ADL tasks included a bilateral and unilateral lifting task at various weight increments, modified box and blocks test, folding a towel, and walk and carry a gallon jug of water. The impact of donning the prosthesis on the participant's RoM and the amount of socket movement during the ADL tasks was analyzed.

The results show that the participant's shoulder RoM significantly decreased while wearing their prosthesis compared to when they were not wearing their prosthesis. The anterior-posterior tilt, medial-lateral tilt, and socket vertical translation were more directly correlated with the amount of residual limb movement than with the force acting on the prosthetic hand. Socket slip was most directly correlated with the force acting on the prosthetic hand. The results also show that the amount of translation was reduced when the pin locking suspension was used compared to when it wasn't for the individual participant who used both suspension systems within the same socket.

The motion capture data were used to determine the amount of socket movement during activities of daily living while avoiding many of the limitations of other socket interface studies. The Slip Detection Sensor provided experimental data on the amount of slip occurring between the residual limb skin surface and socket wall. This method seems to be a useful tool for evaluating socket performance in terms of movement. Ultimately, socket interface movement data can be used to providing clinicians with quantitative results of a good socket fit to aid in the socket fitting and prescription process and incorporated into adjustable interfaces. Collection of data on more participants with various socket types is needed to make more general conclusions.

CHAPTER 1: INTRODUCTION

The objective of this dissertation was to develop a method to measure prosthetic socket interface movement and use that method to quantify movement occurring at the socket and residual limb interface of transhumeral prostheses. A Vicon optical motion capture system was used to track upper body and prosthesis segments during common tasks and an optoelectronic sensor (Patent Pending, 61/727,249) designed by the author provided experimental data on the amount of socket slip occurring between the inner socket wall and residual limb skin surface. These systems were chosen because it does not limit the participant to static poses or interfere with the internal volume of the socket. The following hypotheses were defined:

1) There will be a significant decrease in residual limb shoulder range of motion (RoM) while wearing a prosthesis compared to not wearing a prosthesis,
2) Participants with shorter residual limbs will have more socket movement than participants with longer residual limbs,
3) The weight of the task performed will have the most significant impact on the amount of movement occurring at the socket interface.

The goals of the research were to:

1) Develop a motion capture model to calculate residual limb bone position inside the prosthetic socket,
2) Design, prototype, and validate a Slip Detection Sensor to measure the relative motion between the socket and residual limb skin surface (socket slip),

3) Quantify the range of movement of the prosthetic socket relative to the residual limb bone during activities of daily living (ADL) using the motion capture model and Slip Detection Sensor,
4) Correlate the socket interface movement to various outcomes and define possible fit parameters,
5) Make suggestions on how a prosthetist could use the data during the socket fitting and prescription procedures.

Gaining a better understanding of how a socket moves relative to the skeletal features of the residual limb can lead to more comfortable sockets, greater transmission of forces between user and device, result in fewer socket related skin issues, and provide quantitative measures of a movement efficient socket fit to aid socket prescription and fitting.

1.1 Epidemiology and Need

Upper limb prostheses are used to replace the function and appearance of the missing portion of their arm. Prostheses are composed of several components, including the socket, which serves as the connection between the human and the prosthesis. The purpose of the socket is to capture movements of the intrinsic skeletal features of the residual limb and transfer these motions to other parts of the prosthesis. Capturing the motions of the intrinsic skeleton is complicated by soft tissues which allow motion to occur between the human skeleton and the prosthesis as a result of compression and deformation of the soft tissues (i.e. skin, fat, and musculature) as well as slip. The soft tissues are not intended to be mechanical load bearers, and these motions and forces can have damaging effects on the soft tissues [1, 2] and possibly diminish the efficacy of the prosthesis. Furthermore, residual limbs experience volume fluctuations due to environmental and biological factors, creating an ever-changing socket interface that could increase the amount of rotation, translation, and slip of the socket. Few methods exist to quantify socket rotations and translation, and even fewer exist to measure socket slip.

Despite the recognized importance of the prosthetic socket [3-5], little research focusing on socket interface motion has been conducted. The research that has been completed focuses on the prosthetic socket interface and outcomes are hardly conclusive due to the limitations of the testing procedures and equipment used. Additionally, research literature focusing on upper limb prosthetic sockets is noticeably less prevalent than lower limb literature.

It is estimated that the number of individuals with a limb amputation in the United States will increase to 2.2 million by 2020 [6]. Data obtained during a 5 year period from 2001 to 2006 by the Joint Theater Trauma Registry and Military Amputee Research Program reported that 423 service members have suffered one or more limb amputations [7]. Of those, 105 had an upper extremity amputation at a wrist disarticulation level or more proximal. In 2010, greater than 950 soldiers have sustained a combat related amputation in association with the wars in Iraq and Afghanistan [8]. That number rose to 1599 in 2012 from all recent conflicts [9].

A survey of amputee prosthesis users found that socket interface comfort was rated the most important factor over prosthetic weight, agility, power and appearance (Figure 1) [4]. Nearly one third of amputees reported being dissatisfied with the comfort of their device while 18.4% of the respondents reported being fit with a new prosthesis at least once a year according to one survey [10]. This survey also showed that amputees see their prosthetist up to nine times a year.

A review over the past 25 years found that rejection rates among upper limb prosthesis users were approximately one out of five individuals [11]. Rejection of prostheses can occur for a number of reasons, some of which include level of amputation, type and usefulness of prosthesis, poor training, excessive time between amputation and prosthetic fitting, and cost of repairs [12].

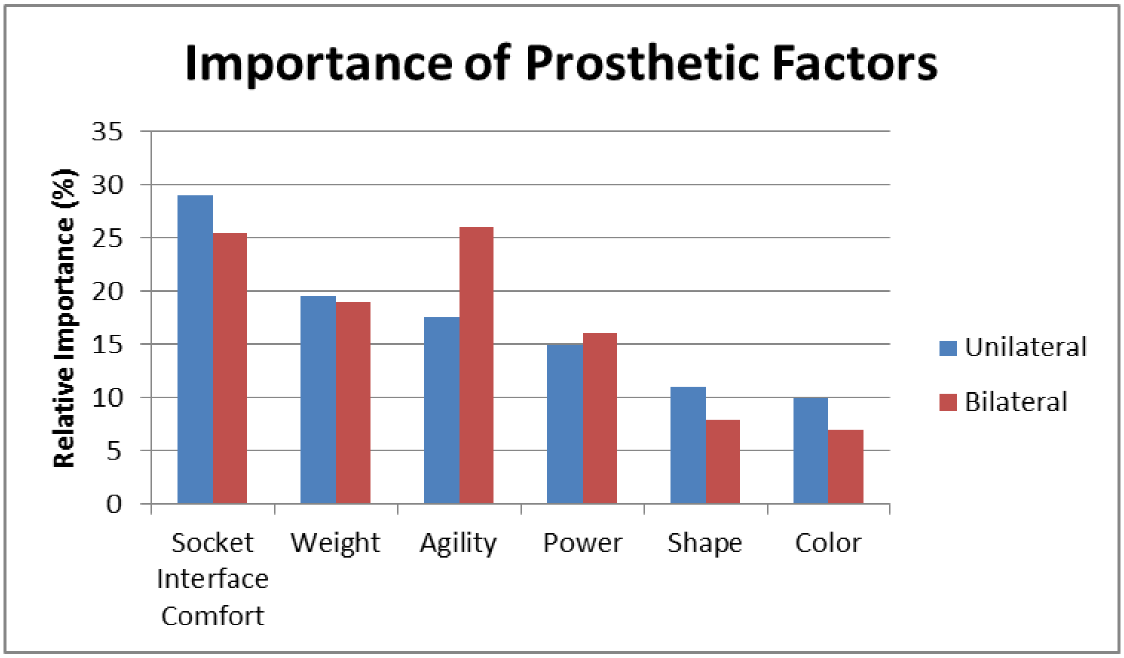


Figure 1: Survey results reproduced from [4]. Shows the importance of the socket interface rated by users.

Another study found that participants with lower limb amputations were significantly more likely to wear a prosthesis and wear it for more hours per day that participants with upper limb amputations [13]. A study comparing Vietnam veterans to veterans of Operation Iraqi Freedom/Operation Enduring Freedom found that upper limb prosthesis users completely abandoned their device 30% and 22% among the two groups respectively [14]. Additionally, focusing on more proximal amputation levels such as transhumeral or shoulder disarticulation find a higher rejection rate of 42% and 40% respectively for the two groups. These statistics highlight the growing demand for upper and lower limb prostheses and indicate the current dissatisfaction with the prosthetic socket among prosthesis users, particularly for upper extremity amputations.

Evidence based research is becoming more valuable in the prosthetic industry. Upper limb prostheses can range from $4,000 to $75,000+ depending on the control type and level of amputation. Additionally, lifetime prosthetic costs for upper limb prosthesis users can range from $100,000 to more than $1,990,000 depending on the type of prosthesis and if the patient is unilateral or bilateral [15]. However, major insurers place financial caps on prosthetic coverage, which can range from $10,000 to one prosthesis during an individual's lifetime [16]. These limits restrict the availability of prostheses and chances to be refit for a new socket. Private insurers regularly categorize new prosthetic technologies as experimental [16], emphasizing the need for evidence based research on these systems.

Prosthesis simulators are currently being developed to allow an amputee to "test-drive" various prosthetic systems to provide evidence based recommendations to clinicians for prosthetic prescription [17]. Expanding simulators to include the prosthetic socket and suspension recommendations could increase the comfort and functional performance of prostheses and decrease the number of visits to the prosthetist for socket related issues. Before such a tool can be designed, a method to analyze the performance of various socket designs and suspension methods is needed.

1.2 Prosthesis Socket Design

The socket couples human and prosthesis, and greatly impacts comfort and prosthetic function. Ideally, the socket would transmit forces to and from the user with perfect efficiency, transferring any movements of the residual limb bone without lost motion to the prosthetic limb. However, because the soft tissues between the prosthetic socket and residual limb bone are not rigid, external forces can cause compressions and deformations of the soft tissue. Therefore, only a portion of the bone movement is transferred to the prosthesis. The socket can apply compressive forces normal, f_n, to the skin surface in localized areas, leading to rotation of the socket relative to the residual limb bone (Figure 2B). These rotations occur about three axes, leading to anterior-posterior tilt, medial-lateral tilt, and rotation about the long axis of the residual limb. Translations of the socket occur due to two effects, soft tissue deformation and slip. Soft tissue deformation occurs when the external forces acting on the socket do not exceed the static friction force, $f_{\mu s}$, occurring at the interface (Figure 2C). The resulting translation that occurs is relative to the intrinsic bone, but not relative to the skin surface. The skin and underlying tissues are pulled with the socket, creating shear forces parallel to the skin surface within the soft tissues of the residual limb. Slip at the interface occurs when the external forces exceed the static friction force, $f_{\mu s}$, of the interface, resulting in kinetic friction, $f_{\mu k}$ (Figure 2D). This type of translation is movement of the socket relative to the skin surface. A shear force is still applied to the skin surface, but that force does not penetrate the underlying soft tissues to the extent that it does during soft tissue deformation.

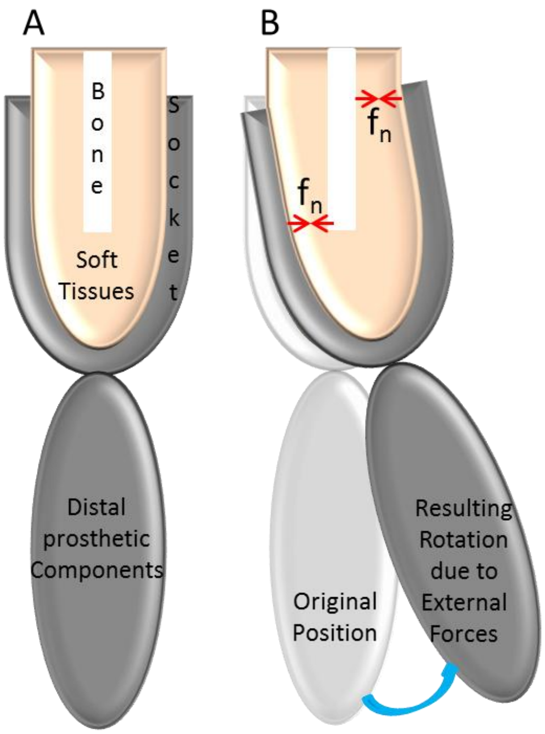


Figure 2: Types of prosthetic socket movement. A) Original orientation. B) Socket rotation. C) Soft tissue deformation D) Socket slip.

The art of designing a socket is to achieve a stable connection with the residual limb while maintaining a comfortable fit that can be worn for long periods of time without causing damage to the residual limb. In order to limit the amount of socket movement and provide a more comfortable connection with the residual limb, every prosthetic socket is custom made for the user.

1.3 Prosthesis Socket Fabrication

Traditional sockets are made by creating a series of positive and negative molds which are used to form the socket shape. Fabrication commonly begins by wrapping the residual limb with a plaster wrap casting. This negative mold is then filled with a plaster mixture to form a positive mold representing the residual limb shape. The positive mold is then altered by the prosthetist, who can make physical modifications by adding or removing plaster in order to decrease or increase the pressure distribution in certain areas. Once an acceptable shape is achieved deemed by the prosthetist's experience, a clear thermoplastic socket is manufactured. For most sockets (those other than an x-frame socket used for shoulder disarticulations), the blister forming technique is used.

Once fabrication is complete, the amputee dons the socket and performs a static and dynamic socket check which includes ambulating for lower limb devices, RoM, strength, and functional assessment for upper limb devices. The prosthetist will monitor the blanching of the skin through the clear socket wall during the dynamic socket check to identify areas that seem to have excessive or insufficient soft tissue compression. Feedback from the amputee is also solicited to determine socket modifications and adjustments that are needed. Based on the visual judgment of the prothetist, feedback from the amputee, and past experiences, modifications are made to the positive mold and another clear thermoplastic socket is manufactured. This process is repeated until a final socket shape is reached, determined by the prosthetist. Sometimes a second check socket is not needed and adjustments made to the first check socket are sufficient to make the definitive socket. Then a final socket is made out of more permanent materials such as carbon graphite. Figure 3 below shows typical flow of the socket fitting process.

Recent advancements in technology have allowed for new approaches in how sockets are made. Optical scanners allow the residual limb anatomy to be digitized and saved on a computer. This technology allows previous geometries to be stored digitally, providing a history of shape and volume. Using this technology would modify the fabrication process shown in Figure 3. However, the accuracy of the process is still dependent on the prosthetist's skill and experience in the field. A tool to help quantify a good fit would greatly benefit prosthetists and amputees.

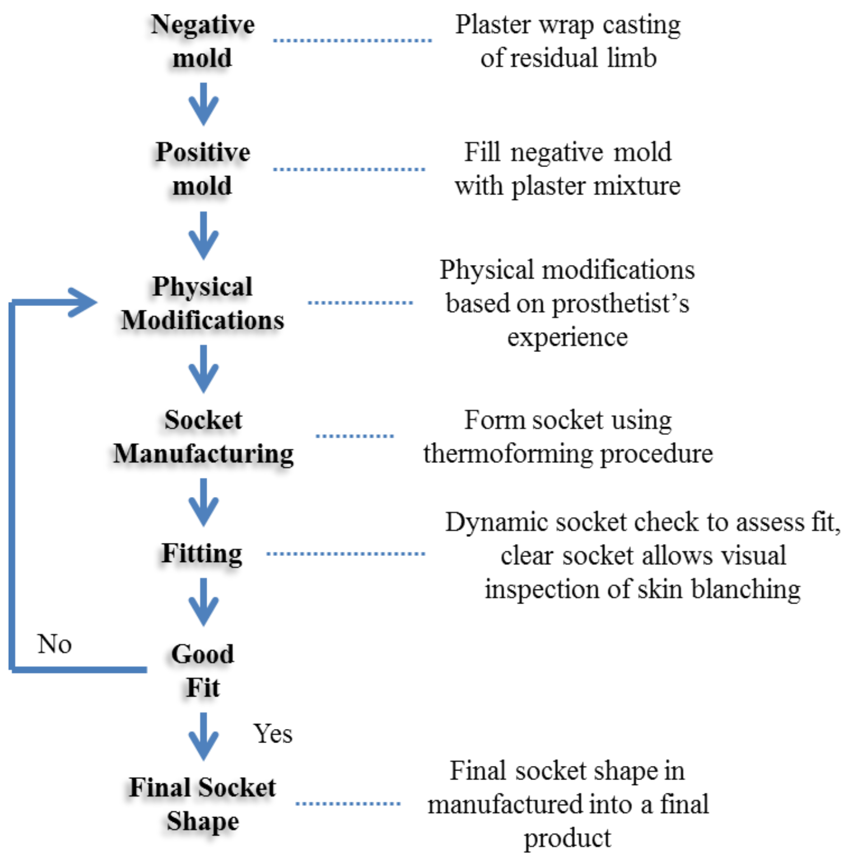


Figure 3: Traditional socket fabrication process.

1.4 Prosthesis Suspension Methods

While the socket is the part of the prosthesis that contains the residual limb, the method of suspension is the manner by which the prosthesis is attached to the limb. There are many options available to the prosthetist for suspension, and the method chosen can affect the way the socket is designed. The methods of suspension include harnessing, anatomic suspension, pin lock systems, vacuum or suction assisted, and osseointegration.

1.4.1 Harness Suspension

Harnessing was one of the first suspension systems applied to upper limb prostheses. These systems were developed and used as early as the 1950’s and have undergone minor changes since then. The socket shape with these systems aims for gross encapsulation of the residual limb and is suspended by a strap that can take different shapes. The shape and configuration of the straps depends on factors such as level of amputation and whether or not the harness is for suspension and control or control only. The Figure-8 strap configuration [18] is commonly used for suspension and fitted around the contralateral shoulder with a cross point in the back (Figure 4). Alternatives to the figure-8 strap are the chest strap [19]. This may provide a more comfortable option to some users who find the figure-8 harness uncomfortable in the axilla region and is more commonly used with shorter residual limb amputees. The harness system also connects to the distal joints of the prosthesis and movements of the contralateral shoulder places tension in the cables and allows the prosthetic joints to move. This type of control scheme is commonly referred to as a body-powered prosthesis, and provides the user with proprioceptive feedback of the position and velocity of prosthetic joints by relating them to position and velocity of anatomical joints [20]. Proprioception can simply be described as the awareness of one’s body position without the use of visual feedback.

Figure 4: Figures 8 harness suspension system.

1.4.2 Anatomic Suspending

Anatomic suspending sockets eliminate the need for the shoulder or chest harness. This type of suspension uses a more anatomically contoured socket to create adequate pressure to keep the prosthesis on the limb. In order to create better myoelectric sensor contact, two types of anatomic suspending sockets were designed for below the elbow amputees. The Muenster socket was initially designed for short transradial amputations and was characterized by anterior-posterior stability at the proximal brim [3]. The Northwestern socket was designed for more medial-lateral control. In lower limb systems, the patellar tendon bearing socket is a popular choice for below the knee amputees. This system pre-compresses the soft tissues in the areas of the patellar tendon, medial and lateral flares of the tibia, and popliteal area. These areas are more load tolerant than other areas of the residual limb. A new socket type for the upper limb takes this idea to an extreme. The high fidelity socket designed by Randall Alley consists of four struts with concurrent areas of relief [21-23]. The four struts compress the soft tissues as much as possible and attempt to minimize the delay between prosthetic movement and skeletal movement. The concurrent windows cut out of the socket provide relief for the soft tissues instead of confining them inside the socket volume. The creators of the high fidelity socket claim the design has better osseosynchronization (connection to the bone) then traditional socket techniques and limit motion between the user and prosthesis.

New suspension methods are constantly being developed, especially those designs that can overcome the challenge of residual limb volume fluctuation. The Revo-Limb socket developed by Boa Technology Inc. (Colorado, USA) is a dynamic interface that works by adjusting the tightness of several panels of the socket [24]. The socket has a main shell with a number of panels that fit into windows cut out of the shell. Wires run on the inside of the socket and connect the main shell to the panels. The user can tighten or loosen the panels to create the compression needed by turning a dial connected to the wires.

1.4.3 Pin-Lock Suspension

The pin-lock suspension uses an inner silicon liner worn by the amputee over the residual limb with a shuttle lock attached [25]. A pin attaches to the distal end of the liner and fits into a port at the distal end of the socket and creates a mechanical lock between the liner and the socket (Figure 5). This type of suspension is commonly used in lower limb systems and occasionally used in upper limb prostheses. Coyote Design's new proximal lock uses a toothed strap that can be attached to the side of the liner. A small window can be cut into the socket and the strap fed through the window, passing through a buckle that locks it in place.

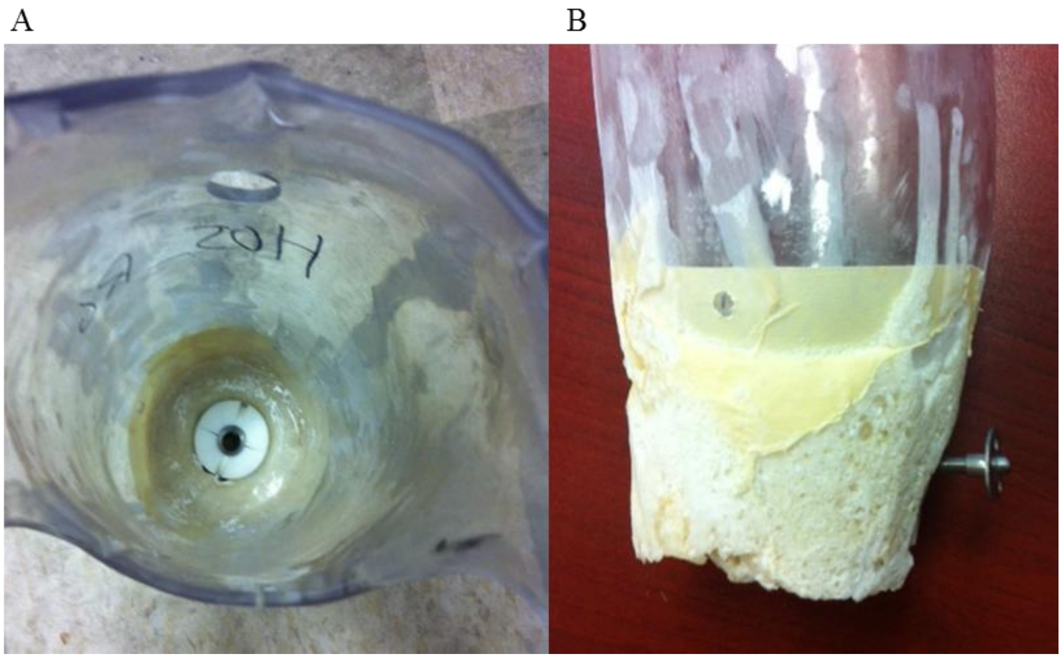


Figure 5: Pin locking suspension. A) Shuttle lock port at distal end of socket. B) Release button.

1.4.4 Vacuum or Suction Suspension

In vacuum systems, the socket creates a seal with the residual limb and a pump is used to draw excess air out of the internal socket volume. This creates the vacuum suspension for the limb. This type of suspension may have benefits for the residual limb such as a reduction in residual limb volume change, but more research is needed to evaluate that hypothesis [26]. One study compared a vacuum assisted suspension system to a pin locking suspension in lower limb systems, and found that the amount of movement between the residual limb and socket (pistoning) was less for the vacuum system [27]. However this study has been scrutinized for its lack of details on how pistoning was measured as well as its testing procedures [28]. An alternate method of suspension is the suction based suspension which is similar, but incorporates a liner that has concurrent rings around it. As the socket is placed over the liner, the rings trap air and create a suction force that provides suspension. These systems are often equipped with a valve which allows the user to allow air back into the socket volume. This allows more comfort for activities other than gait such as sitting. Devices such as the Smart Puck [29] and LimbLogic [30] offer an adjustable vacuum system. A puck-shaped vacuum is sealed into the socket at the time of fabrication and connects to an Apple product such as an iPod Touch. It allows the user to adjust the vacuum settings through the application depending on what activities the user is doing (sitting, walking, or running). These settings are pre-set by the prosthetist.

Figure 6: Vacuum assisted socket with valve.

1.4.5 Osseointegration

Bone anchorage of the prosthesis is intended to overcome many of the socket-related problems experienced by users of conventional socket prosthesis, including improved RoM, less soft tissue injury, increased prosthetic use, and more comfort while sitting [31, 32]. This method requires a fixation device and transcutaneous abutment for attachment of the distal components of a prosthetic limb (Figure 7). Early in its development, no standard protocol for rehabilitation existed and the results were marginal. A Swedish group has sought to standardize the surgical and rehabilitation procedures, and has developed the protocol followed today called the Osseointegrated Prostheses for the Rehabilitation of Amputees (OPRA) [33]. The OPRA procedure requires two surgical procedures, placed six months apart, in order to attach the implant to the bone. The first surgery is required to attach the fixation device. During the period between surgeries, the amputee may continue to use their traditional prosthesis while the area around the fixation device heals from the first procedure. The second surgery attached the transcutaneous abutment to the fixation device. The rehabilitation period post second surgery is another 6 months as weight bearing has to be gradually increased to avoid loosening of the implant. The implant is made from titanium as other attempts with non-titanium transcutaneous metal implants have failed primarily due to infection [34]. While titanium appears to be promising from the current literature, more research and long term studies are needed to determine its effectiveness. One study prospectively followed 39 patients with arm and leg amputations for a period of three years [34]. The most common bacteria were various forms of Staphylococcus depending on if the sample was from superficial or deep tissues. More long term studies following a formalized procedure such as the OPRA are needed to further analyze the effects of osseointegration.

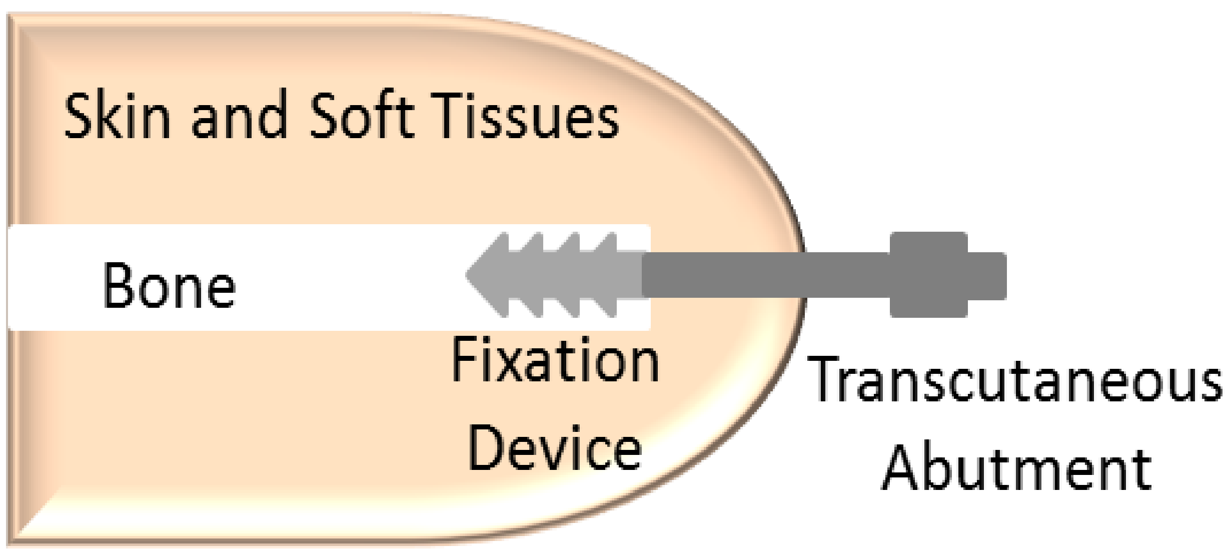


Figure 7: Illustration of direct bone attachment.

1.5 Previous Socket Interface Research

The premise behind the socket designs mentioned in the previous section is to distribute socket forces about the residual limb, in order to create a stable and comfortable connection. Many research projects focusing on the socket residual limb interface have been conducted to better understand what forces the soft tissues can tolerate, what forces the soft tissues are subjected to inside a prosthetic socket, and the magnitude of motion occurring at the socket interface.

1.5.1 Socket Effects on Soft Tissues

The soft tissues of the residual limb are subjected to unfavorable conditions inside a prosthetic socket. Forces from the socket are applied to the residual limb which is already contained in a snug fitting socket. These forces can be pressure which occur perpendicular to the skin surface, shear which occurs tangential to the skin surface, or friction which occurs when shear is applied along with slip between the skin surface and socket. In addition to the socket forces occurring inside the socket, the lack of air circulation inside the socket creates a hot and humid environment and more vulnerable soft tissues. Excessive slip of the socket may result in further heat generation. Additionally, materials chosen for the socket interface may create caustic or allergic reactions for some users. All these factors make predicting soft tissue responses to external forces difficult.

A few conclusions have been drawn from the current research. There exists an inverse relationship between the intensity and duration of external forces until skin breakdown occurs. These results have been found in a study utilizing a pig skin model [35] and others reviewed by Mak [36] and Sanders [37]. The review by Mak also found that damage is greater when applied to a localized area of the soft tissues, rather than distributed evenly. Pressure can also have an effect on the soft tissues, leading to ischemia, or reduction in blood supply to tissues [38]. Improper blood supply reduces oxygen and glucose stores needed for cellular metabolism. The review by Sanders stated that blisters are more likely to develop from friction forces. Skin has been shown to be less tolerant of friction than shear forces [35]. When shear is applied to the soft tissues, the force is distributed through a greater volume of tissue dispersing the stress concentrations. When slip is applied, the friction force is distributed locally and increases the risk of injury. Diabetic and dysvascular amputees are at an increased risk for skin breakdown [39].

The reviews by Mak and Sanders offer more information on this topic, which is outside the scope of this dissertation. While these forces are needed for the suspension of a prosthesis, excessive loading of the soft tissues can lead to unwanted effects like the ones discussed in this section. It is important to understand when these two types of movement occur in order to enhance residual limb health. Therefore several studies have quantified the relative motion or pressure distribution inside the socket to better understand socket interface interactions, in hopes of developing better sockets.

1.5.2 Motion Analysis Studies

A number of motion analysis studies have been conducted to analyze a variety of outcomes. Knee and ankle kinetics have been analyzed during normal stair ambulation [40] and various amounts of ankle dorsiflexion during stair ambulation[41] for unilateral amputees. Gait mechanics has also been evaluated for bilateral amputees during gait [42, 43]. Compensatory motions have also been evaluated for lower limb prosthesis users during normal gait [44], gait with socket misalignments [45], and upper limb prosthesis users [46] during activities of daily living (ADL). The control of a prosthetic knee has also been evaluated with and without early walking rehabilitation [47]. One study compared kinetics of a prosthetic knee measured experimentally to kinetics of various inverse dynamics calculations for transfemoral amputees [48]. The safety of various prosthetic knees has also been evaluated during gait [49]. All of these studies considered the kinematics and/or kinetics of prosthetic function under the assumption that the socket interface was a rigid connection. One study sought to understand how errors in anthropometric data affected kinetic calculations during gait for partial foot amputees [50]. The residual foot and prosthesis were treated as separate segments in order to calculate a more accurate center of mass and mass moment of inertia. It was found that this method yielded an increased peak joint moment and power for the hip and knee. The study still considered the socket-residual limb interface to have a rigid connection. However this interface is not a rigid connection as shown by a previous study at the University of South Florida analyzing a kayaking terminal device for upper limb prosthesis users. The study found a varying elbow angle for the above-elbow user even though the elbow component of the device was locked at 40° [51]. The authors suggest that part of this motion occurred at the socket interface.

One study used motion analysis to investigate movement at the socket interface by defining the residual limb and socket as separate segments [52]. This technique was used on a transtibial prosthesis user to measure the difference in pistoning when using two different liner types. This marker set only measured motion in one direction and could not differentiate between socket translations where the soft tissue deformation occurred and when slip between the socket and skin surface occurred. A recent study at the University of South Florida developed an optical marker set that could track the residual limb and prosthetic socket separately, allowing multi-axial motion between the two segments to be captured [53].

1.5.3 Pressure Mapping and Finite Element Modeling

Several other studies have used pressure mapping systems and force transducer measurements of internal socket pressures and compared the results to finite element models. These studies sought to gain a better understanding of the pressure distribution inside the socket with a goal of improving socket design and fitting. The studies are almost exclusively focused on lower limb prosthesis [54-59]. The finite element models from the lower limb studies could be divided into three main modeling methodologies. The first group modeled the interface such that socket slip, separation between elements of the socket and residual limb, was not permitted [57, 58]. A second group modeled the interface the same way as the first, however during post processing of the data, detected elements under tension and removed those forces [56].The last main methodology allowed slip at the interface to be permitted [54, 55, 59]. All of the studies mentioned above sought to build models to predict the interface stresses occurring. However differences in modeling the elemental properties and boundary conditions, the type of pressure transducer used and its placement, and the activity or task performed make inter-study comparisons difficult. Additionally, placing a pressure mapping system inside the socket may alter the user's normal fit and thus affect results. Transducers like those used by Sanders et al require sections of the socket wall to be removed in order for the sensor to work [57]. The results of the slip permitted modeling methodology were not confirmed experimentally, because no method existed to measure the amount of slip occurring at the interface.

One study analyzed an upper limb prosthesis using a pressure mapping system and found the location of peak pressures varied depending on arm position [60]. Analysis of the pressure mapping results on the residual limb indicates that the socket seemed to rotate about the center length of residual limb bone. Lighter pressures were found around the middle of the residual limb while higher pressures were at the proximal and distal portions of the residual limb. This study highlights the increased variance of socket pressures of upper limb socket with respect to lower limb. While the peak pressures in lower limb systems are also dependent on the position of the limb, gait is the typical motion of the lower extremities and is a more cyclic pattern.

1.5.4 Radiological, Acoustic, Optical, and Other Methods

Other studies have used radiological [61-65], acoustic [66], and optical [67] methods to analyze the movement of the residual limb bone inside the socket for lower limb systems. The radiological studies primarily analyzed tibia movement inside a socket referred to as pistoning, or the up and down movement of the residual limb relative to the socket. A range of pistoning was found from 22 to 75 mm. One study looked at slip using lead markers placed on the skin and socket liner [68]. The study found the amount of slip increased from 2 mm to 6 mm when an additional 133.5 N of load was applied in the axial direction while the total distal translation was 10 mm for the tibia. Only one study analyzed the rotational stiffness of an upper limb socket using a radiological method [69]. This study found the rotational stiffness of the interface could be modulated through contractions of the residual limb musculature. This study also used the center point of the length of bone inside the socket as the rotation center for the socket. However, due to the limited viewing window of the measurement device, testing protocols were limited to imitating phases of gait in static positions or only allowing for one step.

In order to analyze gait, Convery designed a mountable ultrasound system to monitor bone movement inside the socket [66]. The RoM of the intrinsic bone relative to the socket was 12.2° for medial lateral socket tilt and 17.4° for anterior-posterior socket during gait. This method required bulky equipment to be mounted to the socket wall, which may have been intrusive to the participant.

An optical sensor mounted to the underside of a participant's socket was used to track the amount of pistoning of the socket during gait [67]. An average of 41.7 mm of pistoning was found. The optical sensor used only recorded movement in one direction and thus could not differentiate between socket translations that resulted in shear forces and those that resulted in frictional forces on the residual limb.

Slip has also been measured using a pen rigidly attached to the well-fit total contact suction socket [70]. The pen left an ink trail on the skin surface that could be analyzed once the plug holding the pen was removed. The results indicate that for the socket type tested, the slip was less than 6 mm. The author acknowledged the high inaccuracy of analyzing the data and noted it as a limitation. Additionally, the data from this method could not be analyzed in real time, and would not be advantageous to use as a controller of a dynamic interface system.

1.6 Gap in Knowledge

The survey results [4, 10-16] highlight the importance of prosthetic fit and comfort to the user and its impact on the success of the prosthesis. Unfortunately, the review of the current literature shows an absence of conclusive research involving the socket interface movement, particularly the interface of upper limb prosthesis users. The studies analyzing the socket interface are limited by the testing procedures and equipment used, leading to limited results that can be used to impact socket design and prescription. Prosthetists acknowledge that movement at the socket interface occurs, but the extent to which that movement should be limited has not been defined. Additionally, slip occurring at the interface between the prosthetic socket and residual limb skin surface is not well understood, due to the limited methods for measurement.

This dissertation sought to fill some of these gaps in knowledge surrounding socket interface movement. These include the amount of rotations, translations, and slip occurring during dynamic activities of transhumeral prosthesis users. A new motion analysis method for calculating the position of the residual limb inside the socket and a novel Slip Detection Sensor were used to track the motions of upper limb prosthesis users during common tasks. This will allow researchers to analyze the amount of socket movement without interfering with internal socket volume or limiting the movement of the participant. Using a motion capture system will also avoid the need to make multiple modeling assumptions as in the finite element modeling methods, and permit researchers to look directly at the socket motion occurring. Additionally, the Slip Detection Sensor designed to measure the amount of slip occurring between the internal socket wall and residual limb skin surface or inner liner surface will provide experimental data during dynamic activities. The results from these measurement methods may provide data that researchers and clinicians can use to positively impact the socket design and prescription procedures.

CHAPTER 2: DEVELOPMENT OF THE KINEMATIC MODEL

Motion analysis involves quantitatively evaluating the movement of bodies. For this study, motion analysis was used to track the movement of the socket relative to the residual limb. Eight infrared cameras tracked the position of passive reflective markers placed at specific locations on the subject's upper body. Each of the eight Vicon (Oxford, UK) cameras yields the 2D position of each marker in the camera frame and the Vicon system uses triangulation to obtain the 3D marker position based off the intersection of the projections from the camera frames into the lab frame. The motion analysis system was chosen to capture movements at the socket interface because it does not interfere with the internal volume of the socket, does not limit the motions of the user, and comparable to other studies. The motion analysis marker set was developed after collecting pilot data of one above elbow subject.

2.1 Motion Analysis Model

The model was adapted from the methods developed by Freilich [53], who used markers (RSLA, RSLP, SCKTA, SCKTP) above and below the socket trim lines as shown in Figure 8. The RSLA and RSLP markers were used to create a vector to the shoulder joint center defining the residual limb segment and the SCKTA and SCKTP markers were used to create a vector to the elbow markers defining the socket segment. Defining the segments as described above allowed the rotation and translation about all axes to be captured. This marker set was used in a study to validate a robotic human upper body model (RHBM) [17], and the results from this study used as pilot data. Results from the pilot data showed that the intra-task rotation of the socket about the residual limb was highly variant when using the RSLA and RSLP markers but not highly variant when using the elbow markers on the prosthetic side. These results suggested that the RSLA and RSLP markers would not be reliable to use in the study due to limited distance between the shoulder and socket as well as soft tissue artifacts.

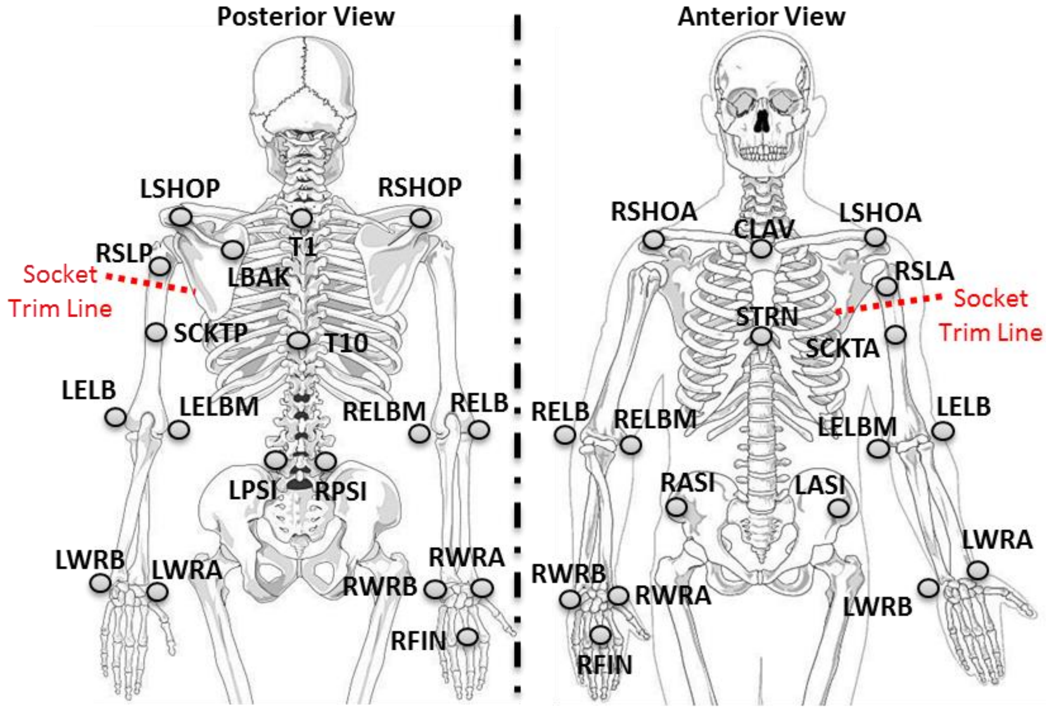


Figure 8: Marker set used in a previous study. RSLA and RSLP are used to define the residual limb position while SCKTA and SCKTP are used to define the socket. Skeleton image taken from the public domain.

The pilot participant also completed RoM tasks without wearing a prosthesis. Two sets of residual limb markers (RSLA and RSLP) were used; one set placed at a more proximal position on the limb and the other at a more distal position as illustrated in Figure 9. This was performed to analyze the accuracy of proximal residual limb markers, such as those required in the marker set developed by Friedlich, to markers at a more distal location on the residual limb. Analysis of the results highlights the difference between using the proximal and distal residual limb markers. When defining the residual limb position using the distal residual limb marker pair, a greater angle was found. Proximal markers were in close proximity to the shoulder markers due to the height of the socket trim lines, resulting in difficulty for the cameras to distinguish the shoulder and proximal residual limb markers from each other, especially at the peak of elevation of the shoulder joint. Another problem with the proximal markers was discovered when the subject went to perform tasks while wearing their prosthesis. The superior edge of the socket was near the acromion of the subject, leaving no space for marker to fit between the socket and the shoulder. From these two results, it was decided that the RSLA and RSLP markers should be excluded during tasks with the prosthesis and a new method for calculating the intrinsic bone position necessary.

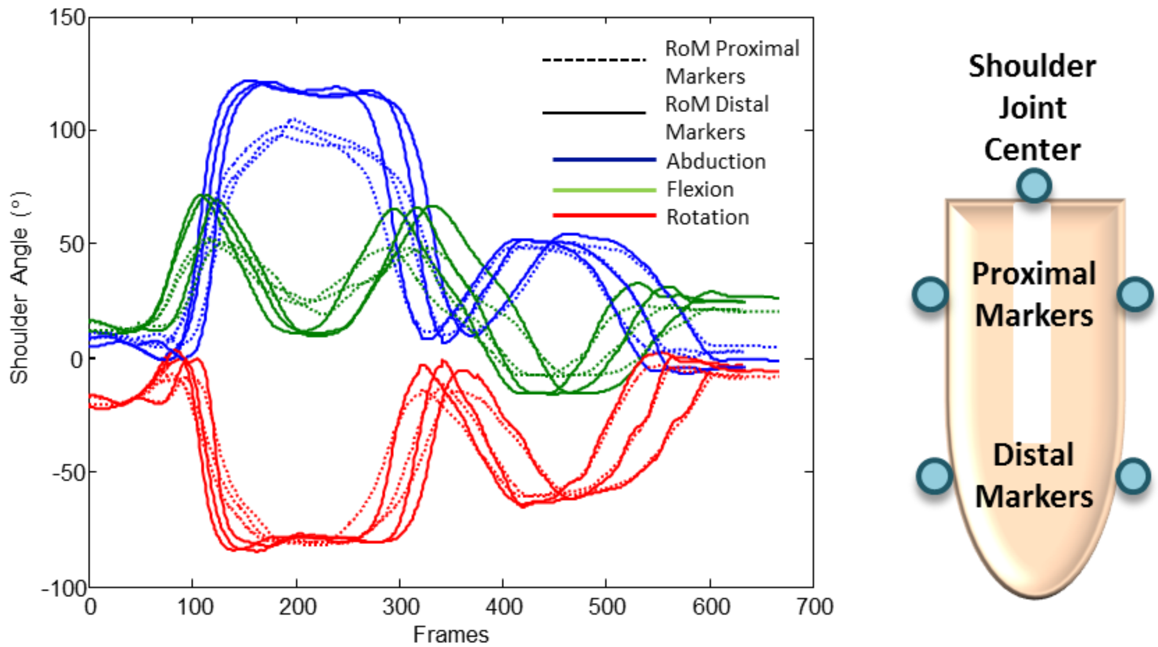


Figure 9: Difference in RoM calculated using the proximal and distal residual limb markers of one above-elbow amputee.

At first it was thought that the residual limb could be described using the average of the anterior and posterior socket markers (SCKA and SCKP). While the method provided a good approximation of the bone position without any socket rotation, the approximation became increasingly worse as the socket rotates as shown in Figure 10. The method still captures rotation (angle between the red arrow and the green dotted line which projects the socket vector) but is not accurate to the position of the intrinsic bone.

To improve the accuracy of the intrinsic bone position, the socket was assumed to rotate about the center of the length of bone inside the socket, an assumption used in a previous study of rotational stiffness in above elbow prostheses [69]. This point is the center of rotation and remains in the center of the socket. The average of the anterior and posterior markers represents the middle on the socket, and can be translated in the proximal-distal axis of the socket frame. The amount the average socket marker position was translated and calculated based on the marker set and subject measurements as illustrated in Figure 11.

Using this method, the residual limb position could be approximated and the amount of rotation between the residual limb and socket calculated. Figure 10 shows the how the new approximation of the residual limb position gives a more accurate angle between the residual limb and socket. The final marker set used is described in Table 1.

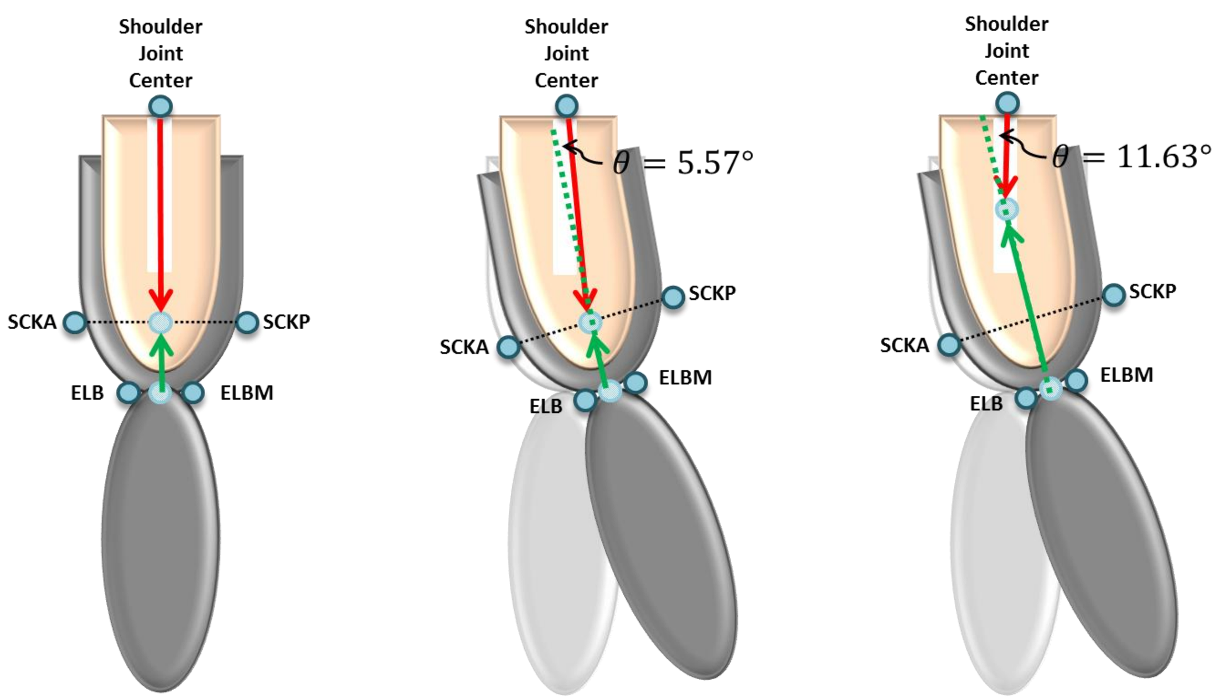
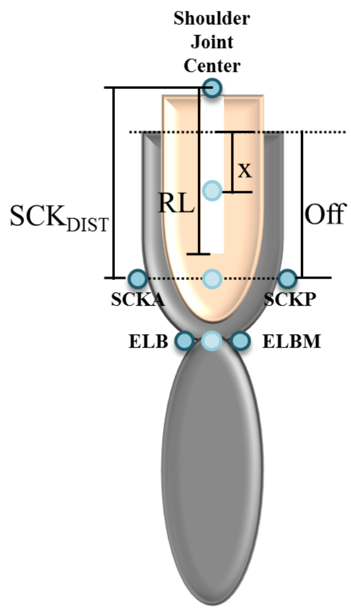


Figure 10: Difference in residual limb bone approximation using socket markers versus new method.



<u>**Constant Paramters**</u>

$RL = residual\ limb\ bone\ length$

$Off = offset\ length\ of\ socket\ markers$ from trim lines

<u>**Variable Parameters**</u>

$SCK_{DIST} = length\ from\ joint\ center\ to\ socket\ markers$

$x = center\ of\ bone\ inside\ the\ socket$

$$x = \frac{RL - (SCK_{DIST} - Off)}{2}$$

Figure 11: Calculation of the center of residual limb bone inside the socket volume.

Table 1: Marker placement descriptions.

Name	Placement
T1	Spinous process of 1st thoracic vertebrae
T10	Spinous process of 10th thoracic vertebrae
CLAV	Jugular notch
STRN	Xiphoid process
LBAK	Left scapula (used for assymetry)
R/LASI	Right/Left anterior superior iliac spine
R/LPSI	Right/Left posterior superior iliac spine
R/LIC	Right/Left iliac crest
R/LSHOA	Right/Left anterior acromion
R/LSHOP	Right/Left posterior acromion
R/LELB	Right/Left lateral epicondyle
R/LELBM	Right/Left medial epicondyle
R/LWRA	Right/Left raial styloid
R/LWRB	Right/Left ulnar styloid
R/LFIN	Right/Left 3rd metacarpal head (dorsal side)
SCKTA	Anterior socket 10 cm from superior trim lines
SCKTP	Posterior socket 10 cm from superior trim lines

2.2 Segment Definitions

The marker set described above is used to define the body segments of the upper body which include the torso, scapula, upper arm, forearm, and hand. Note, the marker set included pelvis markers; however a pelvis segment was not defined. The pelvis markers were used to help the Vicon software label each trial, decreasing the post-processing time. The segments were created in Matlab using a script called *createSegment.m* [17]. The script defined each segment using an origin, two defining lines, and an order. The segments were centered at the origin. The first defining line became the first axis. The cross product of the first and second defining lines became the second axis. Finally the cross product between the first and second axis became the third axis. The order given defines which axis corresponds to the X, Y, and Z axis. In order to maintain the right hand rule, the direction of the third axis may be switched to the negative cross product of the first and second axis if the right hand rule was not satisfied. A series of virtual marker points were created in Matlab and were used in the segment definitions. These virtual markers were created by taking the average of two markers and are described in Table 2 below.

Table 2: Virtual marker descriptions.

Virtual Marker	Description
UTOR	Average of the CLAV and T1 markers
LTOR	Average of the STRN and T10 markers
R/LSHO	Average of the R/LSHOA and R/LSHOP markers
ELBR/L	Average of the R/LELB and R/LELBM markers
RLBONE	Center residual limb bone position inside socket

2.2.1 Torso

The torso segment was the base reference frame for the upper body. The origin was set at the LTOR virtual marker. The first defining line was defined parallel to the line connecting the UTOR and LTOR virtual markers, with the positive direction going toward UTOR. The second defining line was defined parallel to the line connecting the CLAV marker and T1 marker, with the positive direction pointing to the TI marker. The convention order used was ‘yzx’. Figure 12 shows the orientation of the torso frame relative to the markers.

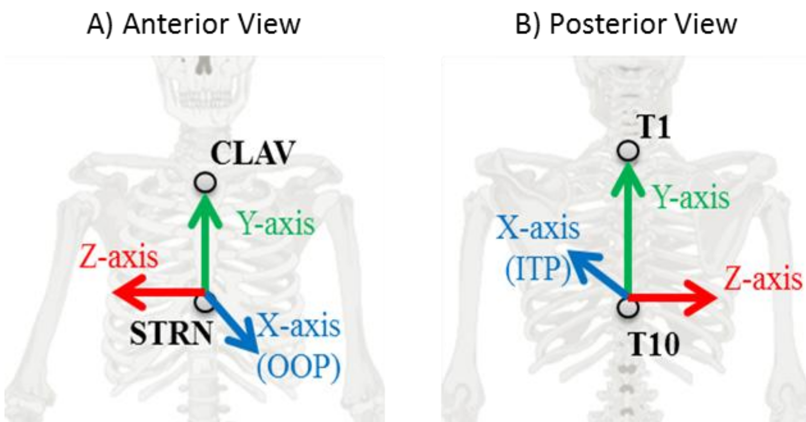


Figure 12: Diagram of the torso frame relative to markers. Skeletal image taken from public domain.

2.2.2 Scapula

Connecting the torso and upper arm segments, the scapula segment approximates clavicle and scapula movement, which is important to track, especially for body-powered prosthesis users. Figure 13 shows the orientation of the scapula frame relative to the markers.

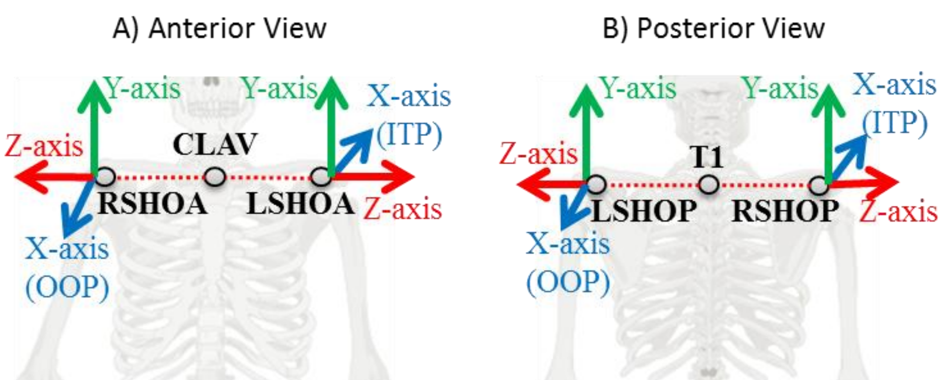


Figure 13: Diagram of the scapula frame relative to markers. Skeletal image taken from public domain.

The origin of the scapula was defined as the midpoint (RSHO/LSHO) between the RSHOA and RSHOP markers for the right side and the LSHOA and LSHOP markers for the left side. The first defining line was defined parallel to the line connecting the origin of the respective shoulder and the UTOR position, with the positive direction going toward the shoulder. The second defining line was the line connecting the posterior and anterior shoulder markers. The convention order used was ‘zyx’.

2.2.3 Contralateral Upper Arm

The sound upper arm refers to the side of the subject that is not amputated. A different segment definition is used for the residual limb. The origin of the sound upper arm was defined as the R/LSHO points depending on the side of the body being described. The first defining line is the line from the upper arm origin to the midpoint (ELBR/L) of the medial and lateral elbow markers, with the positive direction going toward the shoulder. The second defining line was defined parallel to the line connecting the lateral and medial elbow markers. The convention order used was ‘yxz’. Figure 14 shows the orientation of the sound upper arm markers. Note, the study was limited to unilateral amputees so only one side will be defined as the contralateral upper arm, and the other will be defined as the residual limb described in Section 2.2.5.

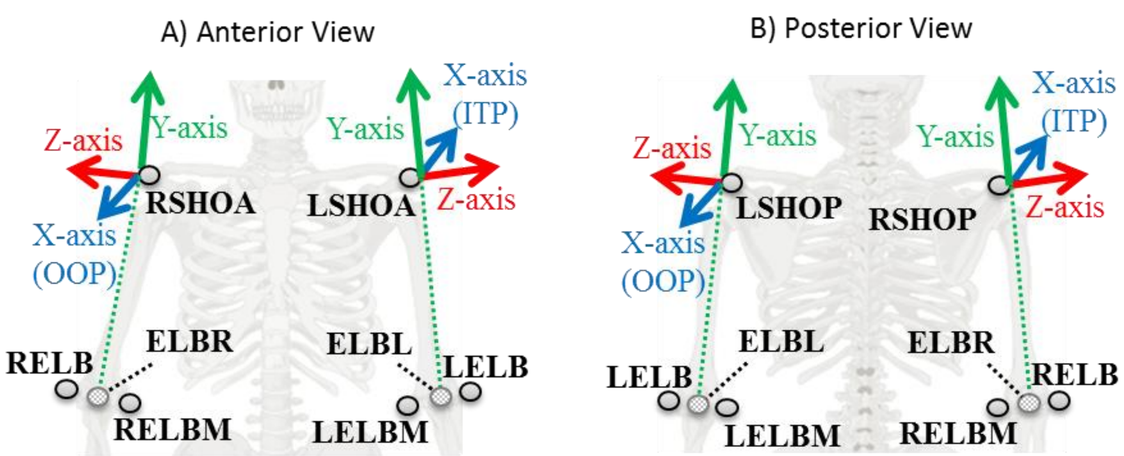


Figure 14: Diagram of sound upper arm frame relative to markers. Both the right and left sound arm definitions are shown, however, study participants had an amputation on one side. Skeletal image taken from public domain.

2.2.4 Socket

The origin was set to the midpoint of the anterior and posterior socket markers. The first defining line connected the origin to the midpoint of the lateral and medial elbow markers. The second defining line connected the anterior and posterior socket markers. The convention order used was ‘yzx’. Figure 15 shows the orientation of the socket frame relative to the markers. Note the figure shows socket frame for both right and left arm prosthesis for visualization purposes only. The study was limited to unilateral amputees so only one prosthesis would be worn.

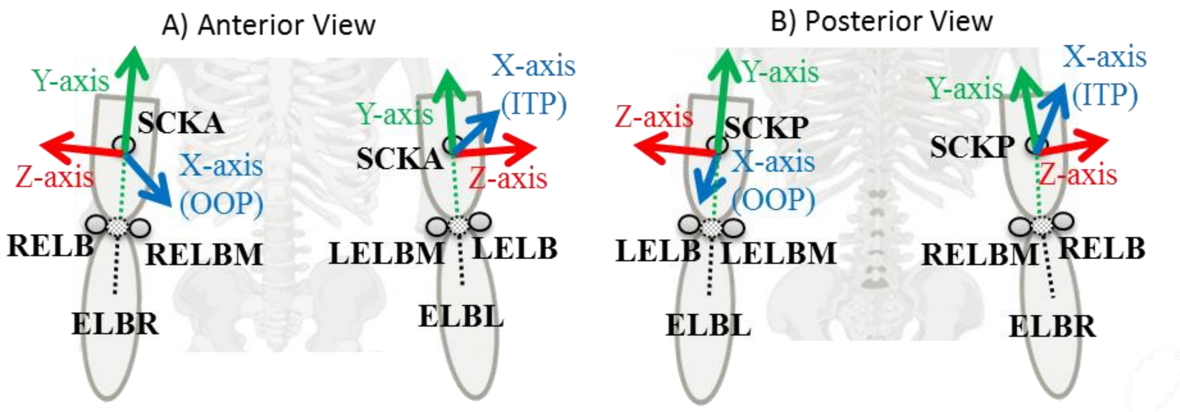


Figure 15: Diagram of socket frame relative to markers. Skeletal image taken from public domain.

2.2.5 Residual Limb

The origin was placed at the R/LSHO virtual markers depending on which side was amputated. The first defining line was defined from the origin to the RLBONE virtual marker. The second defining line was set equal to the X axis of the socket segment. This made any socket rotations about the long axis of the residual limb equal to zero and is a limitation of the marker set. This simplification was done because the marker set was unable to track rotation of the residual limb about the Y axis using surface markers. The convention order used was ‘yzx’. Figure 16 shows the orientation of the residual limb frame relative to the markers. Note the figure shows residual limb frame for both right and left arm prosthesis for visualization purposes only. The study was limited to unilateral amputees so only one side will be defined as the residual limb, and the other will be defined as the sound contralateral upper arm described in a previous section.

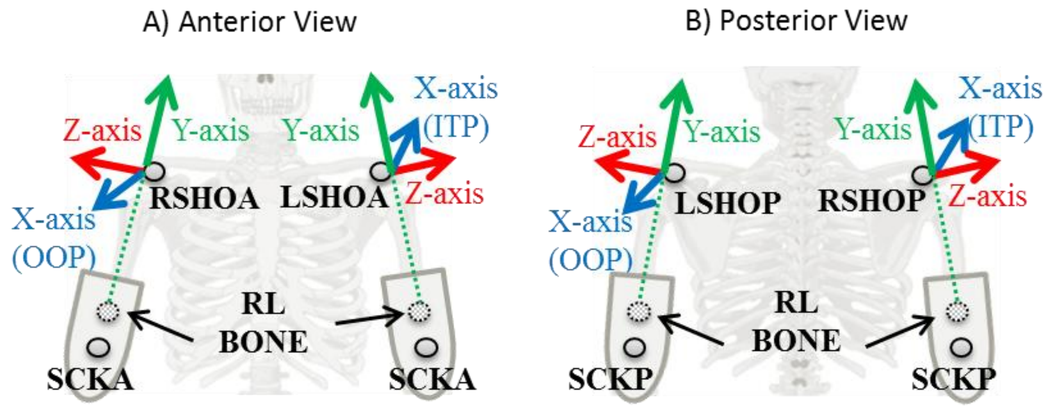


Figure 16: Diagram of residual limb frame relative to markers. Skeletal image taken from public domain.

2.2.6 Prosthetic Forearm

The origin was placed at the ELBR/L virtual markers depending on which side the amputation was on. The first defining line was defined from the origin to the average of the wrist markers (R/LWRA and R/LWRB). The second defining line was defined set equal to the Z axis of the socket segment. This made any rotations besides flexion and extension between the socket and the forearm equal to zero, limiting movement of the elbow angle to flexion and extension only. This simplification was done because the prosthetic limbs did not allow forearm pronation/supination. The convention order used was 'yxz'. Figure 17 shows the orientation of the forearm frame relative to the markers.

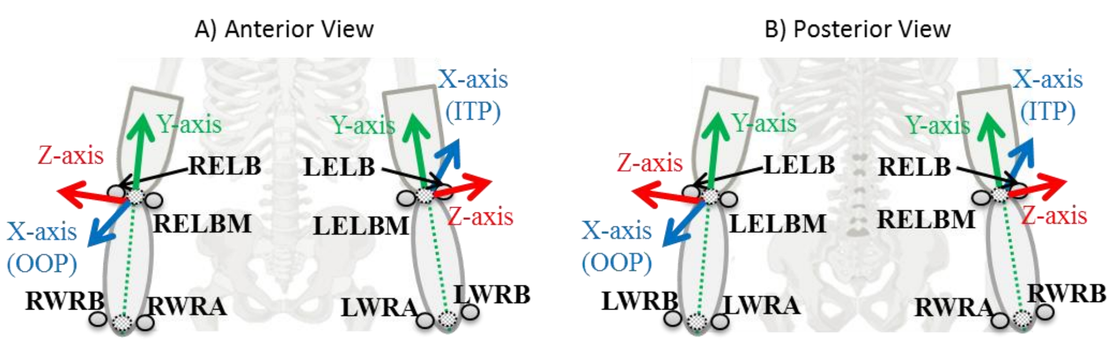


Figure 17: Diagram of forearm frame relative to markers. Skeletal image taken from public domain.

Note only the forearm segment for the prosthesis was defined so that the elbow angle at which the prosthesis was holding objects during the ADL tasks could be used as a covariate for statistical purposes. The coordinate frame definitions for each segment described above were used to calculate the relative position and orientation of body segments.

2.3 Joint Angle, Socket Translation, and Socket Slip Calculations

The information needed to completely specify one coordinate system relative to another is position and orientation. Position refers to the distance between the origin of one system to another, measured along the X, Y, and Z axes of one of the systems. Orientation refers to the angle(s) about which one system is rotated relative to the other. Robotics uses a set of four vectors to describe this information in an entity called a frame. The term transformation matrix is given to the 4 x 4 matrix representing a frame. These matrices (also called homogeneous transform) describe a coordinate system relative to the laboratory coordinate system or to another coordinate system. A generic homogeneous transform is shown in Equations 1 and describes a frame A with respect to a laboratory frame L.

$$
{}^{L}_{A}T = \begin{bmatrix} \widehat{X_A} \cdot \widehat{X_L} & \widehat{Y_A} \cdot \widehat{X_L} & \widehat{Z_A} \cdot \widehat{X_L} & p_x \\ \widehat{X_A} \cdot \widehat{Y_L} & \widehat{Y_A} \cdot \widehat{Y_L} & \widehat{Z_A} \cdot \widehat{Y_L} & p_y \\ \widehat{X_A} \cdot \widehat{Z_L} & \widehat{Y_A} \cdot \widehat{Z_L} & \widehat{Z_A} \cdot \widehat{Z_L} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{11} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
$$

The first three rows and three columns are known as the rotation matrix and describe the segment's relative orientation. The first cell, r_{11}, describes the projection of the X axis of coordinate system A onto the X axis of the laboratory coordinate system. Similarly, cell r_{32} describes the projection of the Y axis of coordinate system A onto the Z axis of the laboratory coordinate system. For Euler Angles, describes later, a rotation order was specified for each of the segments, which determined the order the rotation matrices were multiplied together. The rotation orders were chosen to eliminate singularities in the data. Singularities refer to points in which the mapping between two segments is no longer invertible. The terms p_x, p_y, and p_z, describe the position between the two systems.

All calculations were performed from the base script titled, *SRiM*.m, Appendix B.1. First, to ensure the data filenames could be read in Matlab, the script *removewhite.m* (Appendix B.2) removed spaces in the filenames. Next, a marker position reconstruct algorithm was used called *clusterReconstruct.m* (Appendix B.7) and then filtered using a weight moving point average (*WMAfilter.m,* Appendix B.3). A homogeneous transform was defined for each segment using *createSegment.m* (Appendix B.4). The laboratory frame was defined during calibration of the Vicon motion analysis system with the calibration wand, and was always set in the same position and orientation on the floor of the lab. These homogeneous transforms were then used to calculate the relative transformation matrices between two frames, for example the upper arm relative to the scapula frame. This was accomplished by multiplying one homogenous transform by the inverse of the other as shown in Equation 2 where the frame B was describe with respect to frame A.

$$ {}^{A}_{B}T = {}^{L}_{A}T^{-1}\,{}^{L}_{B}T \qquad (2)$$

If frame A represented the scapula and frame B represented the upper arm, the results of the above equation would yield the orientation and position of the upper arm frame relative to the scapula frame. This operation was performed for the scapula relative to the torso, the upper arm (or residual limb depending on amputated side) relative to the scapula, and the socket relative to the residual limb.

The rotational order used was ‘zxy’ between the scapula and the torso. Rotation about the Z axis describes the roll of the scapula or rotation about the sagittal axis. This rotation is positive internally for the right scapula and negative for the left. Rotation about the X axis represents depression of the scapula on both the right and left sides. Finally, rotation about the Y axis signifies protraction of the scapula on the right and retraction on the left.

The rotational order between the upper arm and the scapula was ‘zxy’. Rotation about the Z axis describes flexion or plane of elevation of the upper arm. Rotation about the X axis represents abduction or elevation of the upper arm. Finally, rotation about the Y axis signifies axial rotation of the upper arm. The rotation order used for the residual limb segment and the motions these axis describe are the same as the sound upper arm segment.

The rotational order used was ‘zxy’ between the socket and the residual limb. Rotation about the Z axis describes flexion or plane of elevation of the socket about the residual limb. Rotation about the X axis represents abduction or elevation of the socket about the residual limb. Finally, rotation about the Y axis signifies axial rotation of the socket about the residual limb.

The Euler rotation angles were then calculated once the transformation matrices were computed using *findTheta.m* (Appendix B.5) using the rotation order defined for each segment. In this notation, each rotation is performed about a moving axis rather than a fixed one, therefore the axis of rotation is dependent upon the preceding rotation. The rotation angles are derived from certain cells of the transformation matrix.

$$\beta = atan2\left(-r_{31}, \sqrt{{r_{11}}^2 + {r_{21}}^2}\right) \tag{3}$$

$$\alpha = atan2\left(\frac{r_{21}}{\cos\beta}, \frac{r_{11}}{\cos\beta}\right) \tag{4}$$

$$\gamma = atan2\left(\frac{r_{32}}{\cos\beta}, \frac{r_{33}}{\cos\beta}\right) \tag{5}$$

Euler angles were computed for all of the trials and used for comparison of the magnitude of rotation of the socket. An alternate method for describing the rotation was also used for the residual limb. This alternate method made it more clear the extent of which the residual limb was moving and is known as equivalent angle-axis representation. Using Euler angles for the correlation would mean all the outcomes would have to be analyzed in terms of the amount of flexion and abduction individually, but equivalent angle-axis notation yields one angle. The angle calculated using this method represents the smallest rotation angle needed to align the coordinate systems of two segments. An arbitrary axis is used for rotations calculated by this method. Since the rotation matrix is already known for the transformation matrices, the angle, θ, can be calculated.

$$\theta = acos\left(\frac{r_{11}+r_{22}+r_{33}-1}{2}\right) \tag{6}$$

Note, typically when calculating equivalent angle-axis notation angles, the direction of the axis of rotation is also calculated. However, for this dissertation, the direction of the axis of rotation was not calculated since only the angle was of interest and the axis was not used in any of the calculations.

CHAPTER 3: DEVELOPMENT OF THE SLIP DETECTION SENSOR

While modeling the residual limb with a ballistic gel model, it was found that additional hardware would be needed to fully characterize the motions occurring at the socket interface. This section will discuss in detail the need for and development of the Slip Detection Sensor.

3.1 Ballistic Gel Testing

Ballistics gel is commonly used to replicate the soft tissues of the human body and is frequently applied to weaponry simulation [71]. Ballistic gel was used to simulate the residual limb of a person with an amputation and test how the socket rotates as forces are placed on it. A thermoplastic socket with an eye bolt attached to the distal end as a point of force application was suspended on a ballistic gel mold (Figure 18).

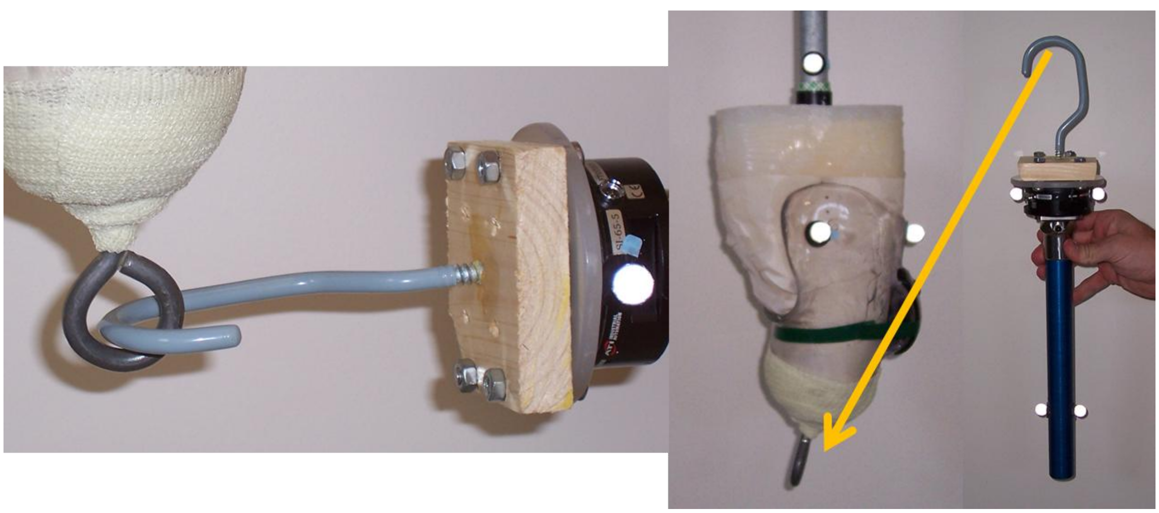


Figure 18: Ballistic gel simulation of residual limb.

The ballistic gel was a positive mold of the inside of the socket so it would fill the socket volume, similar to a residual limb. The ballistic gel residual limb model and socket were suspended from a wooden frame and a force applicator was used to apply forces to the socket. A force transducer on the force applicator recorded the forces placed on the socket. A Vicon motion analysis system tracked the amount of movement between the socket and residual limb model. Note markers on the force applicator tracked the orientation so the direction of force application was known.

The results were used to show that the rotation could be tracked by the Vicon system during dynamic movement and that the movement at the interface could be modeled based on the force placed on the system (Figure 19). Two models were used to describe the soft tissues; one based off the non-linear form of Hooke's Law and a second biaxial model that related the stresses and strains on the system. Both models showed good results but the biaxial model was more computationally efficient.

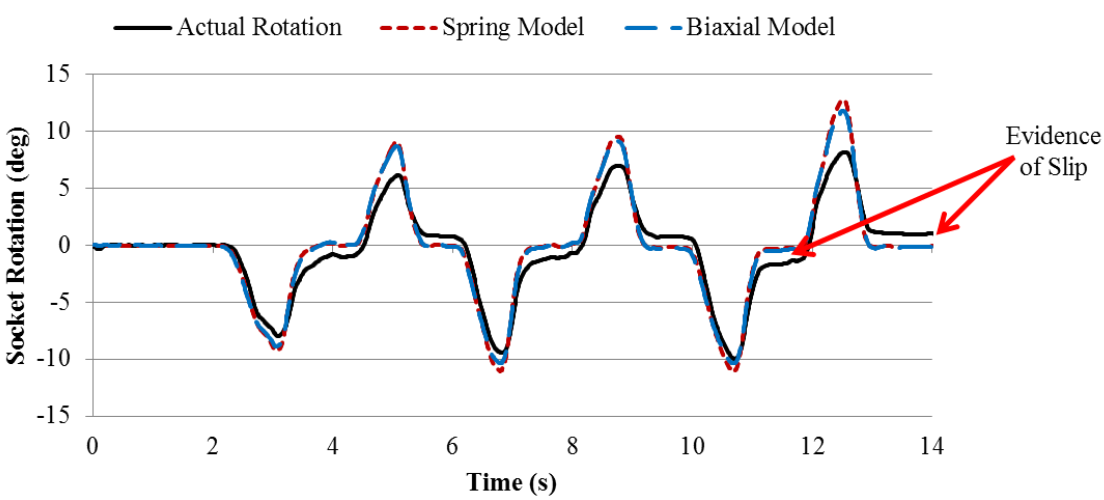


Figure 19: Results of ballistics gel simulation: Red arrow indicates area of possible slip. Black line should return to zero.

After further review of the results, it was noticed the amount of rotation predicted by both models returned to the starting point as the force exerted was removed. However, this was not the case for the amount of rotation measured by the Vicon motion cameras. The error was attributed to slip between the socket and simulated residual limb. Slip motion of the socket will cause more hysteresis in the position of the socket relative to the residual limb and is important to track. The Vicon system can detect this type of motion, but combines slip translation with translation caused by soft tissue deformation. Therefore it was determined that an additional sensor was necessary to measure when slip occurred between the socket and skin surface or inner liner, as well as the magnitude of movement so it could be compared to the Vicon motion capture data.

3.2 Slip Detection Sensor

An optoelectronic sensor was chosen to measure the movement of the socket relative to the residual limb. This sensor is a noncontact sensor and only required a small portion of material removed from the socket, and did not interfere with the internal socket volume. The Slip Detection Sensor had other advantages over previously used methods, such as the ability to measure more than one degree of freedom and differentiate slip from soft tissue deformation [67], did not limit the participant to a small workspace [68], and provided results that could be quickly analyzed [70]. The rest of this section describes development of the hardware and software for the optoelectronic sensor.

3.2.1 Hardware Development

A laser mouse made for computers was selected as the most logical starting point because it was already well suited for tracking movement between two surfaces. Several laser mouse options were reviewed before a final one was chosen. The criteria for selection were that the optical sensor needed to be as small as possible, already capable of wireless connection to the computer via a Universal Serial Bus (USB) port, and small circuit board size. A Genius 2.4 GHz Wireless Pen Mouse was selected (Figure 20). The small sensor shape and circuit board could easily be repackaged in a custom casing to allow for placement into the socket.

Figure 20: Left: Pen mouse; Right: Sensor and circuit board.

The next step was to design a custom casing that would hold the sensor, allow it to be attached through the socket wall, and maintain contact with the inner liner or skin surface inside the socket. Initially it was thought that the sensor would need to move in or out of the hole in order to adjust for movements when the skin surface was not in contact with the socket wall. The first prototype allowed for this movement by having the sensor rest on an insert that could translate inside the outer casing (Figure 21).

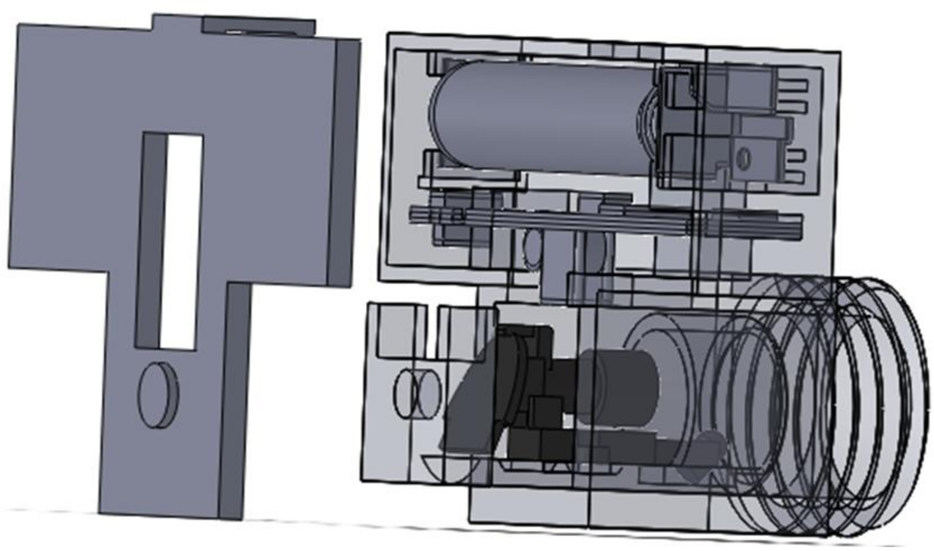


Figure 21: SolidWorks assembly of first prototype slip detection sensor casing.

The insert was forced against the skin by a low force spring. The front end of the outer casing was threaded so it could screw into the socket wall and be secured. The casing was prototyped using a Dimension Elite (Stratasys Ltd., Eden Prairie, MN) fused deposition modeling 3D printer. The casing was tested against a simulated residual limb and it was found that having the sensor translate inside the outer casing caused significant strain on the wire connecting the sensor and circuit board, ultimately resulting in its failure. Since this drastically reduced the life of the sensor a new design was created.

The second prototype still allowed for movement of the sensor in and out of an outer casing, but moved the sensor and circuit board together (Figure 22). The box that houses the circuit board and power source was moved behind the sensor instead of on top and reduced the overall size by over 50%. A separate piece was designed as an insert into the socket wall. This piece was threaded so it could easily be inserted into the socket and had mounts on the side where a rubber band could be placed and wrap around the back of the sensor casing, crossing in the back. The rubber band kept pressure on the sensor casing and kept it against the skin surface. A relative low tension rubber band was used so the magnitude of force the device placed on the skin surface would not interfere with the socket movement or sensor readings.

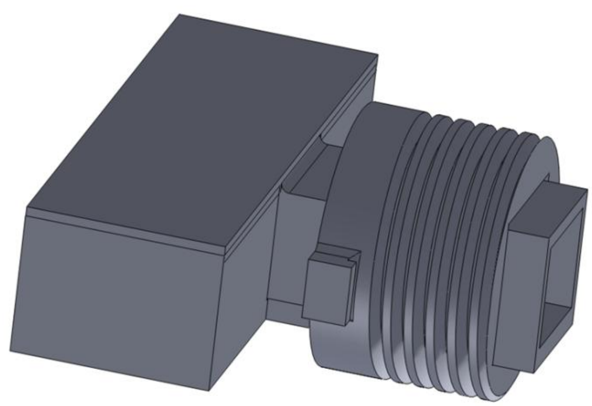


Figure 22: SolidWorks assembly of second prototype slip detection casing.

A sleeve was made from thermoplastic material and Velcro was attached to it. This allowed the sensor to be tested in a pseudo socket setting against actual skin. A Vicon motion capture system was used and markers were placed on the cuff, the participant’s limb, and on the back of the sensor. The amount of slip as well as the amount of translation toward the skin of the sensor was tracked. The results showed that the amount of translation of the sensor toward the skin surface was very negligible and the translation of the casing was not needed. Without the need for the sensor to translate in and out of the socket, the size of the casing was further reduced. The next version of the casing was broken into two parts (Figure 23).

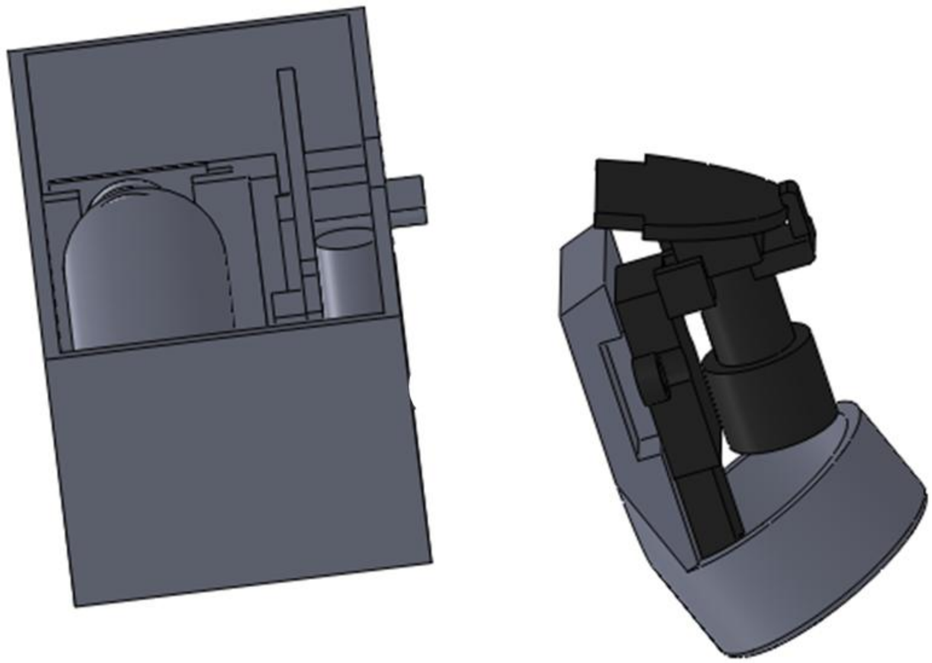


Figure 23: SolidWorks assembly of third prototype slip detection sensor casing.

The first part was a box that held the power source and circuit board and the second part held the sensor through the socket wall and against the inner liner or skin surface. Separating the insert from the other components lowered the impact the sensor made on the socket wall, reducing the size hole required for placement to 16 mm. To further improve tracking, the base of the insert was bent at an angle relative to the skin surface. This more closely matched the orientation of the sensor inside the pen mouse and yielded better sensor imaging. This improved the tracking capabilities of the sensor, which was visually analyzed by watching the pointer position change on the computer screen. However, differences between movement of the sensor in the real world and the movement of the pointer on the computer screen tested by repeated movements of a known distance were still shown.

It was concluded that the end of the pen mouse which housed the optical sensor was too difficult to replicate and precisely match the position and orientation of the sensor. Therefore, the tip of the pen mouse was cut off and a custom insert was made to hold the sensor inside the socket.

Since the end of the pen mouse has an unusual shape, it was necessary to make a custom insert to hold the piece in the socket wall. This simplified attachment to the socket, and allow the prosthetist to use standard drill bits to bore out a circular hole, making socket duplication required in the study much easier. This process is further discussed in the next chapter. The geometry of the pen mouse tip was measured using a caliper and an insert was made to hold that piece (Figure 24). The outer diameter was increased to 20 mm in order to fit the unusual inner shape and was left circular so it could easily be fit into the socket wall. The casing that holds the circuit board and power source was unchanged and used with this insert. Visual inspection of the pointer position using the last casing method showed a near perfect match between movements in the real world and movements of the pointer on the computer screen.

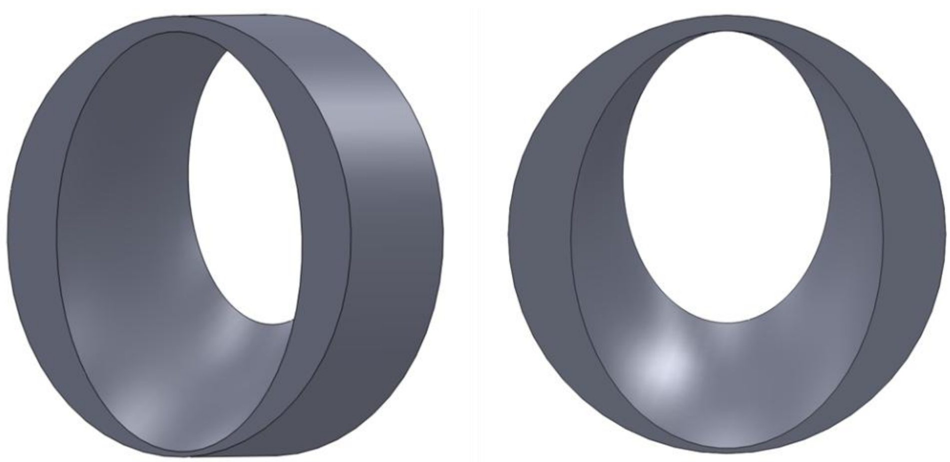


Figure 24: SolidWorks assembly of final slip detection sensor insert used in the study.

3.2.2 Software Development

Computer mice are programmed to move a cursor on the computer screen which represents the movement of the mouse. To aid the computer user, the cursor movements are sensitive to fast movements, referred to as pointer acceleration in the control panel, allowing the user to move the cursor over a greater distance on the screen without having to travel a greater distance on the mouse pad or desk. The pointer settings were changed within the control panel of the computer to neglect pointer acceleration so speed effects would not produce errors in the data. For the purpose of the Slip Detection Sensor, a Matlab script (*SkinMotion.m,* Appendix B.8) was written to determine the distance traveled by the mouse using the cursor position on the screen. The script tracked the cursor position on the computer screen as it moved within a figure window using the sub function *gpos.m* (Appendix B.11). The pointer speed was set to the fourth lowest position on the options menu to avoid instances where the pointer tracked outside of the figure window. If the pointer were to travel outside of the figure window, data would not be collected until the pointer traveled back into the figure window. Any slip occurring during this period would not be captured. To avoid having errors in the data due to the cursor moving outside the figure window, the Matlab script *maximize.m* (Appendix B.9) was added to expand the figure window to the size of the computer monitor.

The script was programmed to record the X and Y coordinates as well as a time stamp from the start of the trial and save the information in a text file (.txt). This file could later be brought into Matlab for further processing and comparison to the Vicon motion capture data. Since the pointer options were adjusted, the program was calibrated so movements calculated by the sensor matched the actual movements in the real world. This was done by scaling the max values for the X and Y coordinates of the figure window. To determine the proper scaling factor, the slip detection sensor was moved between two points, spaced a known distance apart (20 mm). The scaling factor was determined using Equation 7.

$$S.F. = \frac{Actual\ Movement}{Movement\ Recorded\ by\ Sensor} \cdot Previous\ S.F. \quad (7)$$

This process was repeated until the ratio of actual movement divided by the recorded movement was equal to 1±0.05 for three consecutive trials. The final scaling factors set the maximum X dimension on the figure window to 80 and the maximum Y dimension to 40.6, calibrating the results to be output in millimeters. The calibration was then tested against the motion capture system. To ensure repeatability, the same computer monitor was used for calibration and testing.

3.2.3 Slip Detection Sensor Validation

The Slip Detection Sensor was embedded into the lateral socket wall of the thermoplastic socket used for the ballistic gel testing. A silicon positive mold was made from the thermoplastic socket. The motion capture system tracked the position of reflective markers placed on the socket and silicon mold while the socket was manually moved on and off the silicon mold in the vertical direction. The movement of the socket in this case represented a pure slip condition (the silicon mold was significantly more rigid than human skin and did not significantly deform), so the results of the motion capture system could be directly compared to the results of the Slip Detection Sensor. The amount of slip from the motion capture data was calculated by creating coordinate frames for both the socket and silicon mold segments, and finding the relative translation between the two along the long axis of the silicon segment. The Slip Detection Sensor simultaneously recorded the amount of socket slip. The root mean square error was evaluated to compare the amounts of slip found by the two systems and is presented in Figure 25 for all of the trials. The average root mean square error was 0.9 mm. Some of the error may be attributed to small deformations of the silicon mold.

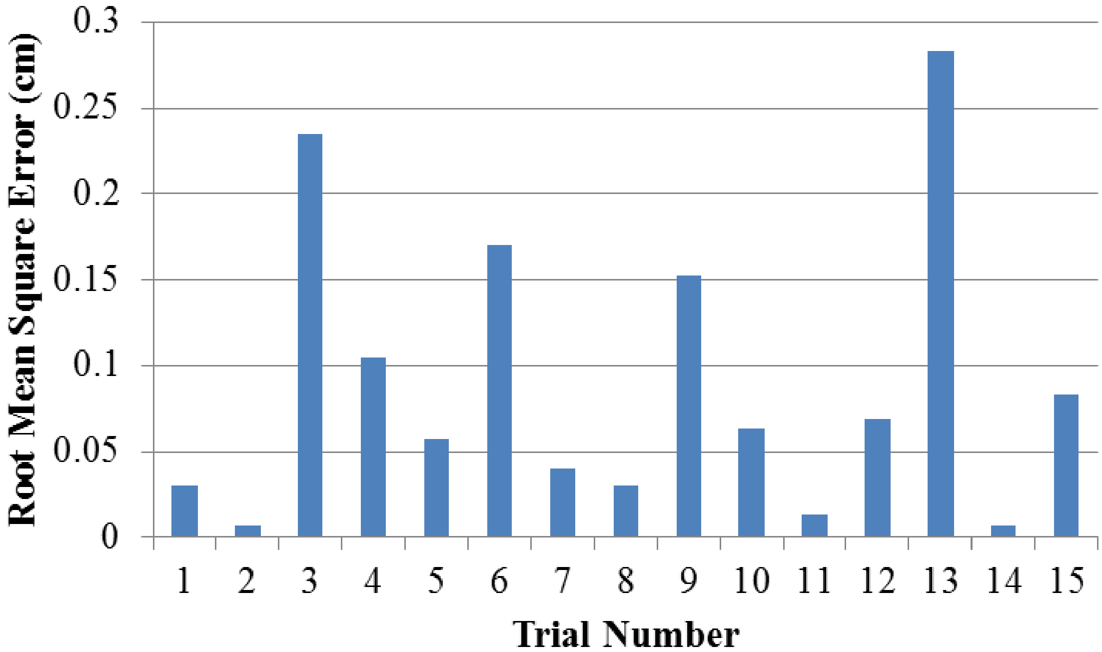


Figure 25: Root mean square error of vertical slip from the initial comparison of the Slip Detection Sensor to the motion capture system.

Due to its rigid shape, the socket could not travel vertically down the mold without losing surface contact. When the loss of surface contact occurred around the sensor, the surface moved outside of the focal length and introduced error into the sensor data.However the error was relatively small and occurred when the gap between the sensor and the tracking surface was larger than expected for typical prosthesis use. It was determined the sensor was ready for testing against human soft tissues.

A cuff was made from thermoplastic and inner liner material in order to simulate the materials found in an actual prosthesis. The cuff design made it easily adjustable to different limb sizes. The sensor was incorporated into that sensor and passive reflective markers were placed on the cuff and sensor (Figure 26). Reflective markers were also placed on a participant's scapula and elbow. The sensor was manually moved about the participant's upper arm while the

8 camera motion capture system recorded the position of the markers and the Slip Detection Sensor recorded the amount of socket slip simultaneously. The thermoplastic cuff was moved in a way to maximize slip and minimize pressure on soft tissues to eliminate soft tissue deformation so that the results of the motion capture system and Slip Detection sensor could be compared directly. The results showed an average root mean square error of 1.9 mm. The error was higher than the initial testing with the silicon mold, but the procedure was prone to greater variance due to differences between the two.

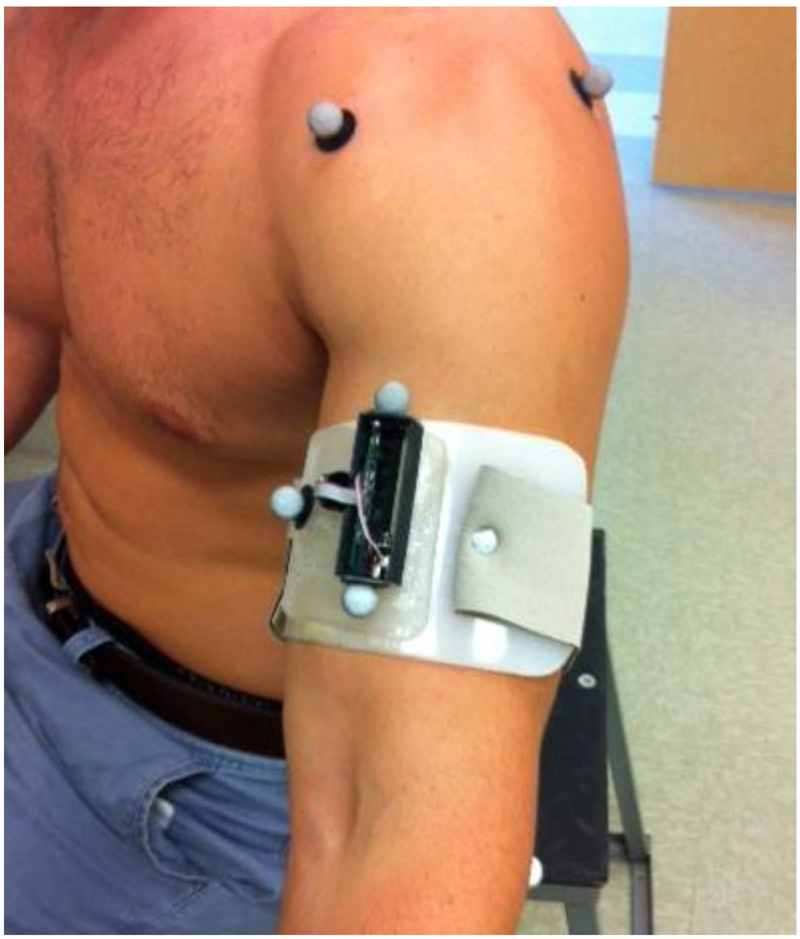


Figure 26: The sensor cuff and Slip Detection Sensor being used to compare the sensor's output to the motion analysis system data.

When testing with the silicon mold, the amount of slip was much easier to control because of the rigid shape of the mold. While care was taken to limit the amount of soft tissue deformation while moving the thermoplastic cuff, it was still possible for it to occur and interject error into the data. Additionally, multiple participants increased the variation. Still, the observed error was small and the true error was believed to be less with the removal of soft tissue deformation. Therefore, confident in the performance of the sensor, it was determined it was ready for use in transhumeral prosthetic sockets.

CHAPTER 4: STUDY PROCEDURES AND DATA ANALYSIS

All testing was completed at the Rehabilitation Robotics and Prosthetics Testbed (RRT) at the University of South Florida. The collection procedures were approved by the Western Institutional Review Board, who was contracted by the University of South Florida. Informed consent was given by all participants before participation in the study. The goal of the cross-sectional study was to measure the amount of movement occurring at the socket interface during common tasks without interfering with the internal socket volume.

An eight camera Vicon motion capture system was used to collect data from six participants performing RoM and activities of daily living (ADL) while using a transhumeral prosthesis. All participants had a harness suspension system. Note, one participant had a pin-locking suspension system, but regularly uses his prosthesis without the pin attached to the gel liner. The participant completed the collection procedures with and without the pin attached to the gel liner. This participant was counted as two participants (H04 and H05), bringing the total of participants to seven. For the purposes of group statistics, only one data set from this individual was used to avoid biasing the analysis to the results of the one individual. The data from H05, where the participant used the pin-locking suspension system was excluded from the group statistics because his other suspension system was more comparable to the other suspension systems in the study. The characteristics of the participants and their prosthetic systems are shown in Table 3. These participants all used a body-powered or hybrid (some components are body-powered while other components are controlled by other means) prosthesis and used the same prosthetic socket without a documented skin condition for a minimum of a two month period. The marker set described in Chapter 2 was used to track the body segments during the tasks. The motion analysis collection procedures were divided into two days. Figure 27 shows the flow of participation in the study.

Table 3: Participants' measurements and prosthesis/socket characteristics.

ID	Height (cm)	Weight (kg)	Prosthesis Side	Acromion to Distal RL (cm)	Axilla to Distal RL (cm)	Suspension System	Control System
H01	180	81	Right	22	11	Harness	BP
H02	174	80.7	Right	26	18	Suction	Hybrid
H03	184	77	Left	42	27	Suction	Hybrid
H04	183	102.5	Right	31	20	Harness	BP
H05	183	102.5	Right	31	20	Pin-Locking	BP
H06	172	109.3	Left	23	13	Suction	Hybrid
H07	165	86	Right	35	22	Harness	BP

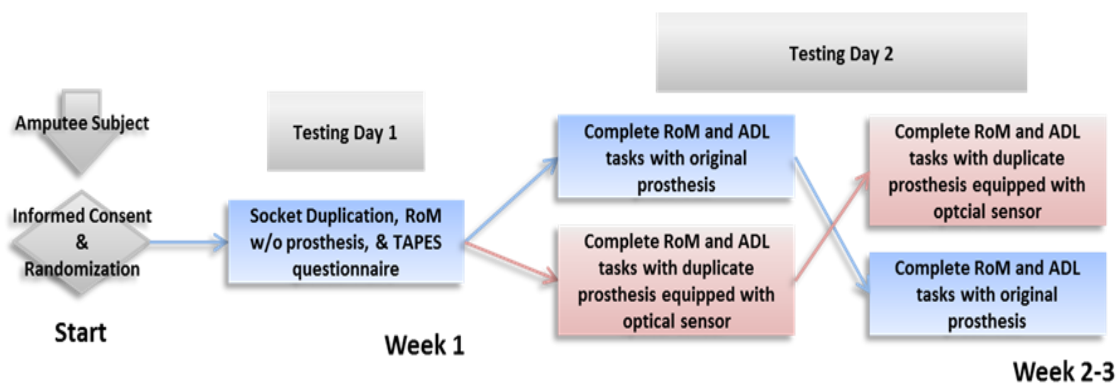


Figure 27: Flowchart of participation in the study.

4.1 First Collection Day Procedures

This day began with the prosthetist (PhD, Certified Prosthetist, Follow of the American Academy of Orthotists and Prosthetists) taking several anthropomorphic measurements of the participant. These measurements included residual limb circumference at the axilla and distal ends, residual limb length, chest circumference, and lengths and circumferences of the arm and forearm of the non-amputated side. Residual limb length was measured from both the axilla to the distal end medially and from the acromion joint center to the distal end laterally. These measurements were used in the calculation described in the previous chapter.

The data collection on the first day began with three active RoM tasks performed without wearing a prosthesis (Table 4). Each RoM task was repeated three times. A member of the study team modeled the tasks for the participant to mimic, and the participant was instructed to move as far as possible without causing discomfort. The marker set used was the similar to the one described in Table 1, however since the participants were not wearing a prosthesis for this portion of the collection, the markers distal to the socket trim lines (SCKA/P, R/LELB, R/LELBM, R/LWRA, R/LWRB, and R/LFIN) were replaced with RSLA and RSLP markers placed on the anterior and posterior portions of the distal residual limb.

Table 4: First testing day RoM task descriptions.

RoM	Description
Shoulder Flexion / Extension	Start with elbows extended towards the floor and palms facing body. Raise arms, reaching forward, then up, then backwards as far as possible (maximum shoulder flexion). After a brief pause, return arms in reverse path to starting position then backwards (maximum extension). Pause briefly before returning to starting position.
Shoulder Abduction / Adduction	Start with elbows extended towards the floor and palms facing body. Abduct arms to maximum then pause briefly. After pause, adduct arms back to starting position then cross arms in front of the body (maximum adduction). Pause briefly before returning to starting position.
Shoulder Rotation	Start with elbow flexed to 90 degrees with arms abducted parallel to the floor, palms facing down. While maintaining the upper arm parallel to the floor, rotate the arms downward as far as possible, pause briefly, then rotate upward to a maximum, pausing again then return to the starting position

After completion of the RoM tasks, the participants completed the Trinity Amputation and Prosthesis Experience Scales [72] (TAPES) questionnaire. The TAPES questionnaire looked at various aspects of having a prosthesis and the information gathered was used as a user-reported score of their satisfaction with their prosthesis and socket. The questionnaire begins with general questions such as age, amputation level, cause of amputation, and amount of experience with prostheses. Part I asks participants to rate statements related to wearing a prosthesis, activities performed during a typical day, and satisfaction with different aspects of their prosthesis. Part II asks participants about amount of use of their device and health related questions such as residual and phantom limb pain. This concluded the day one procedures for the participant.

While the participant completed the day one tasks above, the study prosthetist made a positive mold of the original socket shape using alginate. The entire socket duplication process is summarized in the Section 4.1.1. Once the prosthetist removed the alginate mold from the socket and cleaned any residual material from the socket, the prosthesis was returned to the participant. One week later, the participants returned to complete the second day procedures. During this week gap, the prosthetist assembled the sensor embedded prosthesis using the socket equipped with the optical sensor.

4.1.1 Socket Duplication

Duplication began by making a positive mold of the existing socket shape. The original prosthesis was put in a bucket of sand to hold the prosthetic limb vertical, ensuring the alignment was maintained (Figure 28). Once the vertical position was set, the inside of the original socket was filled with alginate. A metal pipe was inserted vertically into the mixture and held up by tongue depressors while the alginate sets. The metal pipe provides a connection to the vacuum system used during a later step in the blister forming process as well as an indicator of the vertical position of the positive mold. Some sockets have pre-flexion built in to help the amputee operate the system, which was replicated with the sensor embedded prosthesis. Once the alginate reached a solid state, it was removed from the original socket.

Figure 28: Process for making the positive mold representing the internal socket shape.

A negative mold of the alginate positive mold was made with plaster wraps, a more durable material to maintain the mold shape. This negative mold was then filled with a plaster mixture and allowed to solidify. This plaster mold was then smoothed of any impurities. For suction sockets, additional steps were required. Before the thermoforming steps begin, the suction valve was screwed into the side of the positive plaster mold. The positive mold was placed upside down on a vacuum rig (Figure 29). Note this figure includes the suction valve port screwed into the plaster mold. The clear thermoplastic socket was made using the blister forming technique. A sheet of clear thermoplastic was placed in a metal pan with a hole removed in the center (Figure 30).

The metal pan and thermoplastic was placed in an oven (Figure 31) and heated at 325°F until the plastic droops through the hole in the pan. The amount of droop desired is between two thirds and three fourths of the desired socket depth.

Figure 29: Plaster mold with a suction valve is placed upside down on the vacuum rig.

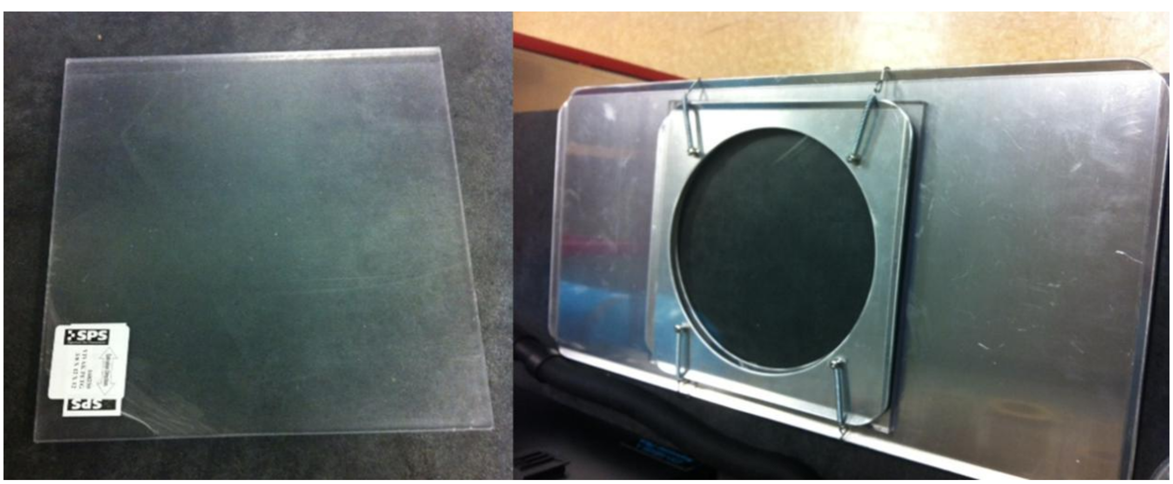


Figure 30: Left: Sheet of thermoplastic; Right: Pan with hole to allow for droop of thermoplastic.

Figure 31: Oven used to heat the thermoplastic and drooping of the thermoplastic at two different time periods. The thermoplastic forms a blister, hence the name of the technique.

Once the thermoplastic had drooped to the desired level, it was removed from the oven, inverted so the pocket of plastic could be pulled down over the plaster mold (Figure 32). A vacuum was slowly applied to remove air between the positive mold and the thermoplastic while the prosthetist used his hands to remove any creases in the plastic and make sure the thermoplastic had a total contact with the plastic mold. The vacuum was left on for approximately twenty minutes to remove any air and help the plastic cool. Once the plastic was cool enough to touch without burning the prosthetist's skin, the pan was removed and the excess thermoplastic cut using a rotary saw (Figure 32). Note, if a suction socket was being replicated, this blister forming process was performed twice. During the first process, the inner liner material was formed over the plaster mold. During the second process, the thermoplastic material was formed over the inner liner and mold.

Figure 32: Forming the thermoplastic over the plaster mold, and removal of the excess material.

The socket was then clamped vertically using the metal pipe and the distal prosthetic components were attached. The first step was to add hardening foam to the distal end. The two part foam was mixed and poured into a masking tape ring constructed on the distal end of the socket. Once the foam hardened, the tape was removed and the end of the foam was sanded down so the trim line to elbow distance matched the measurements taken from the participant during the first data collection day. The elbow component was secured to the sensor embedded socket with epoxy and was then covered with a fiber glass wrap for additional support. Note a generic set of body-powered components were used for all participants (Figure 33). This included a right or left a right or left E400 45mm prefabricated elbow and forearm, a quick disconnect wrist assembly, Hosmer hook 5XA, a quick disconnect insert assembly. A thermo valve if a suction socket was being made.

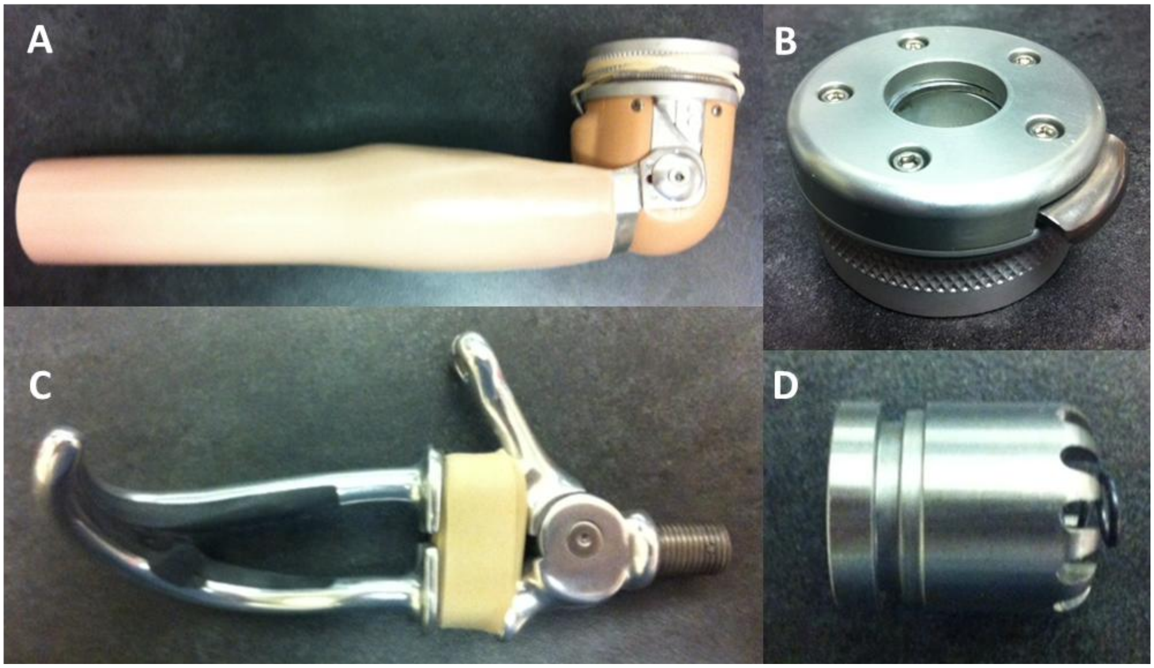


Figure 33: A: E400 45 mm prefabricated elbow and forearm, B: Quick disconnect wrist assembly, C: Hosmer hook 5XA, D: Quick Disconnect insert.

After the elbow was connected, the plaster mold and pipe was removed from the sensor embedded socket. The trim lines of the socket were then smoothed with an electric sander until a smooth finish was achieved. The wrist component was attached and secured with epoxy before putting in the quick disconnect and Hosmer hook. Note, since the wrist component was difficult to remove once secured with epoxy, a standard forearm length of 24 cm was used for all participants. This length was ±1 cm from the appropriate length for all participants. Since the amount of socket movement was being studied and not the function of the prosthesis, it was assumed this difference in length would not significantly affect the results. The last step for the socket duplication required the harness system to be attached to the arm. A Figure 8 harness was used for all participants. Only one of the participants regularly used a chest strap harness system, but was comfortable operating the Figure 8 harness system.

Once the prosthesis was complete, the slip detection sensor was added. A 3/4 inch drill bit was used to cut out a hole in the wall of the socket, leaving stock allowance to ensure a snug fit.

The remaining material was removed with a Dremel tool until the sensor casing had a snug fit and was flush with the interior wall of the socket. The hole was placed on the lateral most aspect of the socket, roughly equal to the height of the axilla trim line.

4.2 Second Collection Day Procedures

The second day procedures required the participant to complete tasks with the original and sensor embedded prostheses. The participants were asked to complete nine tasks, four RoM (Table 5) and five ADL (Table 6), each one repeated three times. The ADL tasks were selected to include a range of task weights and movements, allowing the results to be analyzed based off the weight of the task and the movement of the residual limb during completion of the task. The testing protocol was completed twice, once while wearing the original prosthesis and once wearing the sensor embedded prosthesis. The marker set used for this day is described in Table 1. Participants were randomized into two groups that determined the prosthesis order.

Table 5: Second testing day RoM task descriptions.

RoM	Description
Shoulder Flexion / Extension	Start with elbows extended towards the floor and palms facing body. Raise arms, reaching forward, then up, then backwards as far as possible (maximum shoulder flexion). After a brief pause, return arms in reverse path to starting position then backwards (maximum extension). Pause briefly before returning to starting position.
Shoulder Abduction / Adduction	Start with elbows extended towards the floor and palms facing body. Abduct arms to maximum then pause briefly. After pause, adduct arms back to starting position then cross arms in front of the body (maximum adduction). Pause briefly before returning to starting position.
Shoulder Rotation	Start with elbow flexed to 90 degrees with arms abducted parallel to the floor, palms facing down. While maintaining the upper arm parallel to the floor, rotate the arms downward as far as possible, pause briefly, then rotate upward to a maximum, pausing again then return to the starting position
Elbow Flexion / Extension	Start with elbows extended towards the floor and palms facing body. Flex elbows until maximum is reached, pause briefly, then extend elbows until back to the terminal position.

Table 6: Functional task descriptions.

ADL	Description
Unilateral Lift	Participant picks up and places a series of weights form one spot on a 3 feet high shelf to another spot 3 feet away on the same shelf. The participant must hold the object above the shelf (cannot drag the object) during the transfer. The task weights were 5, 10, and 15 lbs.
Bilateral Lift	Participant lifts a basket containing a series of weights from the floor to a 3 feet high shelf, and then back to the original position. The task weights were 10, 25, and 50 lbs.
Walk and Carry	Participant walks on a treadmill for 1 minute while carrying a gallon carton of milk (task weight approximately 8 lb) with the prosthesis.
Fold a Towel	Participant stands in front of a table with a bath towel on top. Participant folds the towel in half lengthwise, then in half widthwise, then in half lengthwise.
Modified Box and Blocks	16 blocks are placed in 4 rows of 4 on one side of a box with a partition in the middle. The objective is to move one block at a time to the same spot on the other side. Participants were instructed to start at the lower inside corner and complete that row before moving to the next. Participant had 1 minute to move as many blocks as they can. The box started so the blocks start on the same side as the participant's prosthesis.

Changes in the residual limb volume can affect the fit of the socket and can occur during the collection procedures. Therefore it is important to measure the volume of the residual limb. Volume measurement was completed before and after testing both prostheses. To do so Archimedes principle was applied, which states that the force exerted on an immersed body is equal to the weight of the fluid displaced by that body. Participants stood next to a table with a bucket of water placed on top of a digital scale. The digital scale was zeroed with the bucket of water on top. This line was drawn at the area of the limb that the proximal trim lines of the socket rests, which marks the end of the socket. Participants lowered their residual limb into the water until the water level reached a line drawn on the residual limb. The scale measured the change in weight, or buoyancy force exerted on the residual limb, which is equal to the weight of the water displaced. The volume of the body submerged was calculated dividing by density

(Equation 8). The mass of water is given by the scale and the density of water is known, leaving volume as the only unknown variable.

$$\text{Density} = \frac{\text{Mass}}{Volume} \tag{8}$$

4.3 Data Analysis

The goal of the dissertation was to quantify socket interface movements using motion analysis and the Slip Detection Sensor and test the hypotheses defined in the introduction. The information gathered was used to determine the range of socket movement that occurred during a series of ADL tasks. Two types of analysis were performed. The data from the RoM tasks were analyzed using a repeated measures analysis of variance (repeated measures ANOVA). The data from the ADL tasks was analyzed using a multivariate linear regression to analyze the effects of four cofactors on the amount of socket movement. These cofactors were identified as residual limb RoM during task completion, the weight of each task, residual limb length, and elbow angle. The second analysis performed used analytical results on an individual participant basis.

4.3.1 TAPES Questionnaire Analysis

The results of the TAPES questionnaire were used to provide a level of satisfaction with the prosthetic system indicated by the participant. The participants were instructed to complete the questionnaire in regards to their original prosthesis. The scoring for the TAPES was analyzed for each individual section. Note, some of the participants had amputations to various limbs. The sections scores indicated their level of adjustment to using a prosthesis, the degree to which a prosthesis limited their ability to perform activities, and satisfactions with various aspects of the prosthesis respectively. The individual responses for each section were scored based off of scale ratings. Responses with a higher score indicated a greater level of adjustment to prosthetic use, increased limitation to perform activities, and a greater satisfaction level with various aspects of the prosthesis respectively for each section. The participant's responses within a section were summed and divided by the highest total possible score for that section. The TAPES questionnaire also had the participants rate their overall satisfaction with their prosthesis on a scale of 1-10, with 10 being the highest possible satisfaction. The average hours (total, not continuous usage) of prosthesis use per day was also collected. The TAPES results for all of the participants are reported in Table 7 in the results section.

4.3.2 RoM Tasks Analysis

The RoM of the contralateral limb, residual limb without wearing a prosthesis, residual limb while wearing the original prosthesis, and residual limb while wearing the sensor embedded prosthesis were compared to show the effect the amputation and various prostheses had on the RoM for each participant. Euler angles between the scapula and upper arm/residual limb segments were calculated based off the motion capture data using the model described in Chapter 2. The average of the maximum and minimum values over the RoM trials for the amount of flexion, abduction, and rotation for the contralateral and residual limb (for all three conditions) were found. The standard deviation was also calculated using the maximum and minimum values for each degree of freedom respectively. A one-tailed repeated measures ANOVA was used to analyze significant differences between the four factors, using $\alpha=0.05$.

4.3.3 ADL Tasks Analysis

The amount of socket interface rotation for both the original and sensor embedded prostheses was calculated from the motion capture data for all trials following the procedures described in Chapter 2. Euler angles between the residual limb and socket segments were calculated. The amount of socket anterior-posterior and medial-lateral tilt were reported for each of the trials by finding the maximum and minimum values of each direction of movement. The standard deviation was calculated the same way as the RoM data, using the maximum and minimum values. Equivalent angle-axis rotations between the scapula and residual limb were used to represent residual limb movement. This was done to give one angle representing residual limb movement, because the specific direction of movement was not needed for the residual limb (i.e. Euler angle that tell the amount of flexion, abduction, and rotation).

The amount of vertical translation of the socket due to soft tissue deformation was calculated using the motion capture data for each trial. The average amount of translation along the long axis of the residual limb was found by calculating the distance between the origins of the residual limb and socket segments. The averages of the maximum and minimum values were used to provide the full RoM of vertical translation. The standard deviation was found for the maximum and minimum values for each task. The amount of vertical and rotational slip was found by taking the difference of the maximum and minimum values of the Slip Detection Sensor data for each direction of movement. These values were averaged for each individual task and the standard deviation was found. The rotational slip was calculated in millimeters (mm) of movement. Therefore, the values do not represent a rotational angle of slip, rather a distance representing the arc length.

Linear regression is used to show the dependence between two variables. The Pearson correlation coefficient is the most common type of correlation which shows the linear relationship between two variables. The various types of socket movement were correlated to two data sets; the range of residual limb movement during the task completion and the weight of each task, referred to as task weight. A linear regression was fit to each of the correlation graphs to find the R^2 value, or coefficient of determination. Taking the square root of the coefficient of determination solves for the Pearson's correlation coefficient (Pearson's r). The Pearson's r value was compared to critical values found in statistics tables for one tailed test assuming an α=0.05. Data from the participants able to complete the entire study protocol was used in a multivariate linear regression to analyze the effect of cofactors on the amount of socket movement. The cofactors were identified as residual limb movement during the task, the weight of each task, elbow angle and residual limb length.

CHAPTER 5: RESULTS

5.1 TAPES Questionnaire

The results of the TAPES questionnaire are summarized in Table 7 for all of the participants. None of the participants scored socket interface comfort as a three out of three. Two of the participants, H06 and H07, scored the socket interface comfort as a one out of three. The same two participants were the only ones to rate their overall satisfaction with their prosthesis less than 8, instead gave much lower scores of three and one respectively. These two participants also recorded the lowest usage.

Table 7: Results of the TAPES questionnaire for all of the participants.

ID	Level of Adjustment	Activity Limitation	Satisfaction with Various Aspects	Satisfaction with Socket Comfort	Overall Satisfaction 1-10	Usage (hr/day)
H01	70%	75%	67%	2/3	8	10
H02	83%	50%	96%	2/3	8	7
H03	87%	63%	79%	2/3	8	15
H04	92%	25%	79%	2/3	8	5
H06	89%	43%	46%	1/3	3	1.5
H07	40%	100%	38%	1/3	1	1

5.2 Shoulder RoM

The shoulder RoM for the non-amputated limb, the residual limb without wearing a prosthesis, the residual limb while wearing the participant's original prosthesis, and the residual limb while wearing the sensor embedded prosthesis are shown below. Figure 34 shows the amount of shoulder flexion, Figure 35 shows the amount of shoulder abduction, and Figure 36 shows the amount of shoulder rotation.

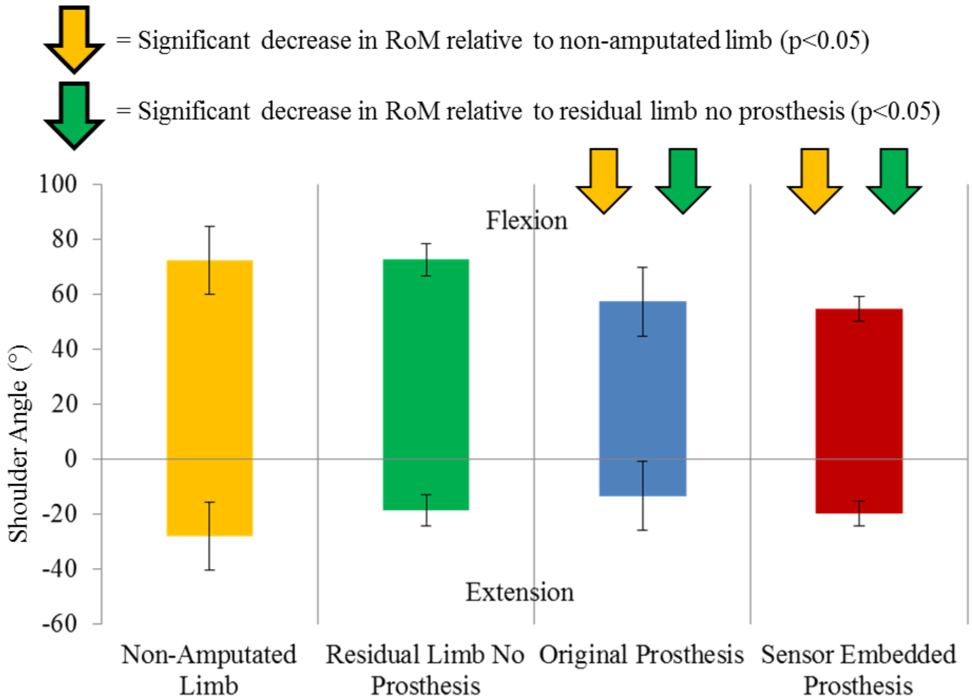


Figure 34: Shoulder flexion results from the RoM tasks for the study sample.

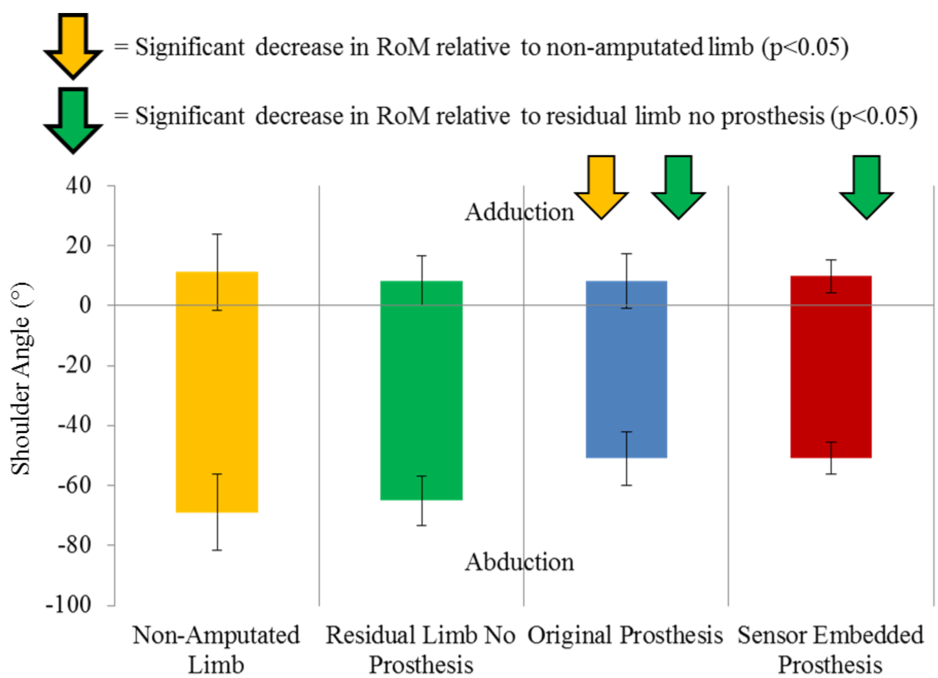


Figure 35: Shoulder abduction results from the RoM tasks for the study sample.

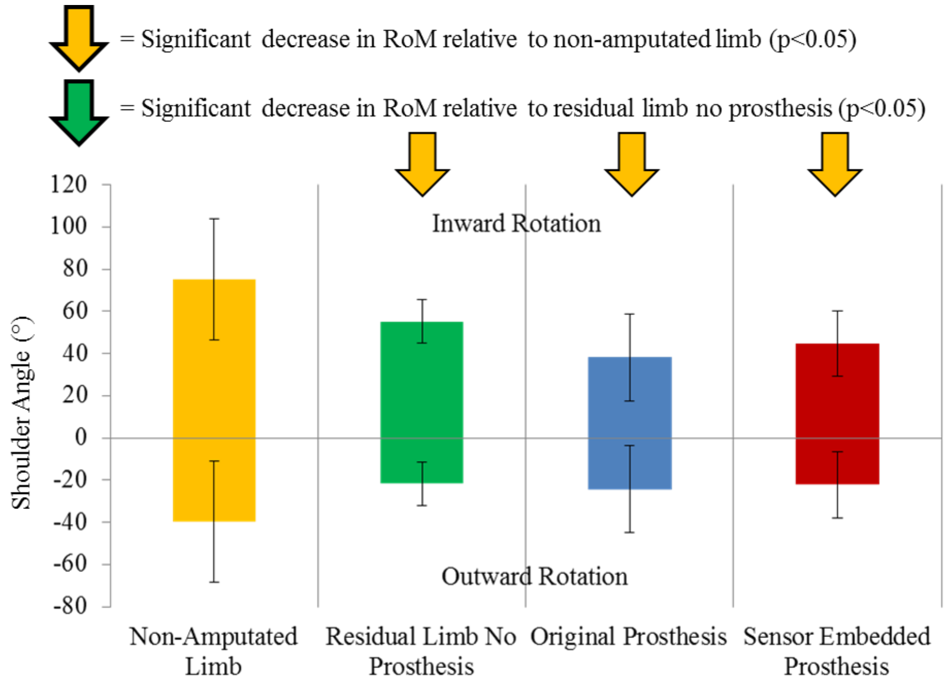


Figure 36: Shoulder rotation results from the RoM tasks for the study sample.

The results of the Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated, finding p values of 0.654, 0.407, and 0.258 for shoulder flexion, abduction, and rotation respectively. The observed power of within-subject effects for the amount of shoulder flexion, shoulder abduction, and shoulder rotation was 0.879, 0.899 and 0.996 respectively.

A pairwise comparison for the amount of shoulder flexion found that there was not a significant difference between the non-amputated limb and the residual limb without a prosthesis (p=0.415) and between the residual limb while wearing the original and sensor embedded prosthesis (p=0.511). A significant difference was found for the amount of shoulder flexion between the non-amputated limb and the residual limb while wearing the original and sensor embedded prostheses (p=0.04 and p=0.034 respectively) as well as between the residual limb without a prosthesis and the residual limb while wearing the original and sensor embedded prosthesis (p=0.016 and p=0.037 respectively).

A pairwise comparison for the amount of shoulder abduction found that there was not a significant difference between the non-amputated limb and the residual limb without a prosthesis (p=0.217) and between the residual limb while wearing the original and sensor embedded prosthesis (p=0.922). A significant difference was found for the amount of shoulder abduction between the non-amputated limb and the residual limb while wearing the original prosthesis (p=0.031) as well as between the residual limb without a prosthesis and the residual limb while wearing the original and sensor embedded prosthesis (p=0.015 and p=0.030 respectively). The amount of shoulder abduction between the non-amputated limb and the residual limb while wearing the sensor embedded prosthesis was very close to being significant (p=0.057).

A pairwise comparison for the amount of shoulder rotation found that there was a significant difference between the non-amputated limb and the residual limb without a prosthesis (p=0.027) and the residual limb while wearing the original and sensor embedded prosthesis (p=0.008 and p=0.006 respectively). The residual limb without a prosthesis had a significant decrease in shoulder rotation compared to the non-amputated limb, but it may be due to errors in the motion capture precision in this plane of movement. This effect is discussed further in the Chapter 7. A significant difference was not found for the amount of shoulder rotation between the non-amputated limb and the residual limb while wearing the original and sensor embedded prostheses (p=0.107 and p=0.338 respectively) as well as between the residual limb while wearing the original and sensor embedded prosthesis (p=0.377).

5.3 Socket Movement During the ADL Tasks

The various types of socket movement were analyzed for each of the ADL tasks. The average anterior-posterior socket tilt and average medial-lateral socket tilt for each of the tasks are shown in Figure 37 and Figure 38 respectively.

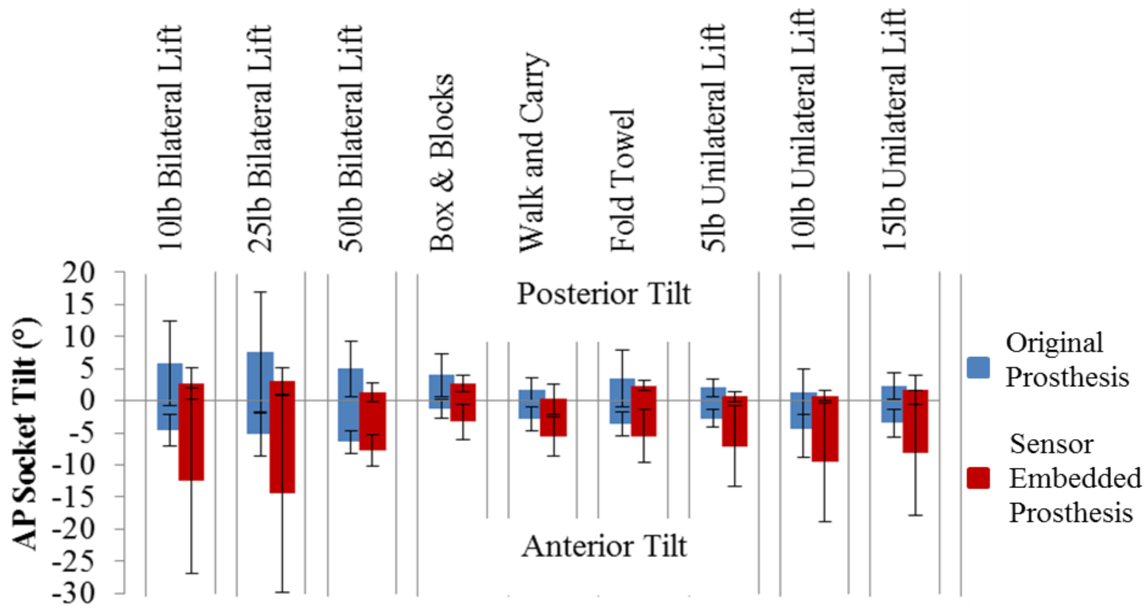


Figure 37: Average anterior-posterior socket tilt for the study sample.

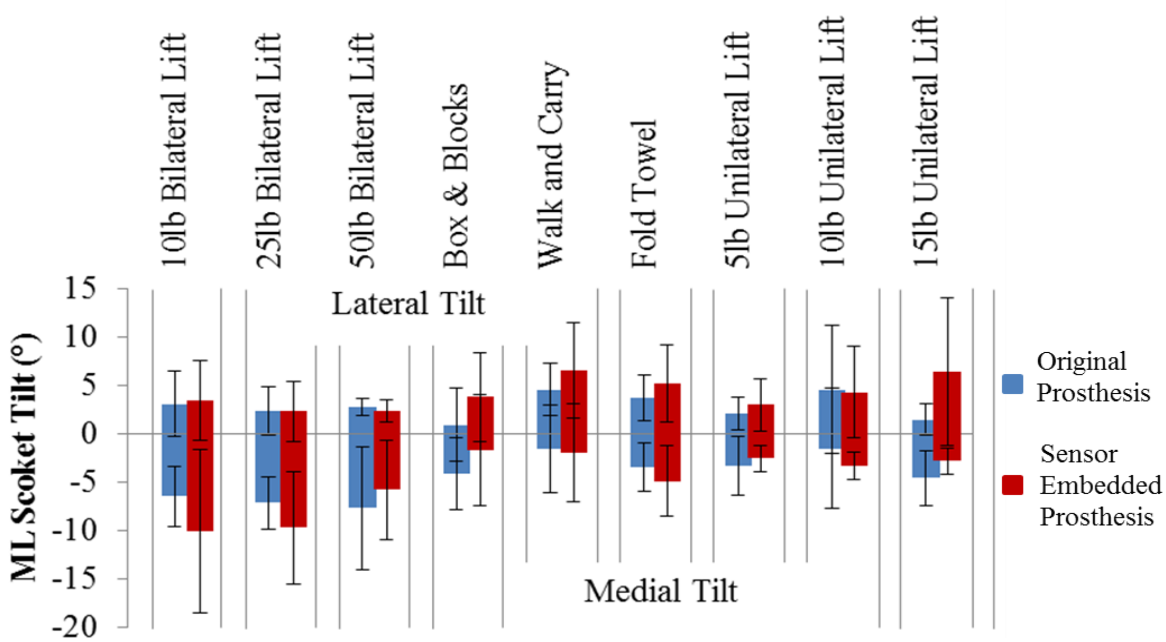


Figure 38: Average medial-lateral socket tilt for the study sample.

The average vertical socket translation for each of the tasks is shown in Figure 39. The average vertical and rotational socket slip for each of the tasks is shown in Figure 40 and Figure 41 respectively.

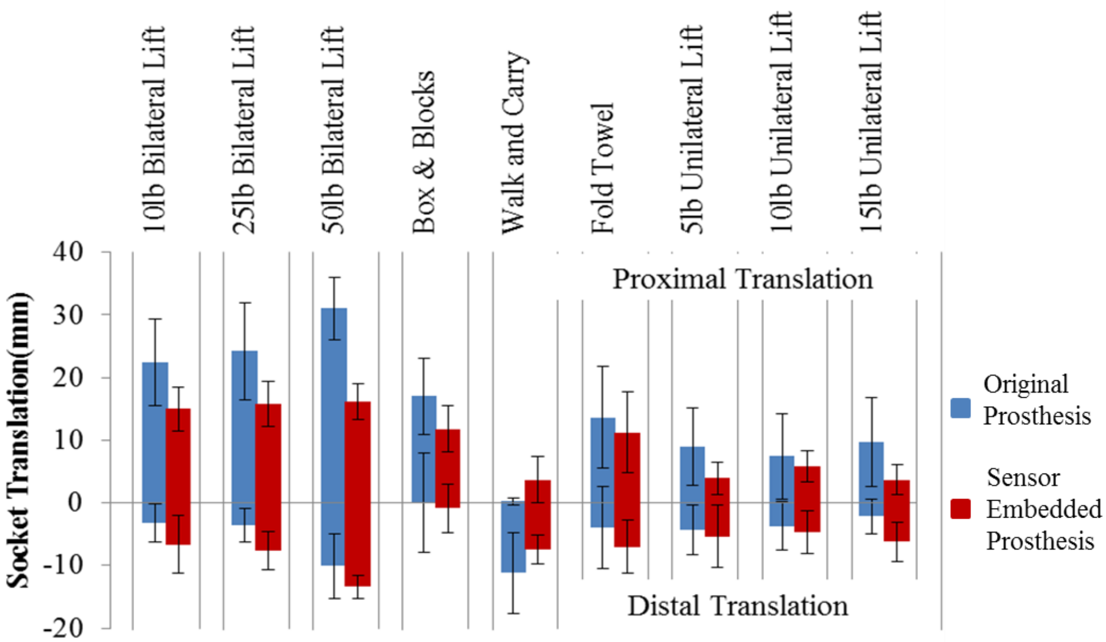


Figure 39: Average vertical socket translation for the study sample.

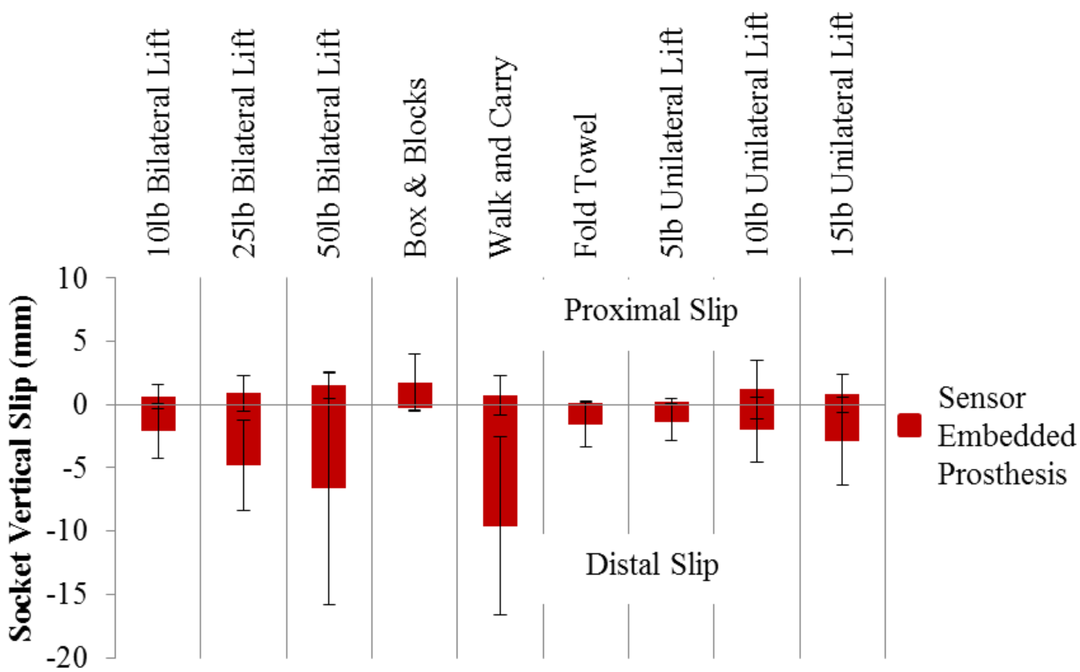


Figure 40: Average vertical socket slip for the study sample.

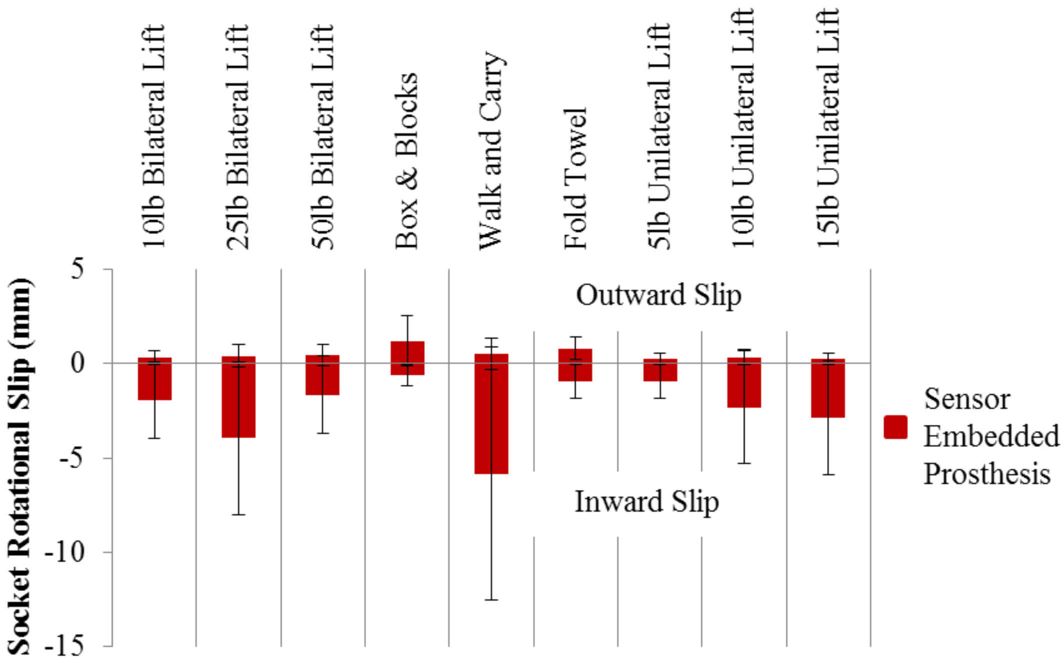


Figure 41: Average rotational socket slip for the study sample.

Linear regressions correlating the amount of the various socket movements (anterior-posterior tilt, medial-lateral tilt, vertical translation, vertical slip, and rotational slip) during each task to the weight of each task was performed on an individual and group basis shown in Figure 42 through Figure 46. The results show that the no correlations were found when correlating to the whole group, but more significant correlations were found on an individual basis. Significant R-squared values are indicated by an asterisk. The R-squared values needed to be significant varied for each participant based off their specific degrees of freedom. The degrees of freedom varied dependent on the number of tasks the participant was able to complete. These higher correlations were found when correlating the amount of slip and translation to the task weight. The same linear regression analysis was performed to correlate the various socket movements to the residual limb RoM during each task (shown in Figure 47 through Figure 51). These results found higher correlations when comparing the amount of socket tilt and vertical translation to residual limb RoM, and low to no correlations when comparing to socket slip. From these results, it was determined an individual analysis of socket movement should be performed for each of the participants. These results are further discussed in the next chapter.

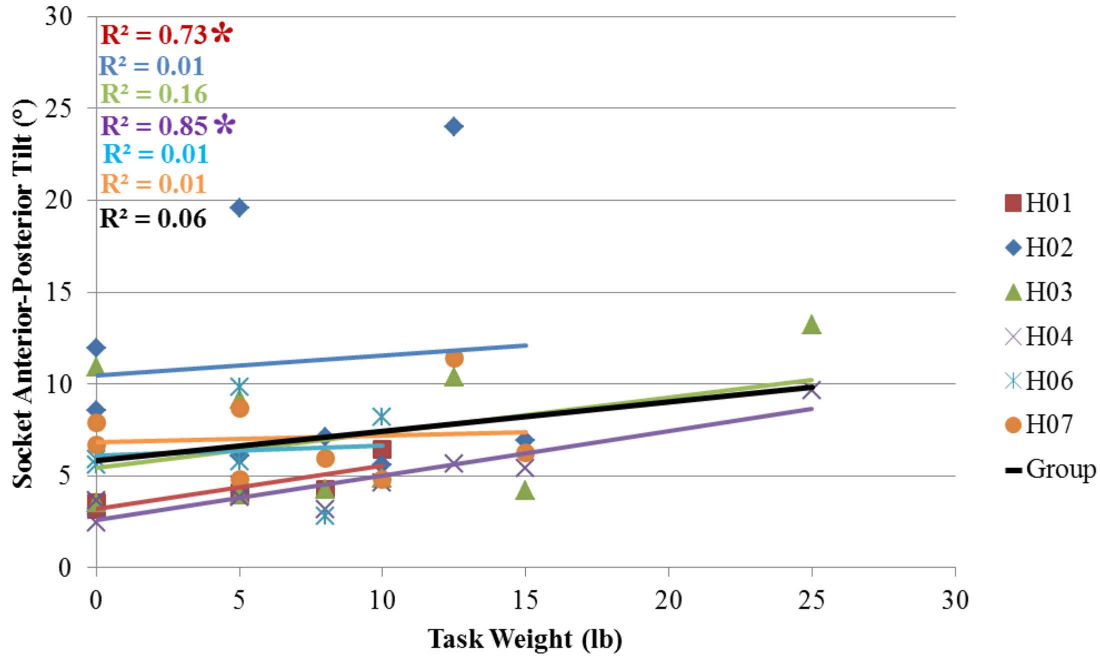


Figure 42: Linear regression plot correlating anterior-posterior socket tilt to task weight.

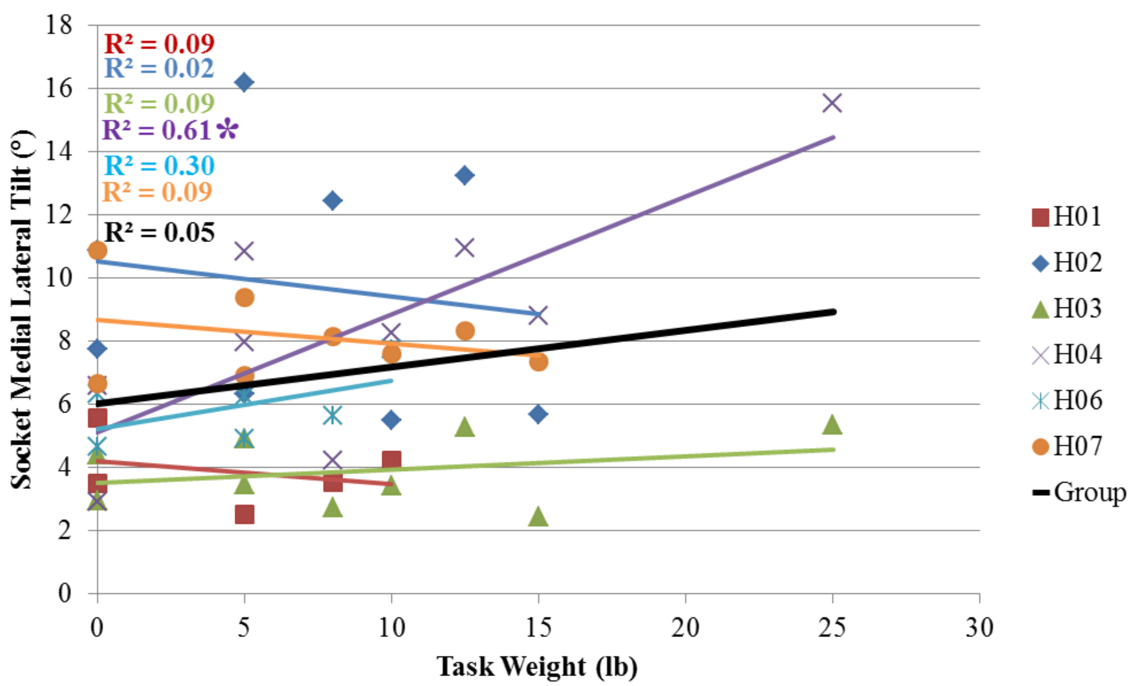


Figure 43: Linear regression plot correlating medial-lateral socket tilt to task weight.

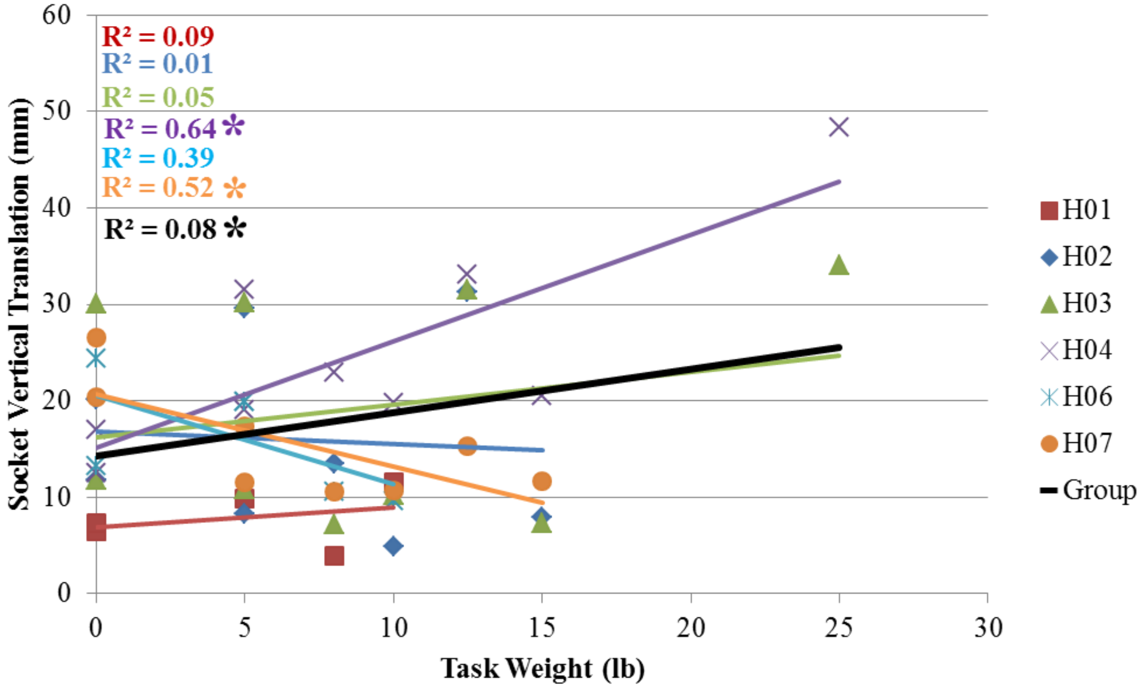


Figure 44: Linear regression plot correlating vertical socket translation to task weight.

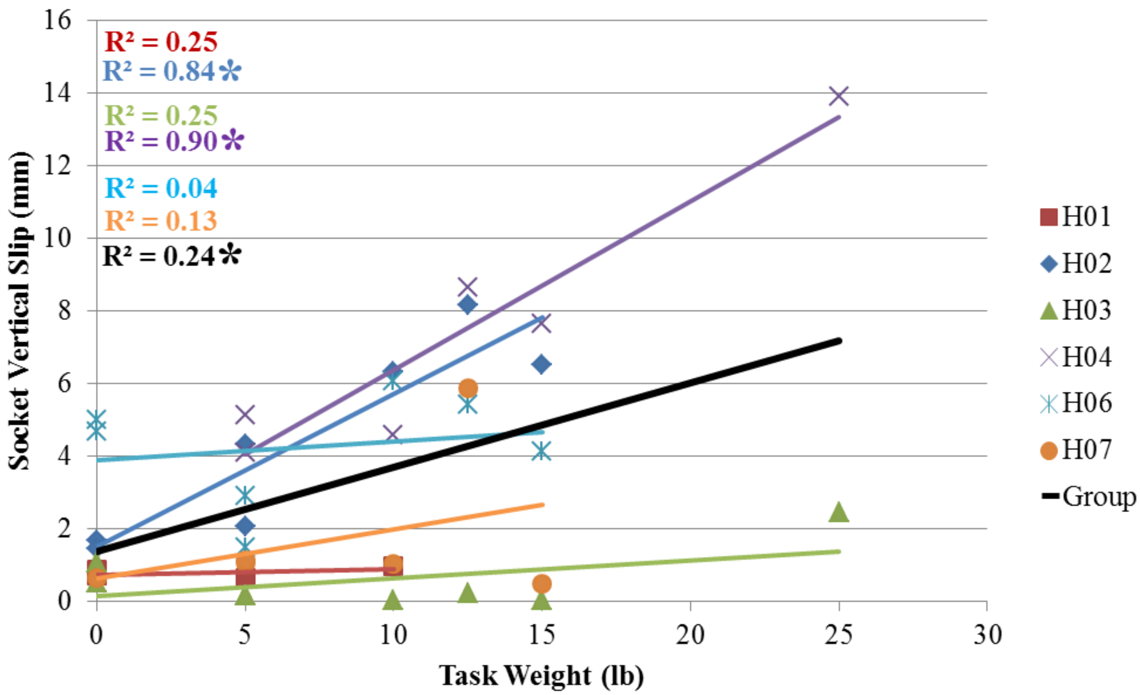


Figure 45: Linear regression plot correlating vertical socket slip to task weight.

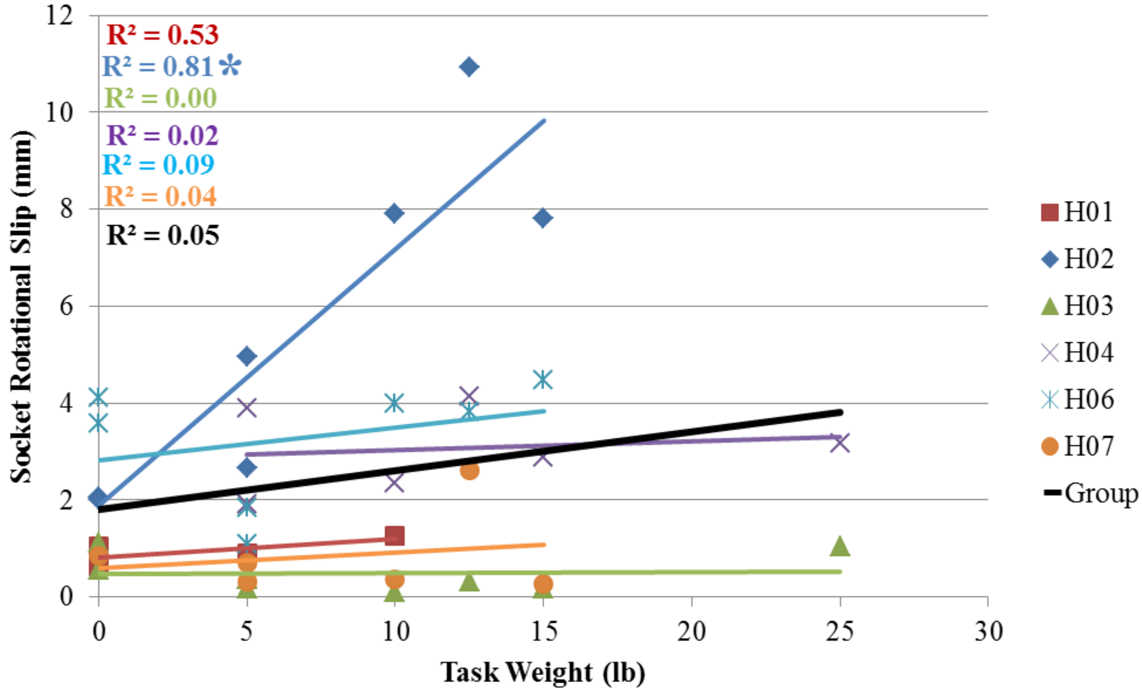


Figure 46: Linear regression plot correlating rotational socket slip to task weight.

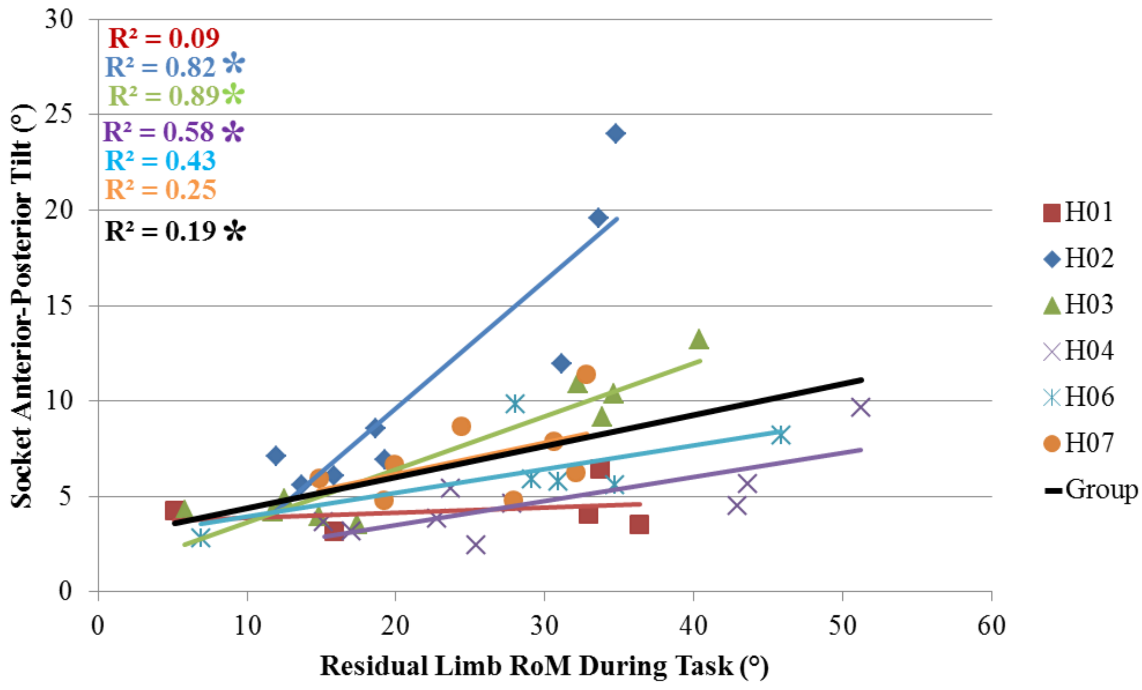


Figure 47: Linear regression plot correlating anterior-posterior socket tilt to residual limb RoM during the task.

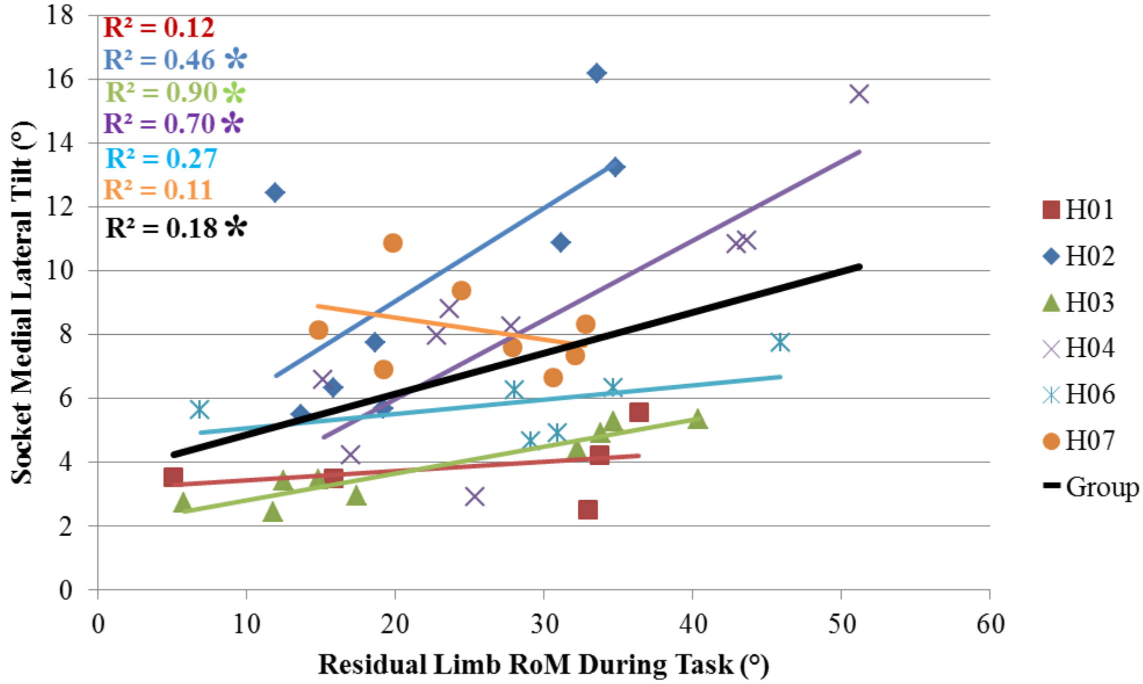


Figure 48: Linear regression plot correlating anterior-posterior socket tilt to residual limb RoM during the task.

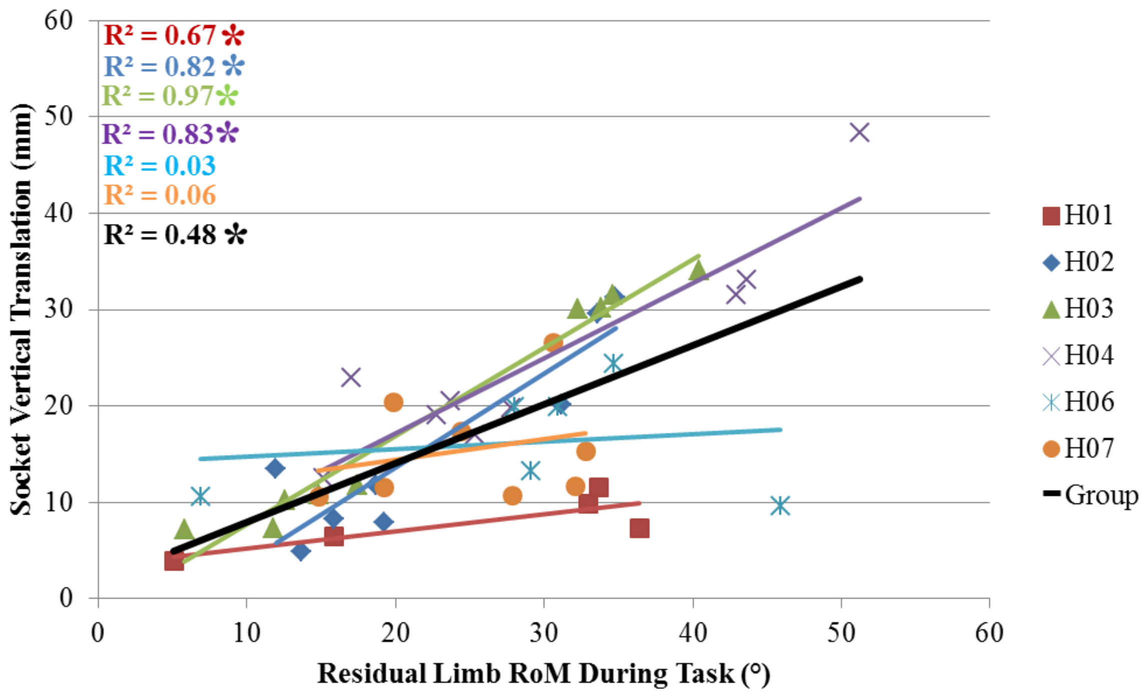


Figure 49: Linear regression plot correlating vertical socket translation to residual limb RoM during the task.

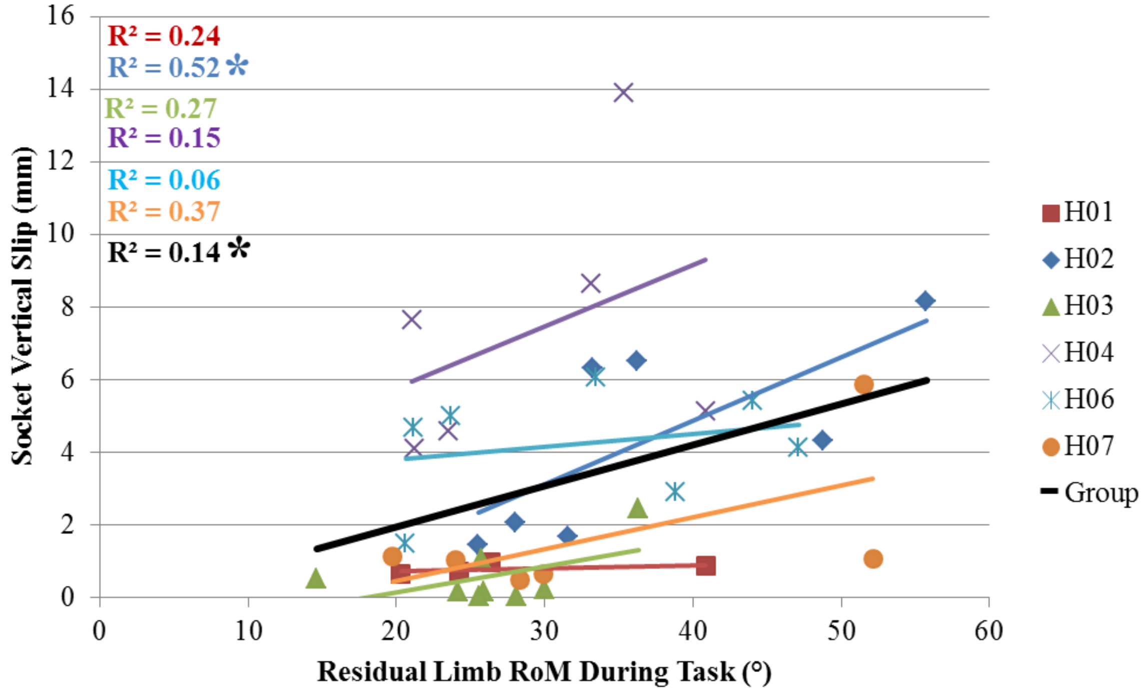


Figure 50: Linear regression plot correlating vertical socket slip to residual limb RoM during the task.

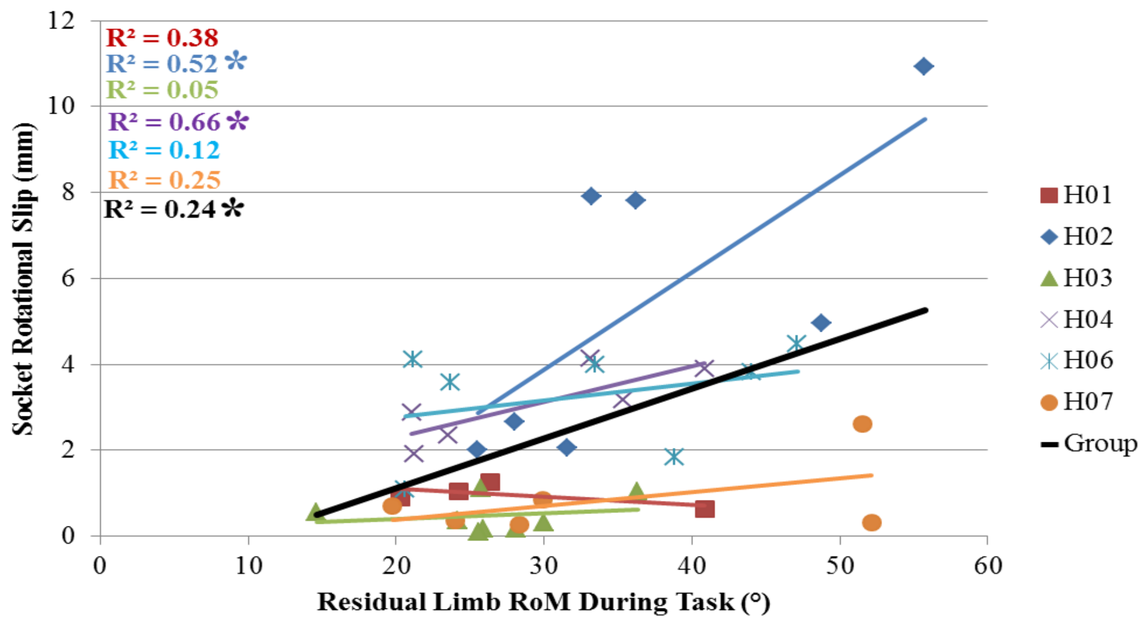


Figure 51: Linear regression plot correlating rotational socket slip to residual limb RoM during the task.

A multivariate linear regression was performed on the data from H02, H03, and H04. These three participants were the only ones to complete the entire study protocol and therefore had equal data sets for comparison. The analysis showed the individual impact of four cofactors on the various types of socket movement. The cofactors were residual limb movement, task weight, elbow angle, and residual limb length. The results from the multivariate linear regression are shown in Table 1. The most significant correlations were found for residua limb movement. Number values in blue indicate correlations that were close to statistical significance (α=0.05). Number values and dashes in red indicate a negative Pearson's r value, therefore representing an inverse relationship. Black dashes indicate no statistical significance.

Table 8: Results of the multivariate linear regression.

Cofactors	Anterior-Posterior Tilt	Medial-Lateral Tilt	Vertical Translation	Vertical Slip	Rotational Slip
RL Movement	p=0.013	p=0.002	p<0.0001	p=0.06	p=0.002
Task Weight	-	-	p=0.049	p=0.07	-
Elbow Angle	-	p=0.004	-	p=0.015	p=0.026
RL Length	-	p=0.0005	-	p=0.006	p=0.0005

CHAPTER 6: RESULTS ANALYSIS AND SOCKET DESIGN

The methods presented in this dissertation are useful for the measurement of socket interface movement and may have an impact on the socket prescription and fitting procedures. The results of the previous chapter showed the maximum and minimum values of the various types of socket movement and how it changed with each task. Additionally, linear regressions were shown for each participant as well as the whole group comparing different socket movements to various outcomes.

This chapter will evaluate the results of each participant, showing his individual data and make recommendations for how a prosthetist could potentially use this data to analyze socket performance. Not all of the figures and linear regressions presented in the previous chapter will be used to analyze an individual participant. Review of the figures in Chapter 5 show that the amount of socket tilt (both anterior-posterior and medial-lateral) and vertical translation were correlated more with residual limb movement and the amount of vertical and rotational slip were correlated more with task weight. Therefore, only those figures will be used in the analysis presented in this chapter. Limiting the data to only the most useful correlations will keep the prosthetist from being bombarded with data that does not provide useful insight to the interactions occurring at the socket interface and help them focus on the data that does provide useful information. This section will also be useful for explaining the differences found between the original and sensor embedded prostheses in terms of the amount of movement found. Similar to the previous chapter, significant R-squared values are indicated by an asterisk.

6.1 H01

This participant had the shortest residual limb of the study cohort. He reported wearing his prosthesis for many hours a day; however he wore it primarily for aesthetic purposes rather than function. He described the socket as loose fitting, which probably made the socket more comfortable but less functional. The RoM data for H01 showed that by wearing his original prosthesis, he had a 22%, 24%, and 31% reduction in residual limb shoulder flexion, abduction, and rotation respectively. This considerable reduction in RoM does not take into account movement at the socket interface, and reports the difference in residual limb movement. This reduction in RoM may stem from the prosthetic socket not being able to transfer the motions of the residual limb to the prosthesis due to the short lever of the residual limb, as well as the weight of the prosthesis being too much for the residual limb musculature to lift to its full potential.

Figure 52 shows the correlation between anterior-posterior tilt of the socket and the amount of residual limb movement. The Pearson Correlation Coefficient was found to be significant ($p=0.027$) for the sensor embedded prosthesis, but not for the original prosthesis. The same correlation plots were made for the amount of medial-lateral tilt of the socket, but no significant correlations were found. Figure 53 shows the correlation to residual limb movement and task weight respectively. The amount of socket vertical translation had significant correlations for both the original and sensor embedded prostheses with the amount of residual limb movement ($p=0.023$ and 0.027 respectively). These results are shown in Figure 54. The amount of socket slip was assessed for the sensor embedded prosthesis only. There were no significant correlations between the vertical and rotational slip RoM and the task weight. These correlations plots are shown in Figure 55.

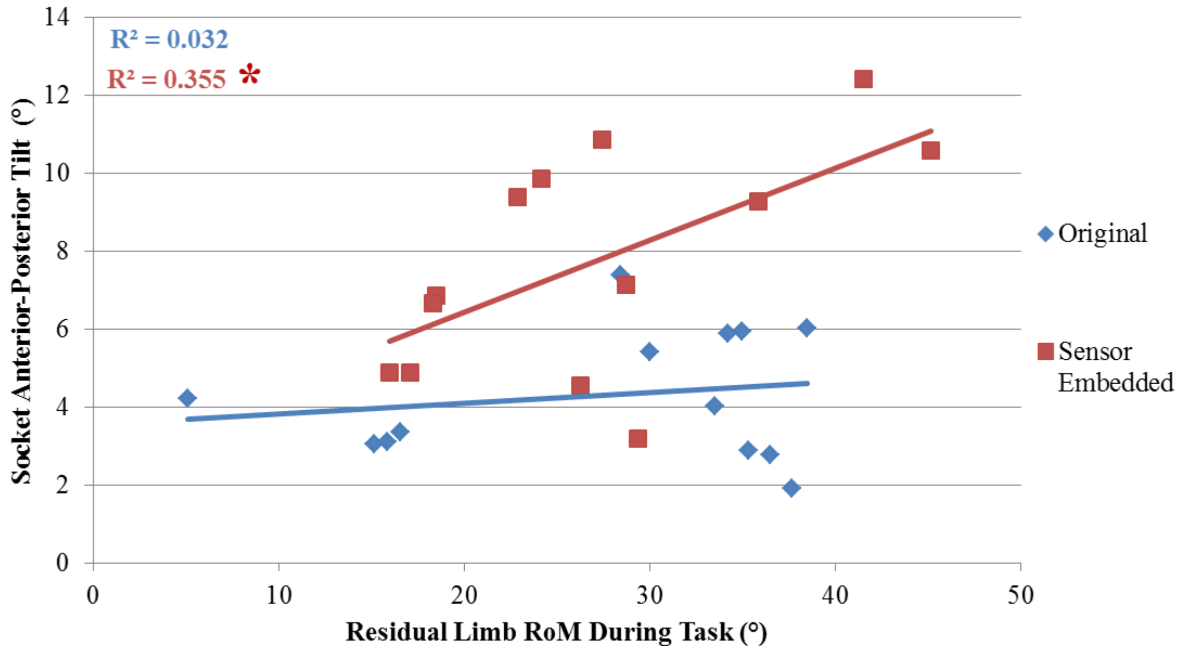


Figure 52: Linear regression for H01 correlating anterior-posterior socket tilt RoM and residual limb RoM for both prostheses.

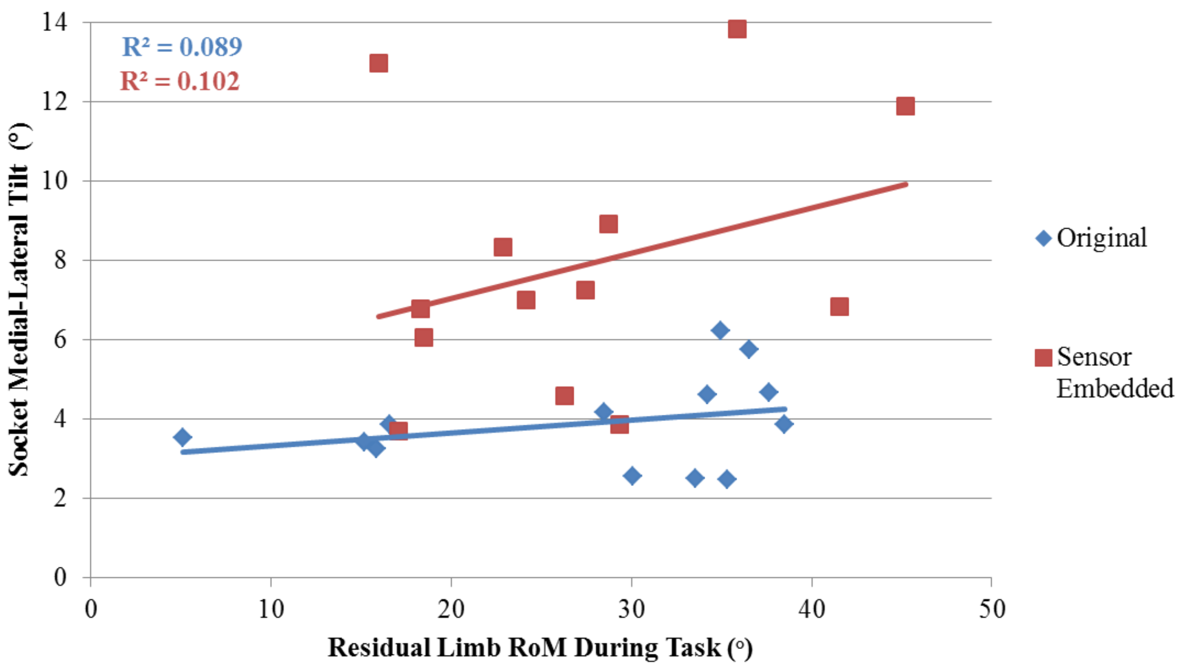


Figure 53: Linear regression for H01 correlating medial-lateral socket tilt RoM and residual limb RoM for both prostheses.

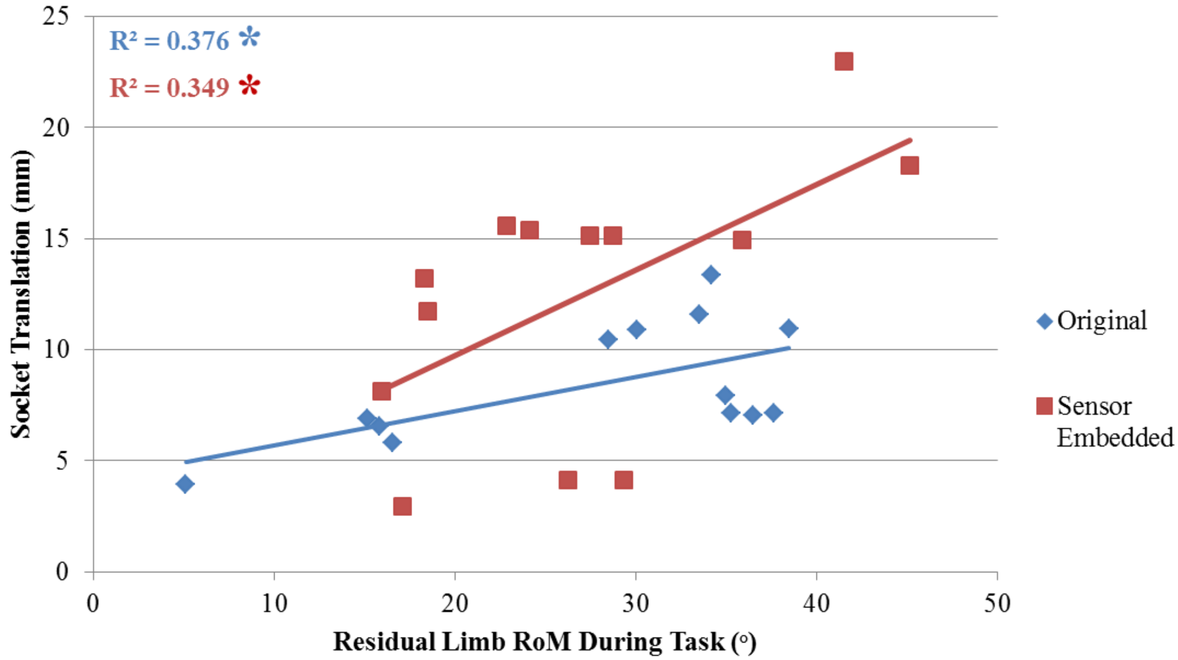


Figure 54: Linear regression for H01 correlating socket vertical translation RoM and residual limb RoM for both prostheses.

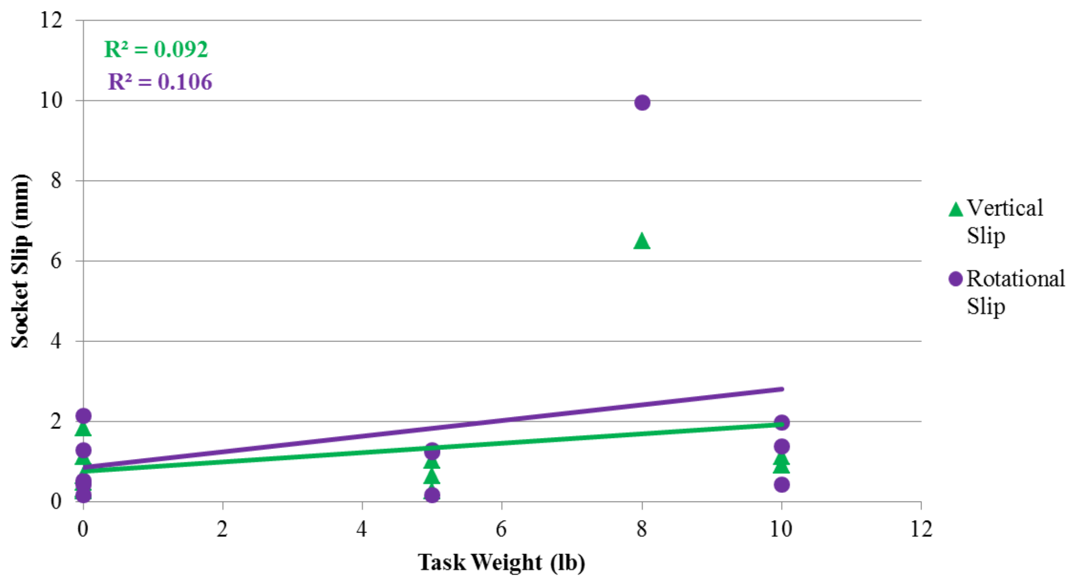


Figure 55: Linear regression for H01 correlating socket slip RoM and the weight of each task for the sensor embedded prosthesis.

H01 was not able to complete the bilateral lifting task at any of the weights or the unilateral lifting task at 15 pounds. This was due to inability to lift the prescribed task weight and/or the socket causing residual limb discomfort. Analysis of the data for this participant had a reduction in range of motion and very few significant correlations with residual limb movement and task weight. Since the socket was described as loose fitting, it was expected the results of socket movement would be higher.

A prosthetist could use this data to assist them in determining what changes to the socket shape should be made to improve function and comfort. The anterior-posterior and medial lateral socket tilt correlation graphs to both residual limb RoM and the task of each weight show an unpredictable amount of tilt. The tilt is unpredictable because H01 could move make the same movement with the residual limb or pick up the same object and get very different amounts of socket interface movement each time. This will affect H01's ability to predict how that socket will behave as they move his residual limb or lift objects. This inconsistent socket movement may make the prosthesis less functional, because the user is trying to control an external device that does not move relative to the residual limb in a level of consistency. The prosthetist could decrease the socket volume to improve correlations. Since both the anterior-posterior and medial-lateral had few significant correlations, the prosthetist could adjust the socket interface to limit movement in both directions.

6.2 H02

This participant presented with a very bulky residual limb due to their regular exercise and resistance training. This created a high soft tissue to bone ratio and an increased volume of the residual limb proximally. This increased volume on the proximal part of the residual limb tended to "push-off" traditional socket as the deltoids contracted. The participant was therefore fit with a suction liner to provide additional suspension. The RoM data for H02 showed that while wearing his original prosthesis, he only had a 10%, reduction in residual limb shoulder abduction, and no reduction in RoM for shoulder flexion and rotation. These data suggest that the socket shape is effective at capturing the residual limb movements and transferring them to the prosthesis.

Figure 56 shows the correlation between anterior-posterior tilt of the socket and the amount of residual limb movement. The Pearson Correlation Coefficient was found to be significant for both the original and sensor embedded prosthesis ($p<0.0001$ for both prostheses). The same correlation plot was made for the amount of medial-lateral tilt of the socket, and significant correlations were found when correlating to residual limb RoM ($p<0.0001$ for both prostheses). Figure 57 shows the correlation to residual limb movement. The amount of socket vertical translation had significant correlations for both the original and sensor embedded prostheses with the amount of residual limb movement ($p<0.0001$ and $p=0.001$ respectively). These results are shown in Figure 58. Again, the amount of socket slip was assessed for the sensor embedded prosthesis only. There were significant correlations between the vertical and rotational slip RoM and task weight ($p<0.0001$ for both prostheses). The correlation plot is shown in Figure 59.

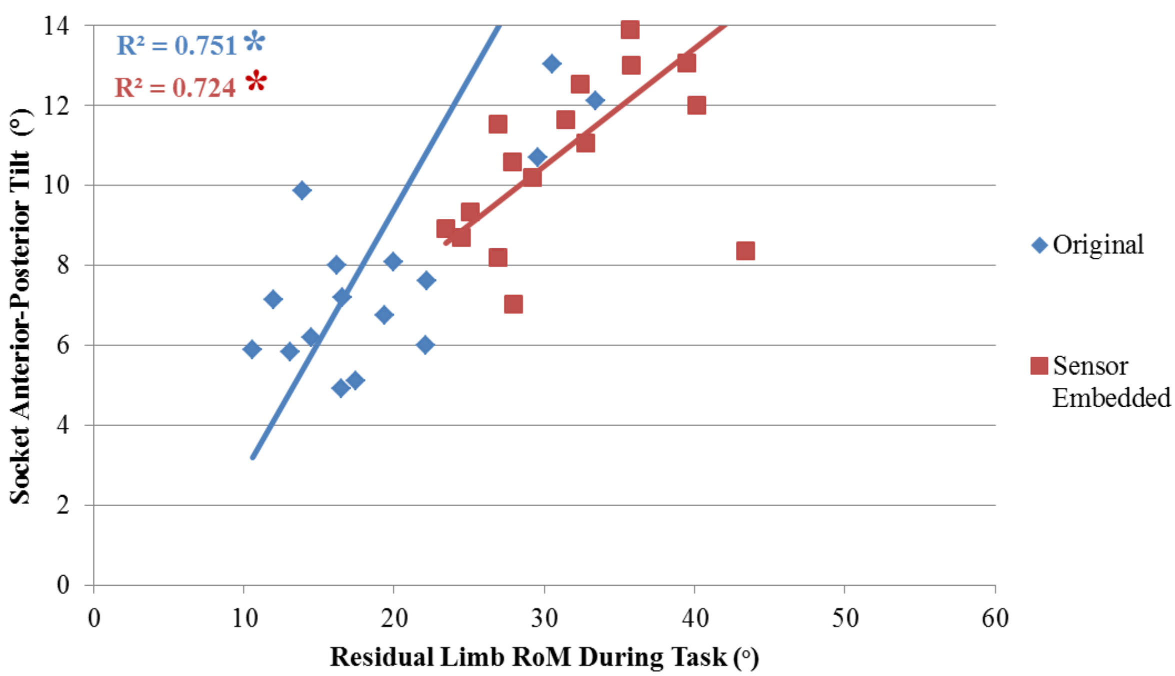


Figure 56: Linear regression for H02 correlating anterior-posterior socket tilt RoM and residual limb RoM for both prostheses.

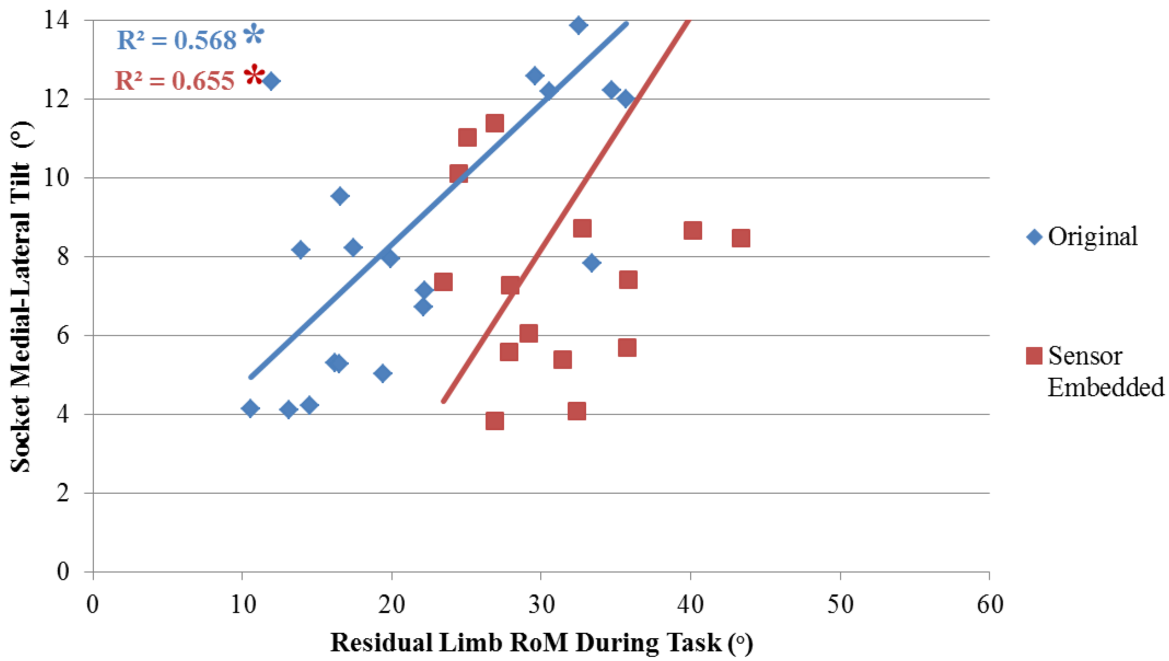


Figure 57: Linear regression for H02 correlating medial-lateral socket tilt RoM and residual limb RoM for both prostheses.

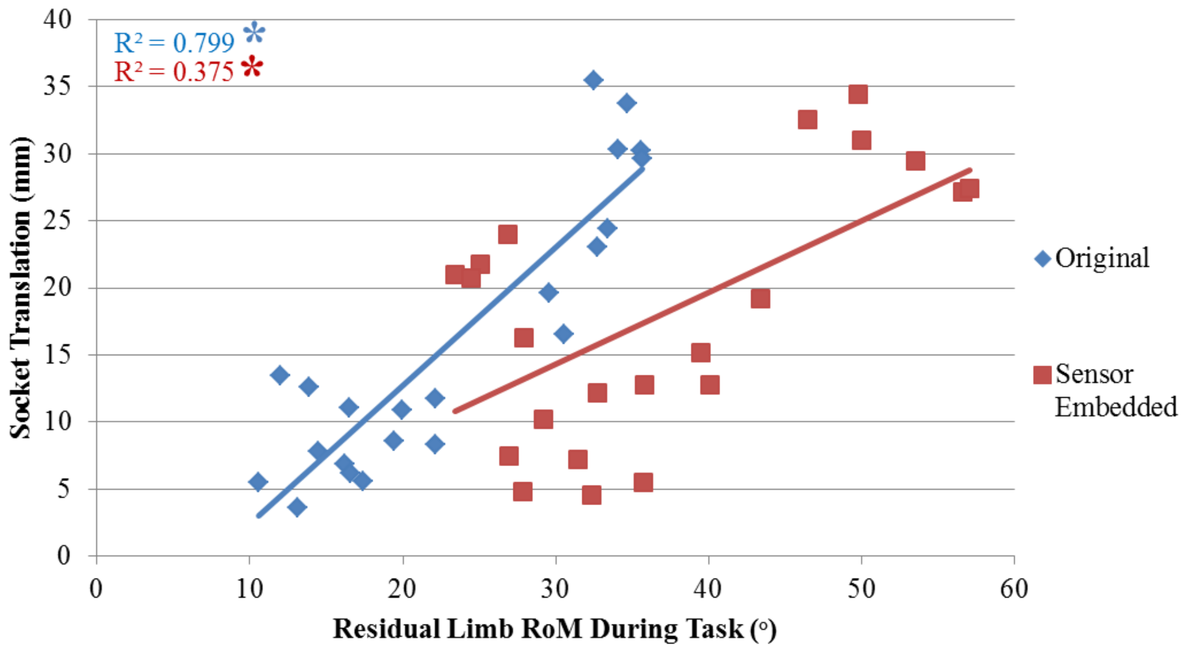


Figure 58: Linear regression for H02 correlating socket vertical translation RoM and residual limb RoM for both prostheses.

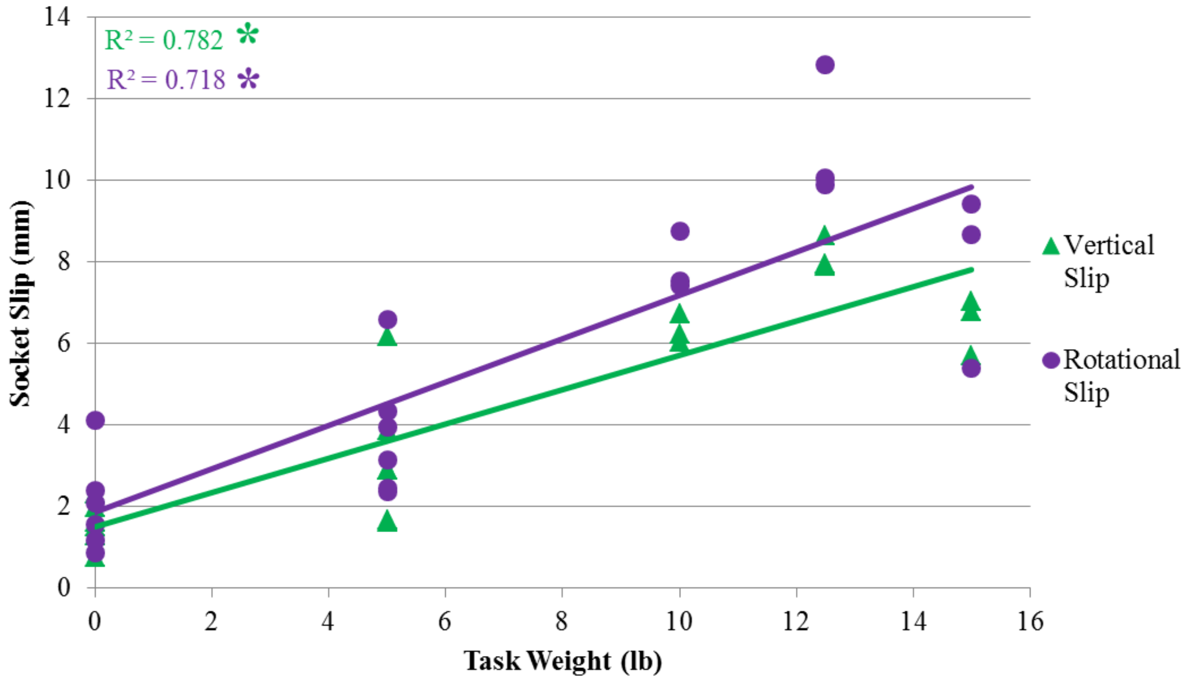


Figure 59: Linear regression for H02 correlating socket slip RoM and the weight of each task for the sensor embedded prostheses.

Unlike H01, H02 was able to complete all of the tasks in the protocol except for the 50 lb bilateral lift, which was due to a previous back injury and not to the prosthesis. The linear regression results show high correlations in many of the comparisons, but the highest being between socket tilt in both the anterior-posterior and medial-lateral directions to residual limb RoM as well as vertical and rotational slip to task weight. The amount of tilt was not dependent on the task weight, but was dependent on residual limb movement. Socket slip seemed to be impacted by task weight as shown in Figure 59.

The sensor embedded prosthesis had a higher magnitude of socket rotation and translation for all of the trials. A suction valve was included but not an inner flexible liner, which may have changed the frictional properties with the suction liner worn over the residual limb. This resulted in a reduced amount of suction and therefore allowed more socket movement. However the sensor embedded prosthesis still had significant correlations among the same categories, but with an increased magnitude of movement.

The case study provides an excellent example of how a prosthetist could use socket movement data to evaluate and redesign a socket shape. Considering only the original prosthesis (blue dots and trend line) for this example, the prosthetist can see the amount of movement compared to various measures. Analysis of the anterior-posterior socket tilt versus residual limb RoM shows a strong correlation between the two, where the more H02 moves their residual limb, the more movement at the interface they experience (Figure 56). The same result is found for the amount of medial-lateral tilt (Figure 57). One thing a prosthetist could notice from these two figures is that while the Pearson's r is significant, the magnitude of socket tilt in either direction is also high. The prosthetist could redesign the shape to increase the pre-compression of the soft tissues and eliminate some of the tilting movement. The prosthetist would retest the new design with the hopes that the data points translate closer to the horizontal axis and the slope of the linear regression trend line is reduced. For the case of H02, a patient with muscular development on the shoulder and residual limb, it may be difficult to lower the amount of socket tilt due to the increased soft tissue to bone ratio. Another course the prosthetist could analyze would be to quantitatively compare different socket suspensions and see what method would keep the prosthesis suspended on the residual limb the best. H02 may be a better candidate for a pin-locking suspension over suction suspension, and this method of measurement would be a great indicator of that.

H02 also had a significant correlation between the amount of socket translation and residual limb RoM. The amount of socket vertical and rotational slip had a high correlation with both residual limb RoM and task weight, but had a more significant correlation with task weight. The data found upwards of 30 mm of translation for H02, with the amount of vertical slip less than 10 mm. Rotational slip reached slightly higher levels, topping out at 13 mm. The prosthetist could try to reduce the socket volume to create a tighter fit and reduce the magnitudes of these movements, but that may difficult due to the extra soft tissues. The magnitudes of movement were some of the highest in the study sample, but the correlations were also among the highest in the group.

6.3 H03

This participant had the longest residual limb of the study sample and had an elbow disarticulation. Since his prosthesis still included an elbow unit, he was allowed to participate in the study. He reported wearing his prosthesis for many hours a day and being a very proficient prosthesis user. The RoM data for H03 showed that while wearing his original prosthesis, he had a 27%, 37%, and 5% reduction in residual limb shoulder flexion, abduction, and rotation respectively. It is interesting to note for H03, the sensor embedded prosthesis ended up being a much tighter fit than their original prosthesis. By donning the sensor embedded prosthesis, H03 had a 4%, 14%, and 0% reduction in residual limb shoulder flexion, abduction, and rotation respectively.

Figure 60 shows the correlation between anterior-posterior tilt of the socket and the amount of residual limb movement. The Pearson Correlation Coefficient was found to be significant for both the original and sensor embedded prosthesis ($p<0.0001$ and $p=0.0005$ respectively). The same correlation plots were made for the amount of medial-lateral tilt of the socket, and significant correlations were found for the original prosthesis when correlating to residual limb RoM ($p<0.0001$) but not for the sensor embedded prosthesis. Figure 61 shows the correlation to residual limb movement and task weight respectively. The amount of socket vertical translation had significant correlations for both the original and sensor embedded prostheses with the amount of residual limb movement (p<0.0001 and p=0.003 respectively). These results are shown in Figure 62. There were significant correlations between the vertical slip RoM and task weight (p=0.014). The correlation plot is shown in Figure 63.

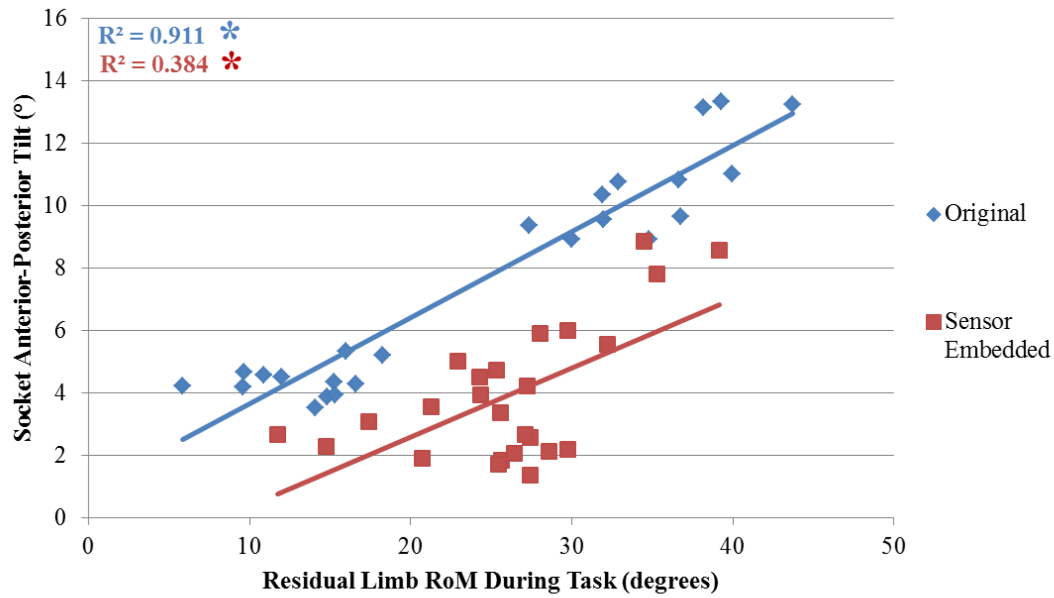


Figure 60: Linear regression for H03 correlating anterior-posterior socket tilt RoM and residual limb RoM for both prostheses.

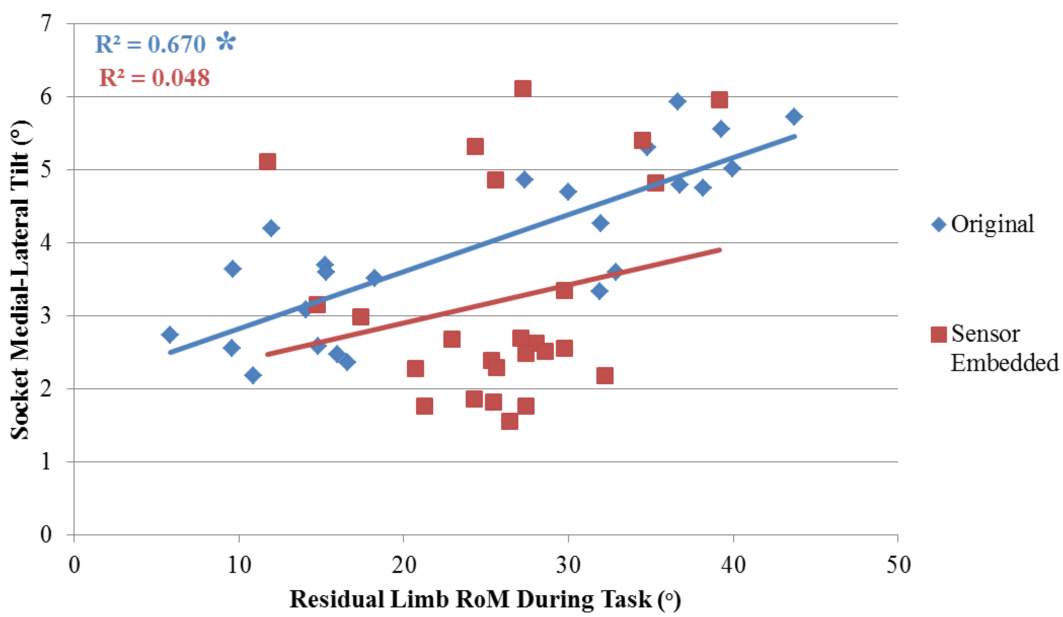


Figure 61: Linear regression for H03 correlating medial-lateral socket tilt RoM and residual limb RoM for both prostheses.

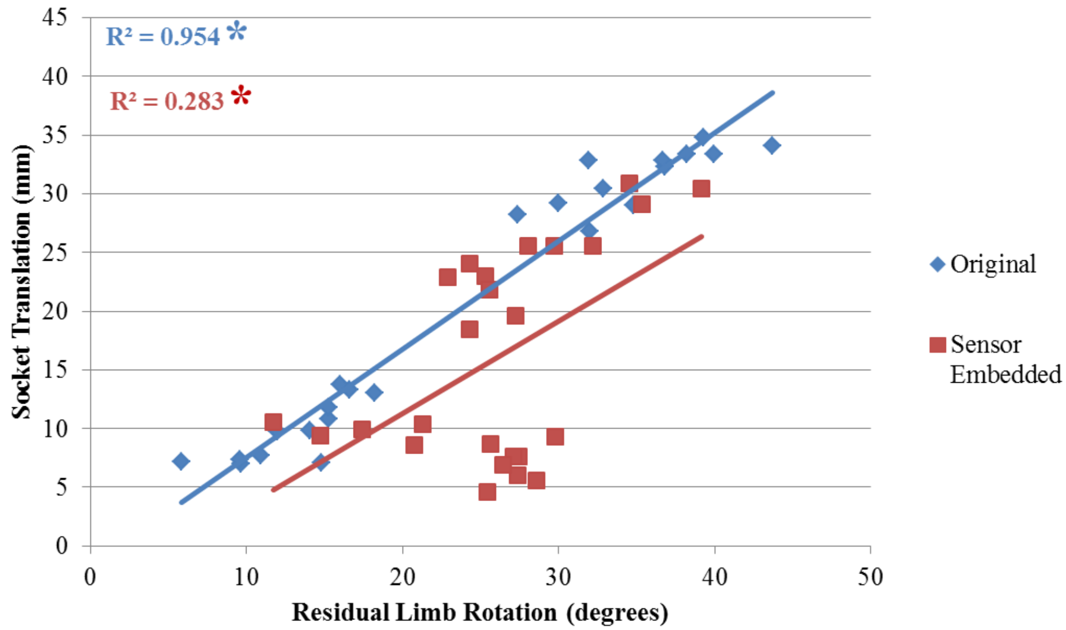


Figure 62: Linear regression for H03 correlating vertical socket translation RoM and residual limb RoM for both prostheses.

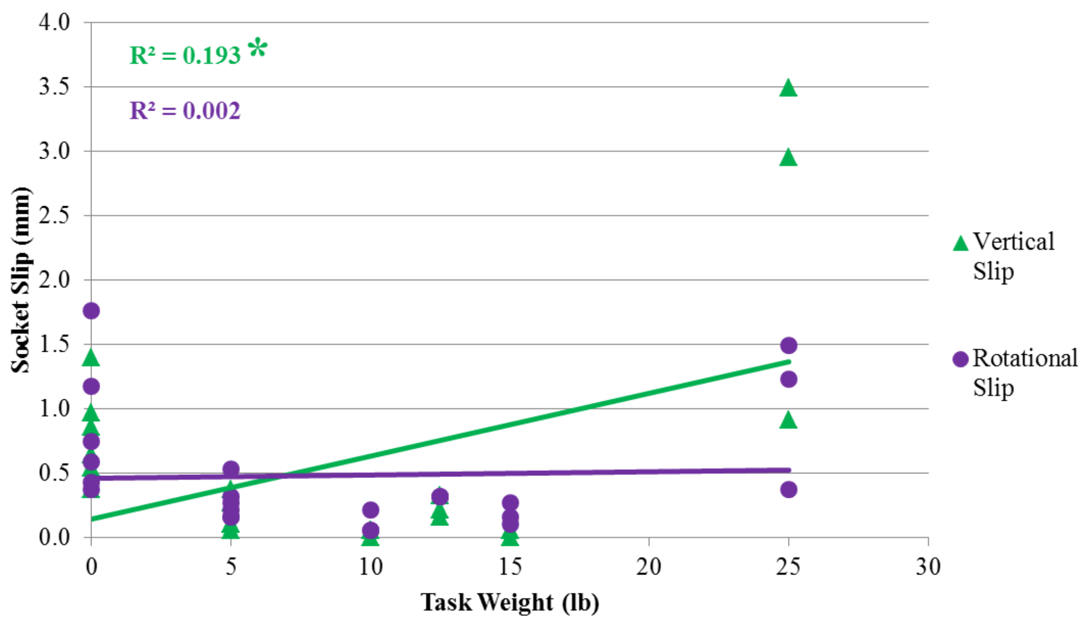


Figure 63: Linear regression for H03 correlating socket slip RoM and weight of each task for the sensor embedded prostheses.

H03 was able to complete the all of the tasks prescribed in the study protocol. The correlation plots show a significant correlation with the original prosthesis in terms of rotation and translation of the socket. Evaluation of the results shows high correlations across the many of the same correlations that were found with H02. Again the strongest correlations were for anterior-posterior/medial-lateral socket tilt and residual limb RoM, and vertical socket translation and residual limb RoM. The vertical and rotational slip data did not have as strong of a correlation as it did with H02 but may be due to the increase tightness of the sensor embedded prosthesis. The sensor embedded prosthesis was a noticeably tighter fit than the original prosthesis, to the point where H03 was almost unable to get his residual limb into the socket. This resulted in less movement at the interface, which can be seen by the concentration of red points at the lower portion of the correlation plots. Also the amount of slip was very minimal, most likely related to the tight fit. These results are interesting in that it shows that creating a tighter interface lowers the amount of socket tilt and translation. It could be assumed that socket slip was reduced also but that claim was not tested because the sensor was only embedded into the duplicate prosthesis.

A prosthetist could look at the difference between the anterior-posterior/medial-lateral socket tilts and residual limb RoM and see that the socket had less movement in the medial-lateral direction. The prosthetist could decide they want to make the socket tilt the same in both directions and adjust the socket shape to limit more anterior-posterior tilt. While the sensor embedded prosthesis lowered movement at the socket interface, it worsened the correlation coefficients across all outcomes, and may potentially be a worse fit than the original prosthesis, even though it reduces movement. The sensor embedded socket may be too tight to be worn for a long time, something that cannot be tested in a relatively short laboratory session. The prosthetist could use his experience as well as the quantified socket interface movement to determine the appropriate socket shape by balancing the amount of movement and strength of the correlation coefficients. The correlations of the different socket tilts and translation to residual limb movement and socket slip to task weight may provide enough useful data for a prosthetist to determine socket fit and performance.

6.4 H04/H05

This participant completed the collection procedures using two different suspension systems within the same socket; a pin-locking suspension and no pin-locking suspension. The participant was able to complete all of the tasks and reached the weight limits for the bilateral and unilateral lifting tasks. H04/H05 reported using his prosthesis for several hours a day and being a proficient prosthesis user. The RoM data for H04/H05 showed that while wearing his original prosthesis without the pin-locking system, he had a 27%, 15%, and 23% reduction in residual limb shoulder flexion, abduction, and rotation respectively. Addition of the pin-locking system did not alter this participant's reduction in RoM.

The pin system appeared to have little effect on the amount of anterior-posterior tilt and the amount of medial-lateral tilt of the socket (Figure 64 and Figure 65). Note, the walk and Carry task was only performed once, therefore standard deviation could not be calculated. The pin-locking suspension appeared to have an effect on the amount of vertical translation occurring at the socket interface (Figure 66), reducing the amount of vertical translation movement for all of the tasks except the box and blocks task, which remained equal between the suspensions. This may be due task requirement that the participant use the hook hand to pick up the blocks. Therefore, the translation is a result of actuating the cable system. The amount of vertical and rotational slip is shown in Figure 67 and Figure 68 respectively. The amount of slip was reduced when using the pin-locking system, except for rotational slip during the walk and carry task. The pin only resists slip in the vertical direction, so the rotational slip may be higher due to the restriction of movement in the vertical direction.

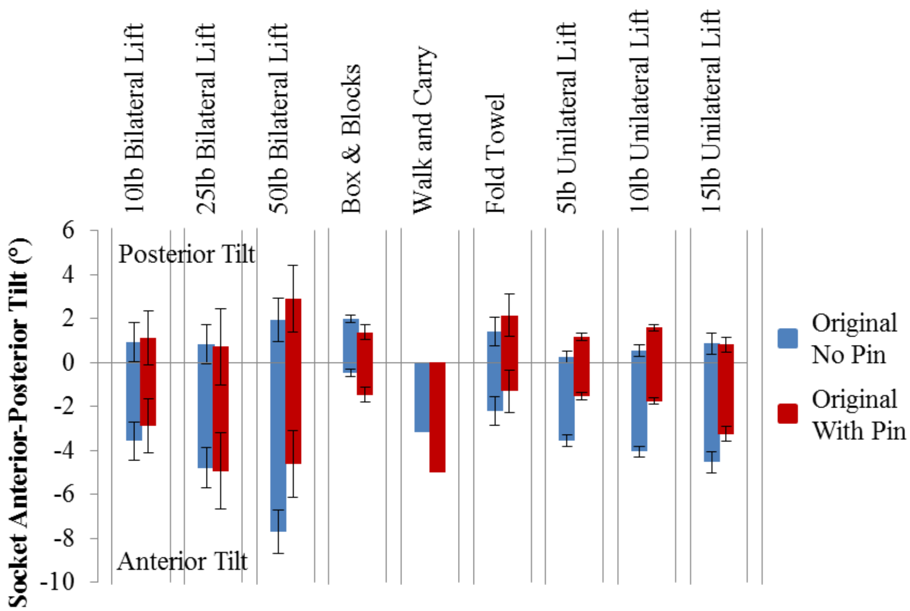


Figure 64: H04/H05 anterior-posterior socket tilt for the original prosthesis with and without using the pin-locking system.

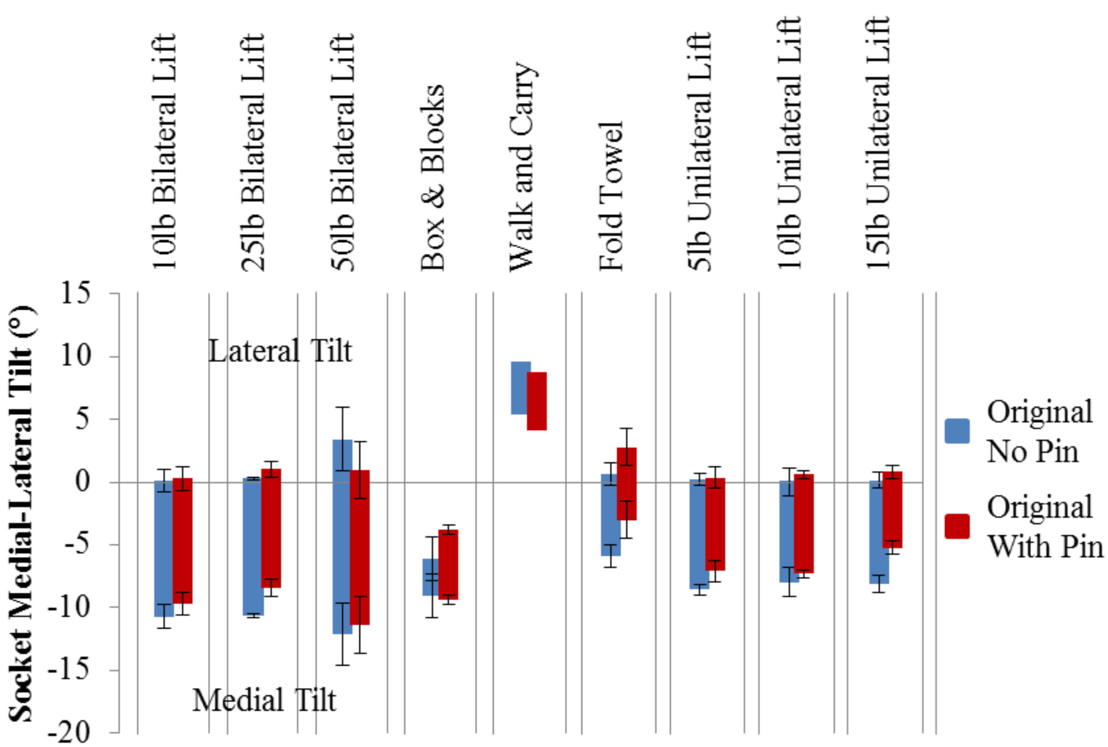


Figure 65: H04/H05 medial-lateral socket tilt for the original prosthesis with and without using the pin-locking system.

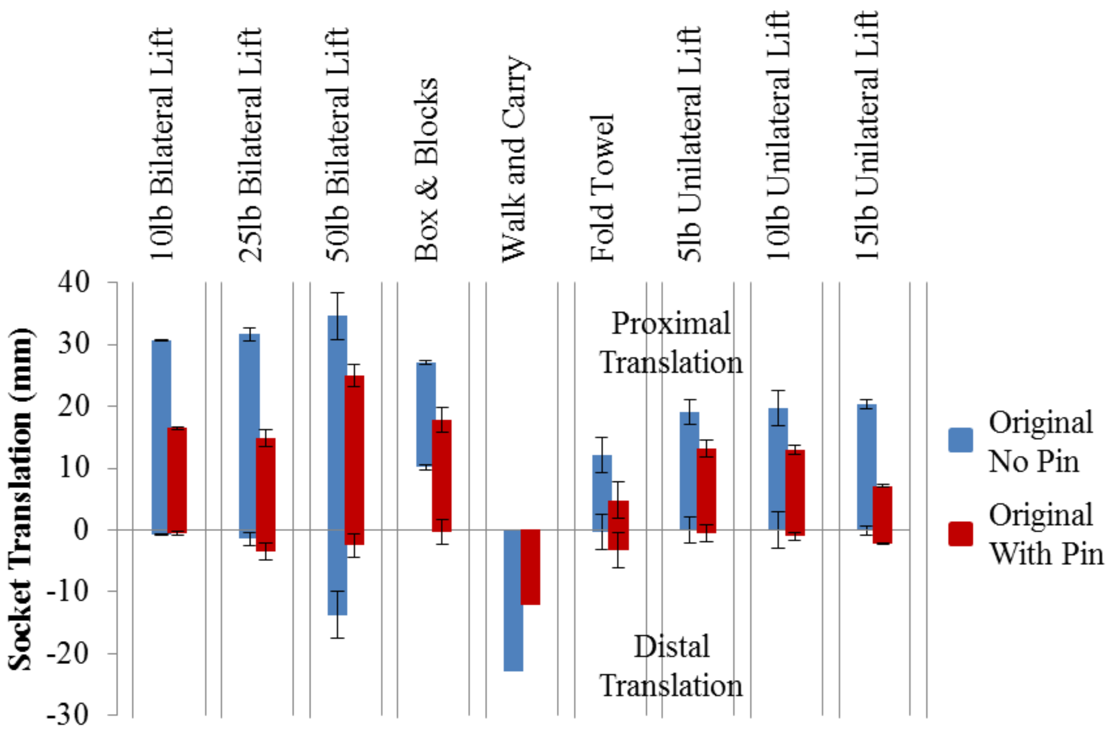


Figure 66: H04/H05 proximal-distal translation for the original prosthesis with and without using the pin-locking system.

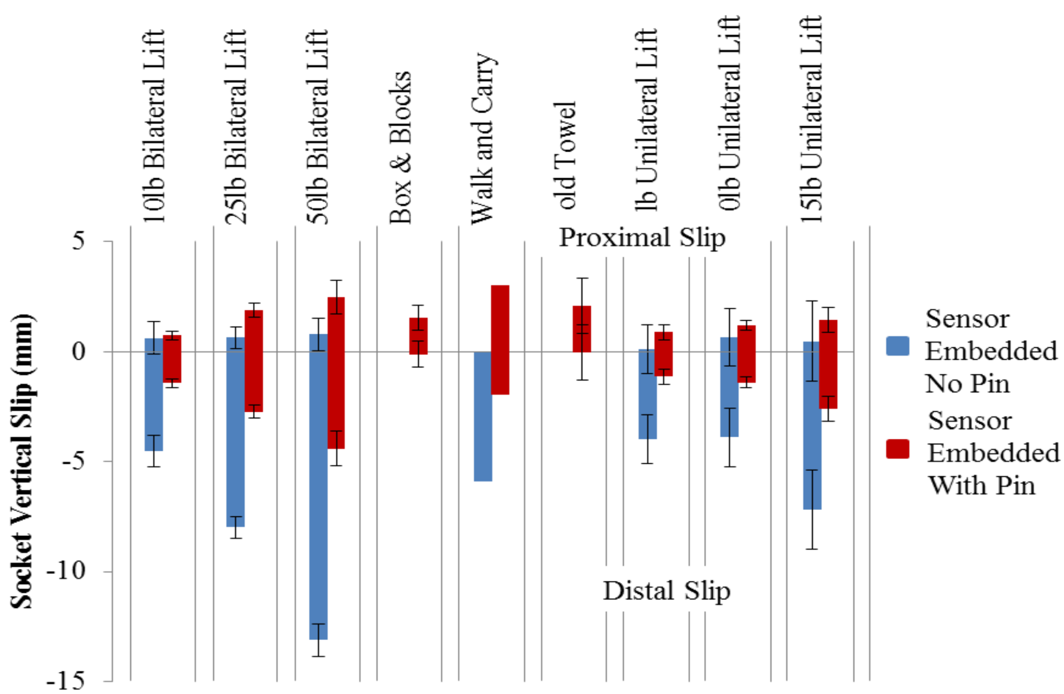


Figure 67: Vertical slip for the sensor embedded prosthesis using the two suspension systems.

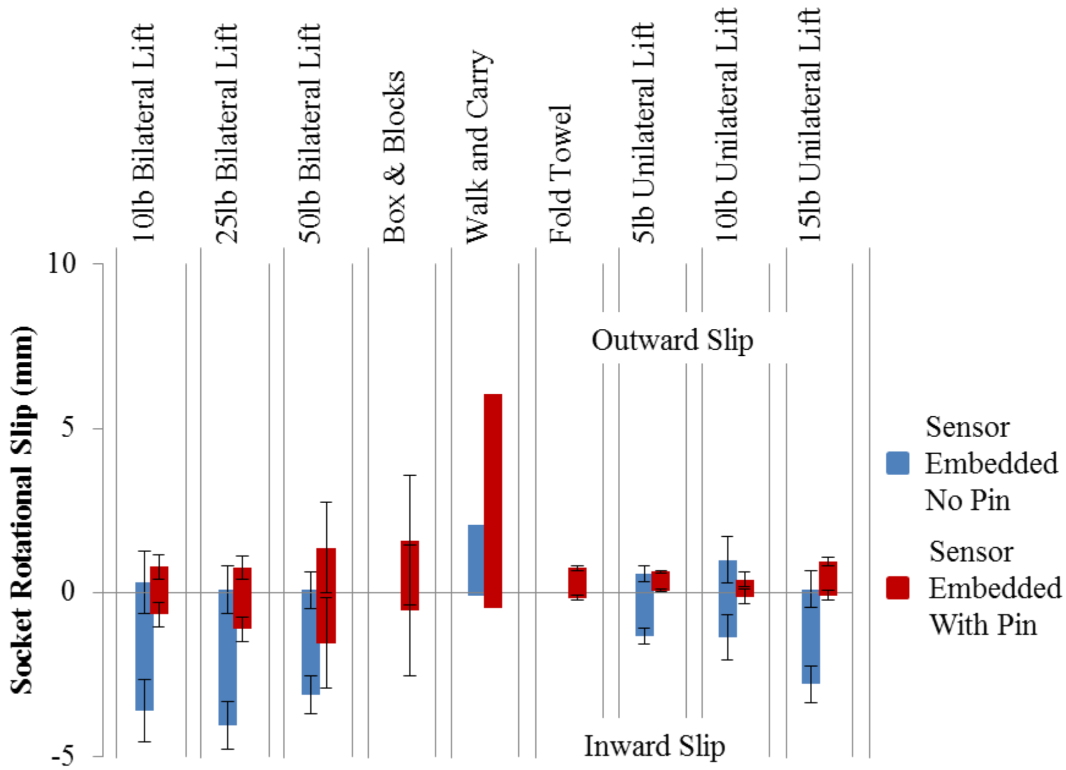


Figure 68: Rotational slip for the sensor embedded prosthesis using the two suspension systems.

The linear regression correlations made for this participant only include data that would be included in a standardized dynamic socket fit procedure proposed and discussed in the next chapter. The data used in the correlation figures only uses the data points from the bilateral and unilateral lifting tasks, and only four correlations are presented. The author believe the tasks provide the most data, as discussed in the sections for participants above, and the two lifting tasks provide a range of weights and residual limb movements that will give the prosthetist enough data to evaluate the socket fit. Figure 69 shows the correlation between anterior-posterior tilt of the socket and the amount of residual limb movement, which was significant for both suspension systems ($p<0.0001$). The same correlation plot was made for the amount of medial-lateral tilt of the socket (Figure 70), and a significant correlation was found for both suspension systems when correlating to residual limb RoM ($p<0.0001$).

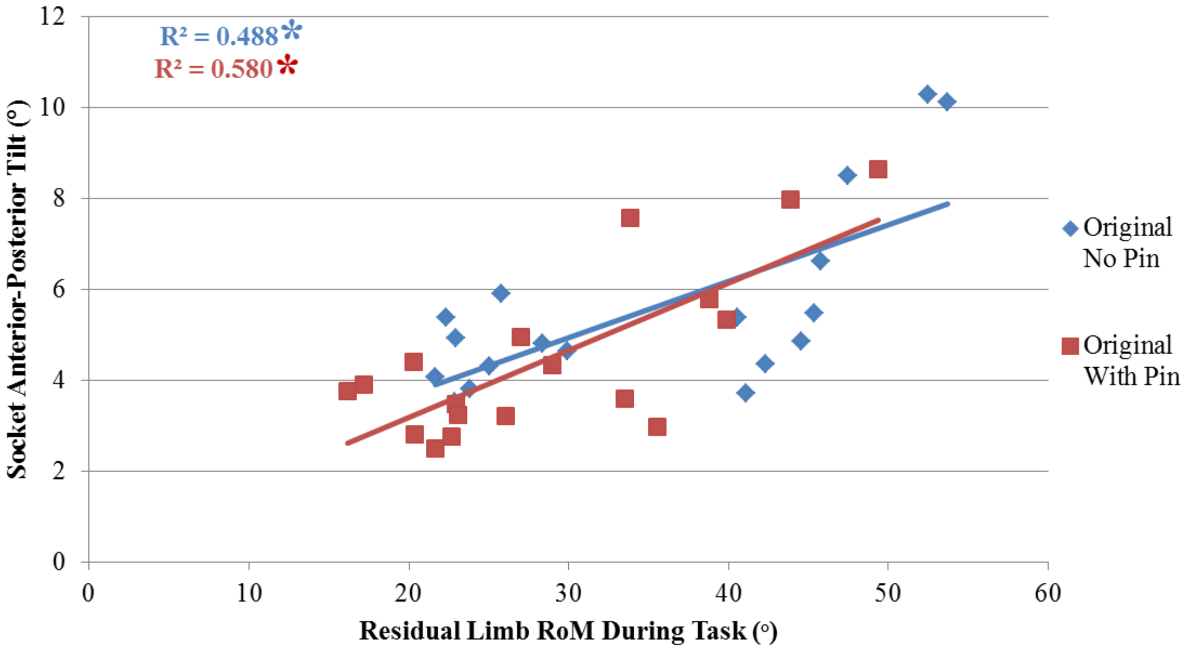


Figure 69: Linear regression for H04/H05 correlating anterior-posterior socket tilt RoM and residual limb RoM for the original prostheses with and without pin-locking suspension.

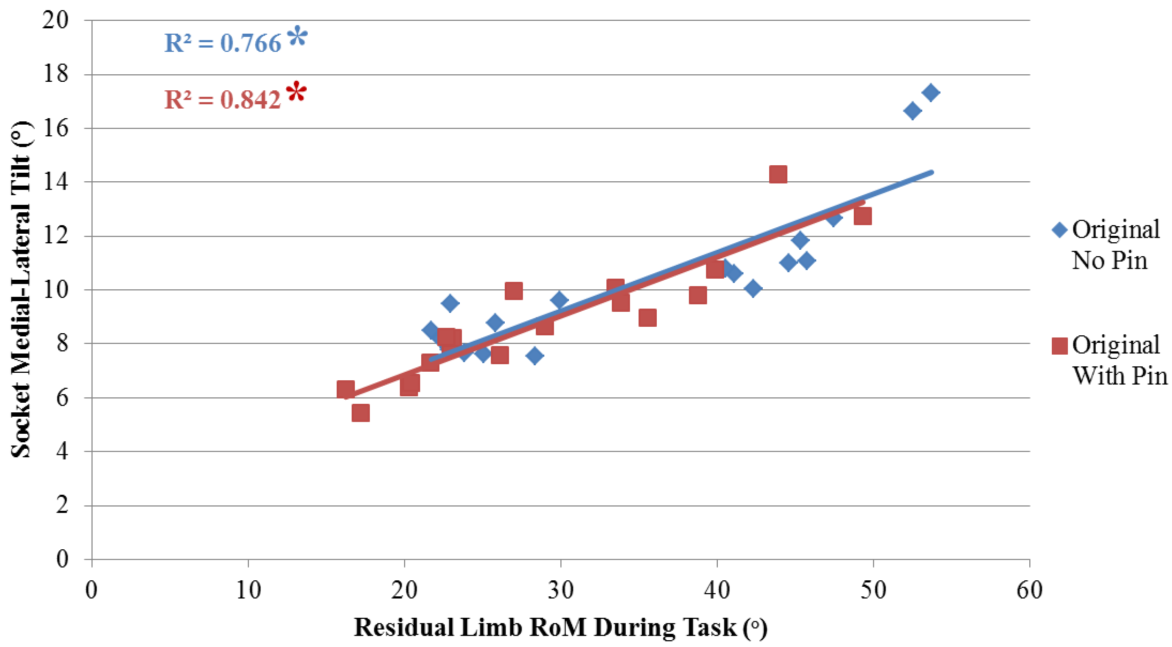


Figure 70: Linear regression for H04/H05 correlating medial-lateral socket tilt RoM and residual limb RoM for the original prostheses with and without pin-locking suspension.

The amount of socket vertical translation had a significant correlation for both suspension systems with the amount of residual limb movement ($p<0.0001$). These results are shown in

Figure 71. There was a significant correlation between the vertical slip and task weight for both suspension systems (p<0.0001), but not rotational slip. These correlations plots are shown in Figure 72.

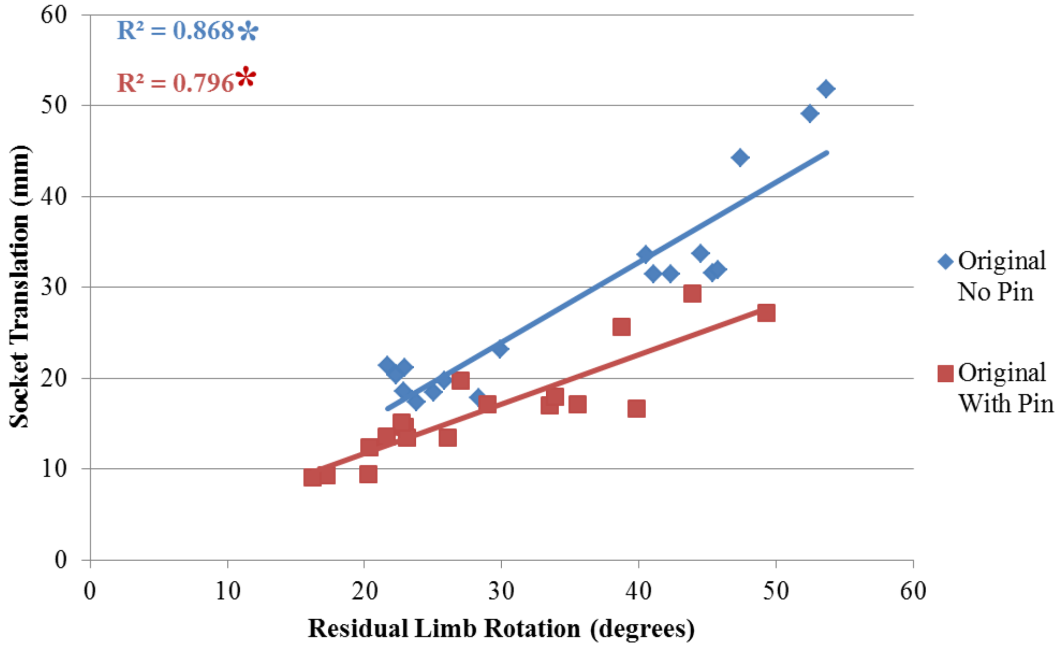


Figure 71: Linear regression for H04/H05 correlating vertical socket translation RoM and residual limb RoM for the original prostheses with and without pin-locking suspension.

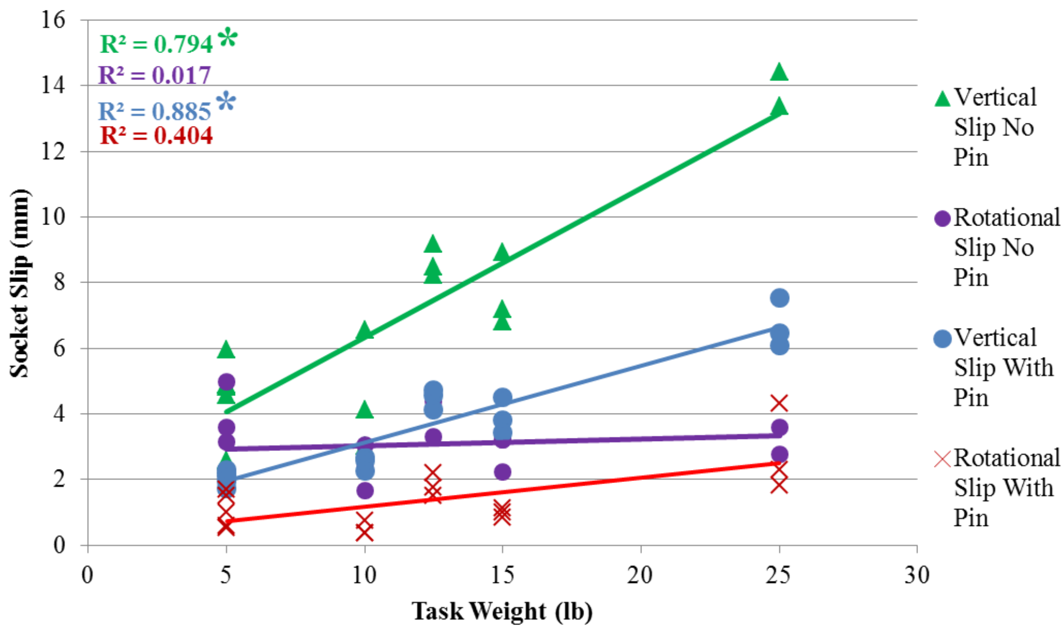


Figure 72: Linear regression for H04/H05 correlating vertical and rotational slip RoM and the weight of each task for the sensor embedded prostheses with and without pin-locking suspension.

H04/H05 provides interesting results since two different suspension systems were used within the same socket. This allows direct comparison of two suspension systems. This participant was able to complete all of the tasks in the study protocol, which the author attributes to the many significant correlations that were found for both suspension systems. The first few correlation plots comparing the different types of socket tilt to residual limb RoM and task weight confirm that the pin locking suspension had little effect on the amount of rotation. The Pearson Coefficient is very significant for both suspensions. A difference between the suspensions was found when looking at the translation and slip correlations. Both the vertical translation and vertical slip are reduced when incorporating the pin locking system. The Pearson Coefficient lowers slightly, but is still highly significant ($p<0.0001$ for most cases).

A prosthetist could use the data to help determine if the patient would benefit from a pin locking system. Dialogue with the patient could reveal the types of activities they perform or would like to perform with their prosthesis. If the patient needed a prosthesis to lift various objects, the pin locking suspension may be a better suspension system to limit the amount of slip while maintaining a high correlation of movement.

6.5 H06

This participant had the second shortest residual limb of the study cohort, which also had a high soft tissue to bone ratio, and was also the oldest participant. He reported wearing his prosthesis for on a limited basis. The RoM data for H06 showed that while wearing his prosthesis, he had a 41%, 11%, and 39% reduction in residual limb shoulder flexion, abduction, and rotation respectively.

Figure 73 shows the correlation between anterior-posterior tilt of the socket and the amount of residual limb movement. The Pearson Correlation Coefficient was found to be significant for both the original and sensor embedded prosthesis (p=0.027 and p=0.0041 respectively). The same correlations were made for the amount of medial-lateral tilt of the socket (Figure 74).

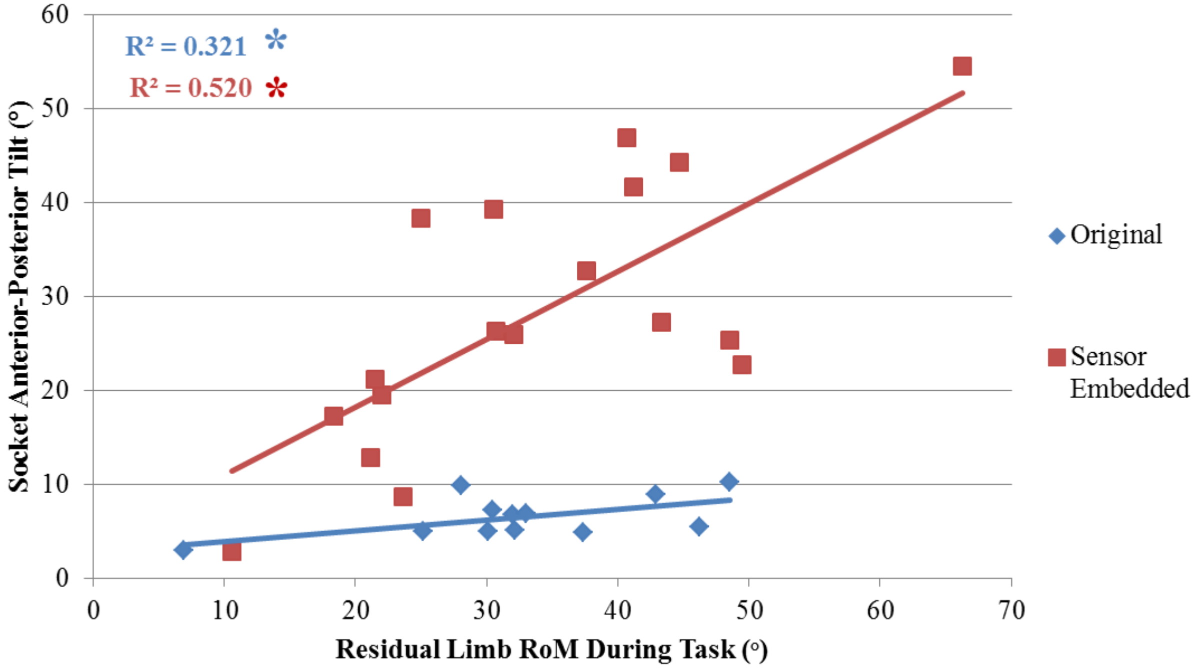


Figure 73: Linear regression for H06 correlating anterior-posterior socket tilt RoM and residual limb RoM for both prostheses.

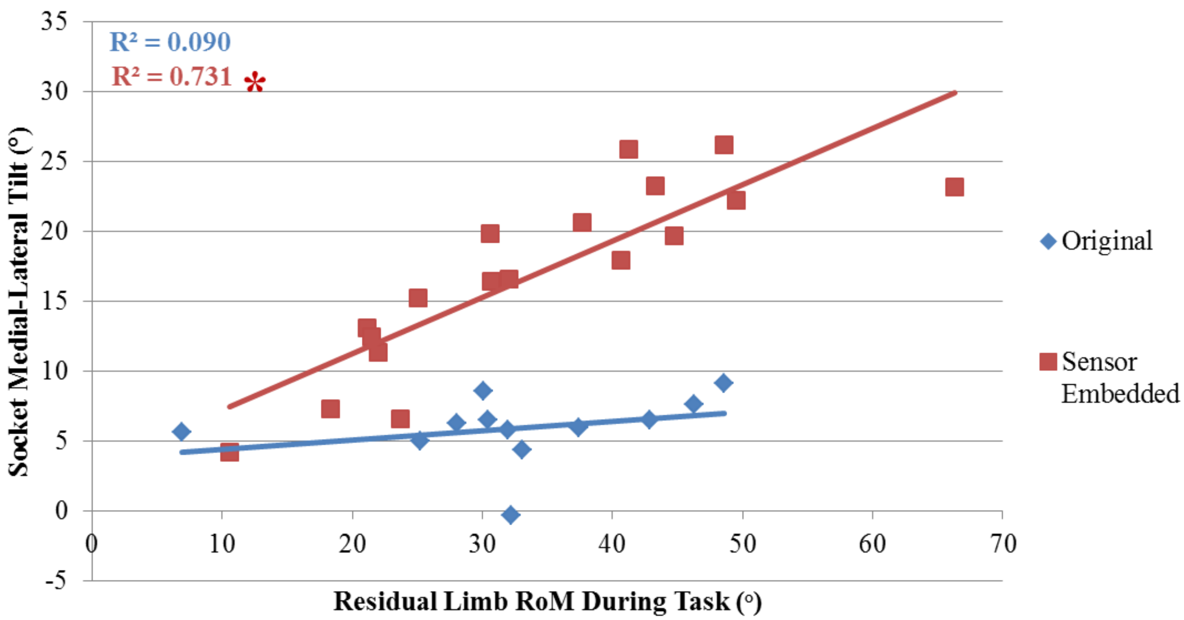


Figure 74: Linear regression for H06 correlating medial-lateral socket tilt RoM and residual limb RoM for both prostheses.

Significant correlations were found for the sensor embedded prosthesis when correlating to residual limb RoM (p=0.0002) but not for the sensor embedded prosthesis. The amount of socket vertical translation had no significant correlations for both the original and sensor embedded prostheses with the amount of residual limb movement. These results are shown in Figure 75. There were significant correlations between the rotational slip RoM and task weight (p=0.076). These correlations plots are shown in Figure 76.

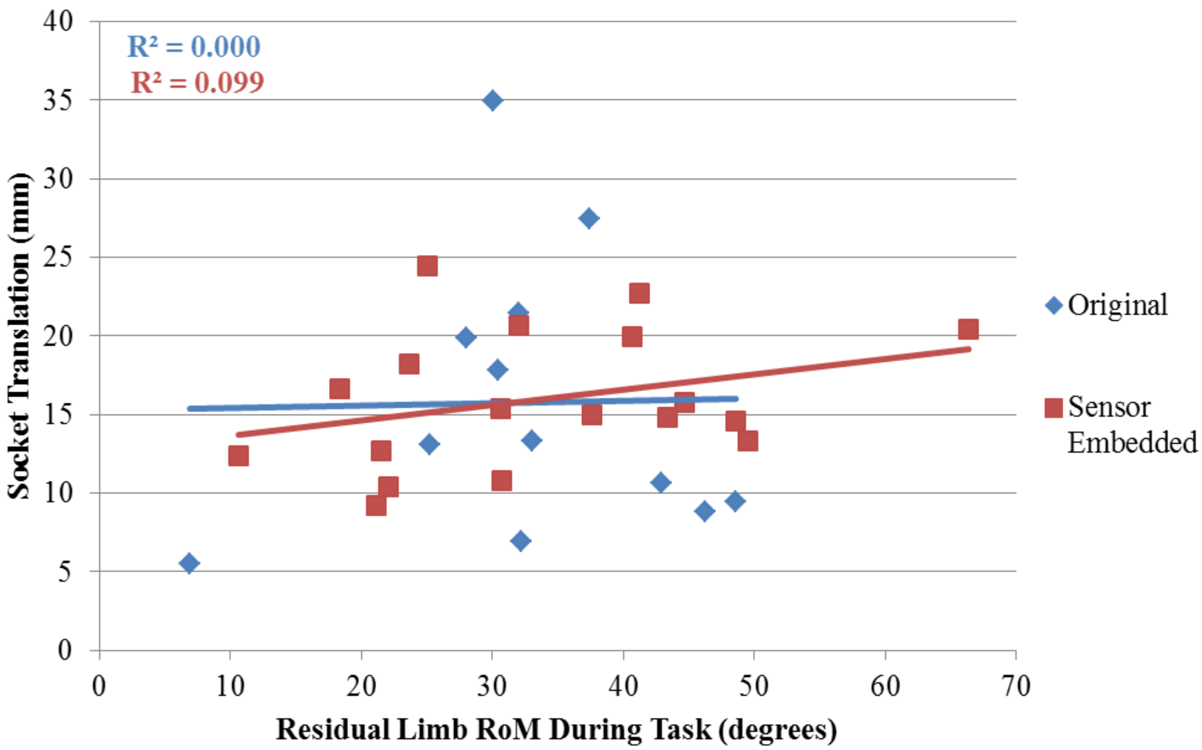


Figure 75: Linear regression for H06 correlating vertical socket translation RoM and residual limb RoM for both prostheses.

H06 was not able to complete the entire study protocol. Fatigue and residual limb discomfort brought the collection procedures to an end. The residual limb discomfort could be from movement of the socket. The original prosthesis had a suction socket that was not added to the sensor embedded prosthesis. Instead the sensor embedded prosthesis used harness suspension. The difference in rotational tilt is quite large between the two prostheses, suggesting the suction suspension did have an effect of the amount of movement.

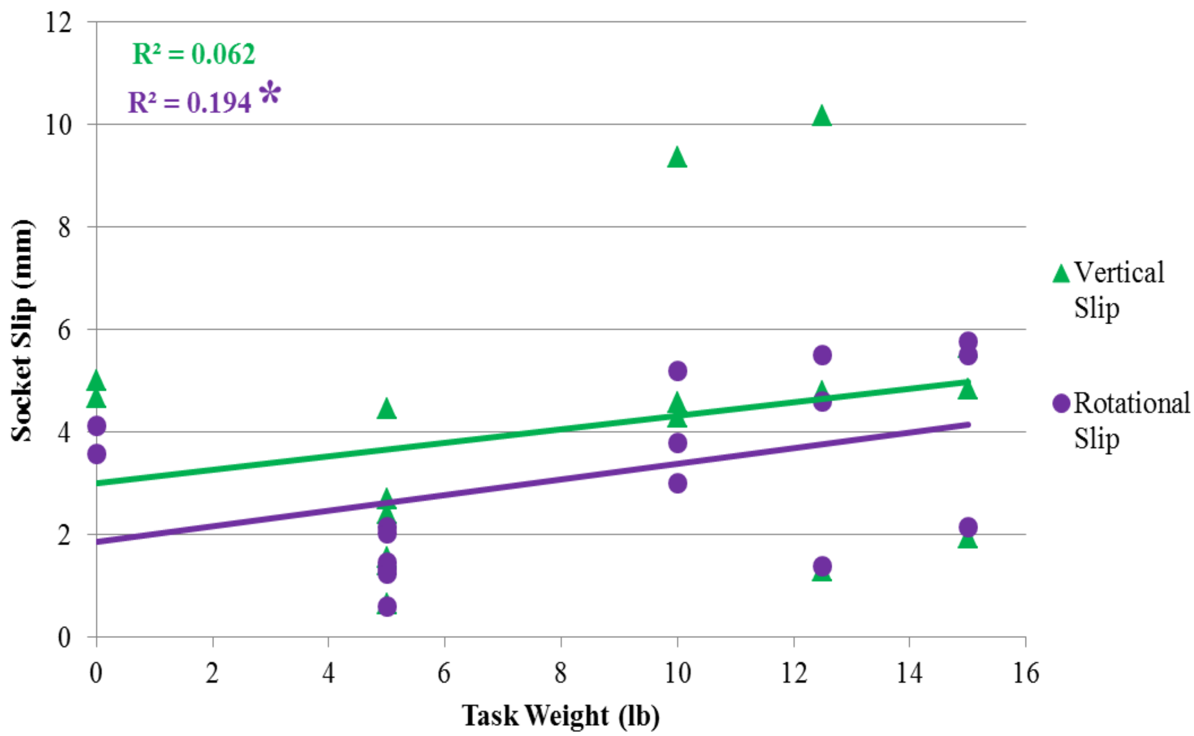


Figure 76: Linear regression for H06 correlating socket slip RoM and the weight of each task for the sensor embedded prostheses.

The amount of vertical translation and slip seems to be sporadic, even though significant correlations were found for the amount of slip. A prosthetist could use the data to redesign the socket shape by making the correlations higher among all measures. The prosthetist could use their experience to find ways to make the socket translation more predictable as well as reduce the magnitude of movement. The prosthetist could also try different suspension system to see what would help limit motion and tailor the socket shape to provide a high correlation of movement.

6.6 H07

This participant had the second longest residual limb of the study cohort. H07 came to a prosthetist in Tampa, seeking a new prosthesis due to dissatisfaction with his existing system. He agreed to participate in this study while his new myoelectric arm was being made. He described the socket as uncomfortable, and it was visually loose at the proximal end of the residual limb, having a gap between one to two inches between the socket wall and skin surface. The RoM data for this participant showed that while wearing his prosthesis, he had a 17%, 17%, and 0% reduction in residual limb shoulder flexion, abduction, and rotation respectively. This was still considered a large reduction in shoulder RoM, especially considering the residual limb length of H07.

Similar to H04/H05, the linear regression correlations made for this participant only include data that would be included in a standardized dynamic socket fit procedure proposed and discussed in the next chapter. The data used in the correlation figures only uses the data points from the bilateral and unilateral lifting tasks, and only four correlations are presented. The author believe the tasks provide the most data, as discussed in the sections for participants above, and the two lifting tasks provide a range of weights and residual limb movements that will give the prosthetist enough data to evaluate the socket fit. Figure 77 shows the correlation between anterior-posterior tilt of the socket and the amount of residual limb movement. The Pearson Correlation Coefficient was found to be significant for both the original and sensor embedded prosthesis ($p=0.016$ and $p<0.0001$ respectively). The same correlation figure was made for the amount of medial-lateral tilt of the socket, and a significant correlation was found for the sensor embedded prosthesis when correlating to residual limb movement ($p=0.0094$) (Figure 78). The amount of socket vertical translation had a significant correlation for the sensor embedded prosthesis with the amount of residual limb movement ($p<0.0001$) (Figure 79). The amount of socket slip was assessed for the sensor embedded prosthesis only. There were no significant correlations between the vertical and rotational slip RoM and the residual limb RoM and are shown in Figure 80.

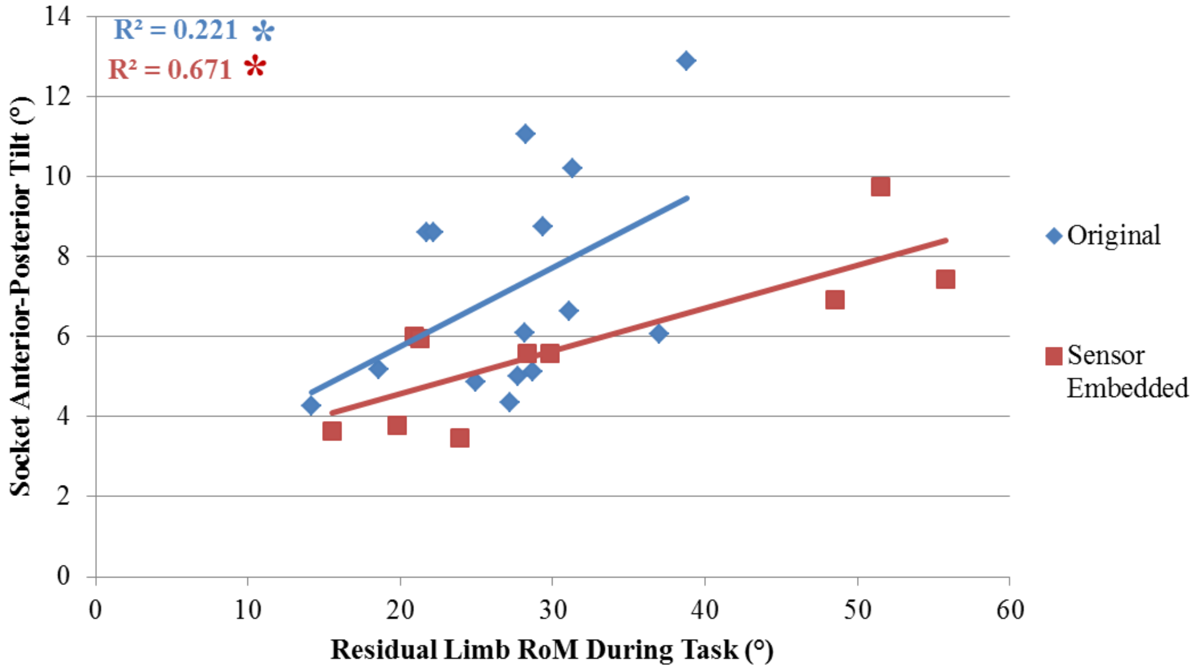


Figure 77: Linear regression for H07 correlating anterior-posterior socket tilt RoM and residual limb RoM for both prostheses.

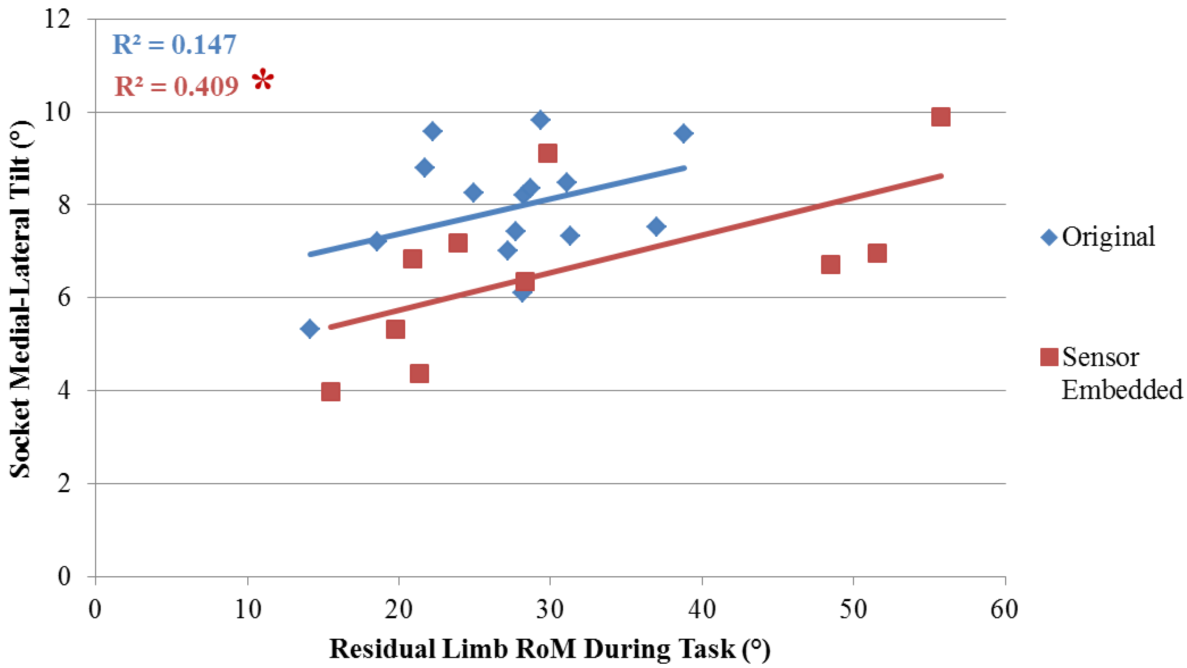


Figure 78: Linear regression for H07 correlating medial-lateral socket tilt RoM and residual limb RoM for both prostheses.

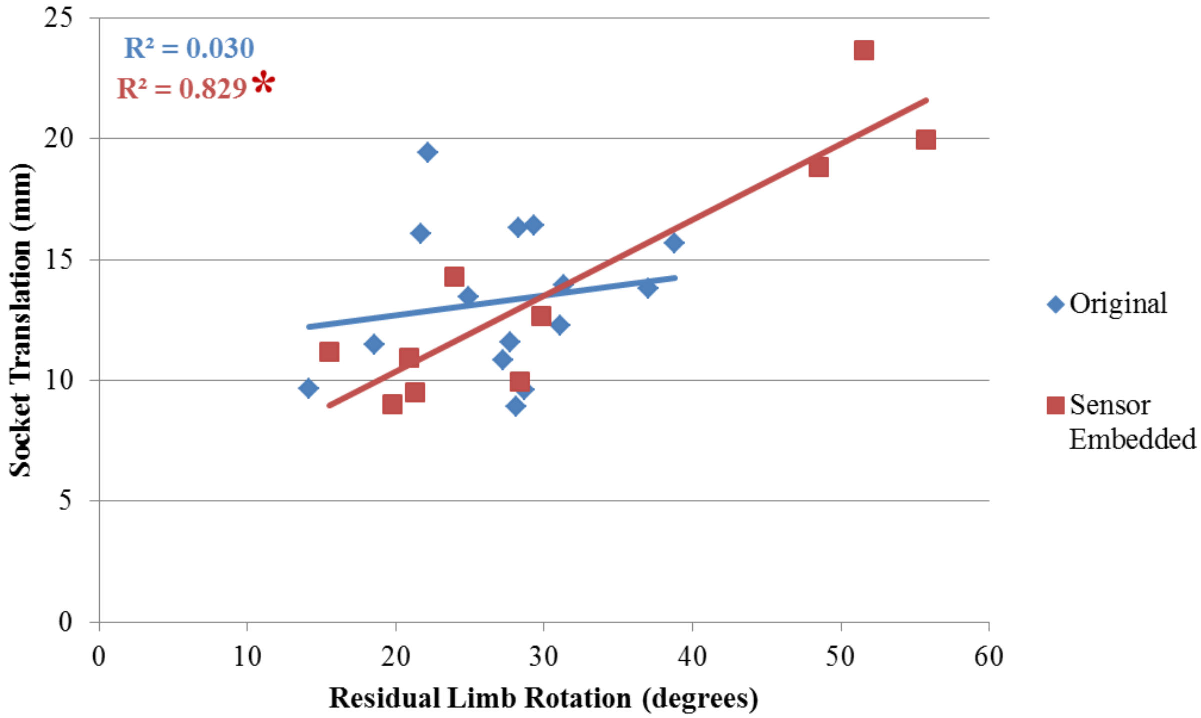


Figure 79: Linear regression for H07 correlating vertical socket translation tilt RoM and residual limb RoM for both prostheses.

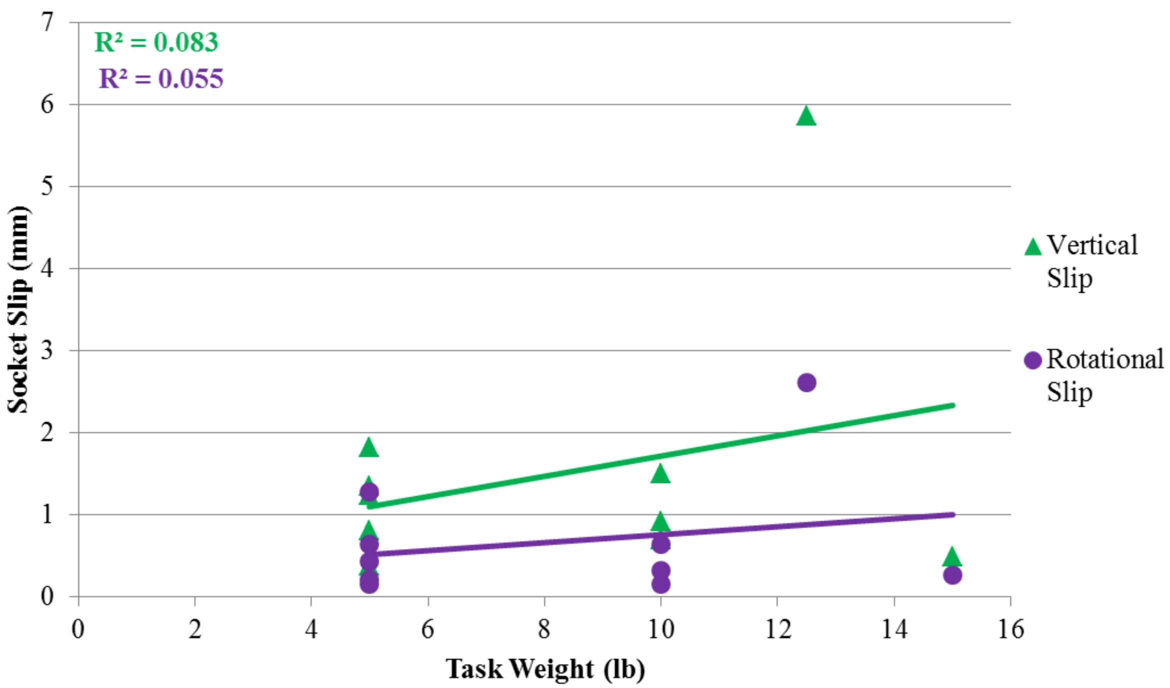


Figure 80: Linear regression for H07 correlating socket slip RoM and the weight of each task for the sensor embedded prostheses.

H07 had a high level of dissatisfaction with their socket and prosthesis. He was unable to complete the same tasks with both arms, due to discomfort developing in the residual limb. Therefore the protocol was stopped. The results above show that the socket had few correlations for the original prosthesis, suggesting the socket does not have a good fit with the residual limb. The sensor embedded prosthesis had higher correlations but may be related to the universal harness system that was used in the study. If a socket shape is not providing a suspension, the harness will have more of an influence on socket interface movement. The graphs show that the medial –lateral direction is worse than the anterior-posterior direction in terms of how the socket moves. The magnitude of movement in the two directions is roughly the same, but the anterior-posterior movement is more predictable, thus having a higher correlation. The prosthetist could use that data to develop a more medial-laterally stable socket.

CHAPTER 7: DISCUSSION AND LIMITATIONS

The motion capture model and Slip Detection Sensor provided a method of measurement to quantify movement between the residual limb and prosthetic socket, including rotations, translations, and slip. Data were collected on six transhumeral amputee participants. The study showed that the movement occurring at the socket interface is very dependent on the participant and his particular suspension system. The results of the TAPES survey provided a self-reported level of satisfaction with each participant's prosthesis. The scores indicated that most of the participants had adjusted to using a prosthesis and their limitation to participant in the particular activities included in the questionnaire was spread over a wide range. A majority of the participants rated socket comfort a 2/3 on the TAPES, regardless of how it performed during the study protocol. However, two participants (H06 and H07) rated socket comfort and fit the lowest score possible, a one out of three, and both had inconsistent movement during the study protocol relative to the other participants. A more sensitive survey utilizing a five or ten point scale may be needed however. Additional questions focusing on socket fit, comfort, and amputee perceived socket movement could provide more information for researchers.

The average socket movements for each task were shown in Figure 37 through Figure 41. The largest anterior-posterior and medial-lateral tilts were found for the bilateral and unilateral lifting tasks. The largest vertical socket translations were found for the bilateral, unilateral, and walk and carry task. The walk and carry task had a lot of translation and slip, but was most likely due to the length of the task which was one minute. The amount of socket tilts, translation, and slips found for the box and blocks, folding a towel, and walk and carry task were relatively equal. The amounts of various movements were also correlated to two different task outcomes, the range of residual limb angle during task completion and the weight of each task.

The amount of vertical and rotational slip was measured to be relatively small magnitudes of movement, on the order of millimeters, relative to the overall movement of the prosthesis. This slip motion however will be important to understand and measure. While they did not result in soft tissue injury during the course of the study, slip motion occurring throughout the course of the day could have more detrimental effects on the soft tissues. Using the Slip Detection Sensor as a measurement device, the amount of slip will be measured in order to provide more comfortable sockets and improve residual limb health.

Only two of the six participants in the study, H03 and H04/H05, were able to complete all of the tasks. An additional participant, H02, would have been able to complete the procedures but had a back issue and the study team decided to exclude the 50 pound bilateral lift. These three participants had the strongest correlations between socket tilts and residual limb angle, vertical socket translation and residual limb angle, and socket slip (both directions) and task weight. The correlations for each of these three participants were much higher than the rest of the participants, suggesting a possible relationship between these outcomes and the functional performance of a socket/prosthesis. This result is quite interesting, and may provide an interesting outcome for socket evaluation. The fact that this outcome is associated with the top performers is not surprising after consideration. The high correlation shows that the socket moves in a consistent manner (i.e. the same movement of the residual limb results in the same movement of the socket). Therefore, the amputee can predict how his prosthesis will move as he completes a task. The amputee can then establish what motions are uncomfortable or cause the socket to put pressure in a sensitive area, and avoid them.

Traditional socket fit belief suggests that motion between the residual limb interface and prosthetic socket should be limited and is the main focus of prosthetists during the fitting process. However the specific threshold of movement that is acceptable in a final socket has not been quantified. The results of the three participants able to complete the entire study protocol suggest that not only should socket interface movement be limited, but it is equally important to maximize the correlations for a few outcomes. This is highlighted by the results of H02, who had one of the highest amounts of socket interface movement out of the study cohort and was still able to have a very functional prosthesis based off H02's ability to complete all but one of the tasks. H02 did however have very significant correlations of movement to a number of the outcomes including the various socket tilts and residual limb RoM, the vertical socket tilt and residual limb RoM, and socket slip (both directions) and task weight, indicating the socket moved in a consistent way.

7.1 Review of Hypotheses

The first hypothesis stated that *"There would be a significant decrease in shoulder RoM while wearing a prosthesis."* The RoM tasks found that there was not a significant difference for shoulder flexion and abduction between the non-amputated limb and the residual limb without wearing a prosthesis. This result indicates that without wearing a prosthesis, the participants of this study were able to perform similar shoulder RoM with the residual limb as the non-amputated limb. The results found a significant difference in shoulder rotation about the long axis of the residual limb between the non-amputated limb and the residual limb without wearing a prosthesis. The author believes this is a result of inherit error within the marker set. These markers are placed on the skin surface and are good at detection flexion and abduction, but are not precise at detecting rotation about the long axis of the intrinsic skeletal features of the residual limb. The RoM for shoulder flexion and abduction was also significantly different between the residual limb without a prosthesis and when the participants wore either the original or sensor embedded prosthesis. Some of the participants had reductions in RoM upwards of 30+ degrees for some directions. This difference may be due to inefficiency in the socket's ability to transfer movements of the residual limb to the prosthesis. Again the shoulder rotation between the residual limb without wearing a prosthesis and the residual limb with wearing each of the prostheses was not significant, but may be due to the marker set's inability to accurately detect rotational movement of the residual limb.

The second hypothesis stated that *"Participants with shorter residual limbs will have more movement at the socket interface than participants with longer residual limbs."* Results from the multivariate linear regression found a negative correlation coefficient when comparing residual limb length to each of the different types of socket movement. A negative correlation coefficient means an inverse relationship between the two factors. In other words, the shorter the residual limb, the more movement that occurs at the socket interface. Significant correlations were found for medial-lateral socket tilt, vertical socket slip, and rotational socket slip. The other two types of socket movement, anterior-posterior socket tilt and vertical translation were not significant but did have negative correlation coefficients.

The third hypothesis stated that *"Task weight will be the biggest factor affecting the amount of movement occurring at the socket interface."* Results from the multivariate linear regression showed that task weight did impact the amount of socket interface movement. Task weight had the most significant impact on vertical socket translation and vertical socket slip. However, residual limb movement was found to have the most significant impact on all the types of socket movement.

7.2 Comparison of Results to Other Socket Movement Studies

The movement occurring at the socket interface is highly dependent on the participant and his/her socket and suspension system. The anterior-posterior tilt found in this study ranged from about 3 degrees to 24 degrees and the medial-lateral tilt ranged from about 2 to 16 degrees of movement. Very few studies on upper limb socket movement exist for comparison. Sensinger [69] found anterior-posterior tilt RoM of the socket to be approximately 10 degrees. This was found during static poses where the participant locked there prosthetic elbow at 90 degrees of flexion and an oscillatory load was applied. The anterior posterior tilt in this study were higher in magnitude but may be a result of examining dynamic activity, which incorporates more factors such as movement of the residual limb, forces from the harness system, and other forces which would increase the amount of movement experienced. Convery [64] used ultrasound to assess socket rotations in lower limb systems during gait and found RoM of 12 and 17 degrees for medial-lateral and anterior-posterior socket tilt respectively. This study was done on transtibial amputees, which have more intrinsic bone for the socket to be designed around. These rotations may increase at the transfemoral amputation level, but are still close to the magnitude of socket tilt movement found in this dissertation.

Pistoning, or vertical translation has also been well documented for lower limb systems The studies reviewed in Chapter 1 found pistoning ranging from 22 to 75 mm. This study had a range of vertical translation of 2 to 16 mm. It is not unexpected that there is a large difference in the range of movement, because lower limb prostheses are subjected to larger forces associated to weight bearing and gait. The translation found in this study is not due to weight bearing, rather operation of the prosthetic joints and forces associated with lifting various objects.

Appoldt measured 6 mm of slip during gait using a pen mounting onto a prosthetic socket of below knee prostheses, but recognized the high error associated with the analysis of data. The average of slip found for the walk and carry task was 12 mm for vertical slip and 7 mm for rotational slip. A summary comparing the results of this dissertation to the results of previous socket interface studies is shown in Table 9.

Table 9: Summary of comparison to other socket studies.

Study	Study Finding	Dissertation Findings	Reasoning
Sensinger	~10° anterior-posterior socket tilt	Average for 25lb bilateral lift task was 12° but 23° for highest individual	Comparing socket movement during static poses to dynamic activity
Convery	17° anterior-posterior socket tilt and 12° medial-lateral socket tilt	Anterior-posterior tilt was higher than medial-lateral tilt	Magnitudes of movement in each direction close between studies
Pistoning Studies	22-75 mm of pistoning	Up to 50 mm of translation	Expect lower limb to have more pistoning movement due to magnitude of load
Appoldt	6 mm of slip with pen	Highest average slip was 12 mm for vertical and 7 mm for rotational slip	Poor accuracy reading ink trail

7.3 Clinical Impact

The prosthetic fitting process is currently highly subjective. The amputee is dependent on the prosthetist's skill and experience to produce a socket shape that provides a high level of comfort and functional connection with the prosthesis. Without quantitative data that can help determine when a proper socket shape has been made or an appropriate suspension method selected, the prosthetist uses his/her judgment based off qualitative feedback from the amputee and an assessment of the residual limb. The methods and devices used in the study offer a way to measure movement at the interface, which can improve the socket fitting and prescription procedures.

First, the methods can be used to compare various socket types and suspension methods, impacting the socket/suspension prescription process. Data can be collected on a number of different design methodologies and suspension methods completing a series of tasks similar to the ones performed for this study. With enough data collected, generalizations can be made for how each socket design and suspension method affects movement at the interface and correlates them to a number of patient parameters. The patient parameters could include residual limb length and composition, and the activities they perform, the activities they would like to perform, on a daily basis. This will provide a reference database that can assist a prosthetist when prescribing a socket/suspension type for an individual. This will give the prosthetist quantitative data to show the insurance company why an individual needs one suspension system over another, and why the insurance should cover the potential cost increase for that system.

After socket prescription, the data can also be used to determine if an appropriate socket shape has been made. Prosthetists could follow their current procedures up through production of the first check socket. Using the check socket, the amputee could then perform a standardized dynamic socket check discussed in the next section. Data similar to the results of this dissertation will be collected during the dynamic socket check. The results will show the prosthetist how much movement is occurring at the interface and in what direction the movement is occurring. The prosthetist can then make a more informed decision on the changes that should be made to the socket shape to improve the socket fit. For instance, data from the Slip Detection Sensor will show the prosthetist how much slip is occurring during the dynamic socket check, and the prosthetist can decrease the socket volume to create a snug fit and thereby reduce the amount of socket slip. The correlation plots presented will also provide information on how the socket is performing, and can be used in conjunction with the actual movement data for each task. The data could reduce the number of check sockets made while producing a better socket for the amputee. Therefore, prosthetic care costs could be lowered by reducing prosthetist time and material costs, as well as reducing the number of visits due to comfort related issues.

Another clinical impact would be the creation of an automated dynamic interface using the Slip Detection Sensor as a control device. A range of “allowable” slip will be programmed into the software, and data from the Slip Detection Sensor will be used to measure the amount of slip at the interface. If the sensor detects slip that is above the allowable range, the dynamic interface system would automatically adjust the interface settings to correct for excess slip movement. One possible system would be the LimbLogic system described earlier [30]. This is an adjustable vacuum system that is currently controlled by the amputee. Incorporating the Slip Detection Sensor with this system removes the user from the loop and may provide better comfort and reduce soft tissue irritation through better interface management.

Lastly, challenges with insurance coverage are another big problem in the prosthetic industry. All of the clinical impacts described in this section relate to this issue. The insurance companies may not be willing to pay for a new socket type if the cost is too great. However, using the measurement method developed in this dissertation could provide quantitative data for why one socket design is superior to another and how it can improve residual limb health over time, presenting evidence for why the insurance companies should cover the initial increased cost.

7.4 Standardization of the Socket Fitting Procedures

Tampa, Florida and the surrounding cities are fortunate to have capable and knowledgeable prosthetists providing excellent prosthetic care. The local VA hospital, a regional provider of prosthetic care, helps attract these talented professionals. However, other parts of the country and world are not as fortunate. Socket fitting and prescription therefore varies widely geographically. Developing a formal socket fitting procedure will standardize the fitting process in hopes of improving the end result, providing comfortable and functional prostheses.

The procedures of this study could be used as a basis for the standardized socket check, making some adjustments to provide more control of the variables. After forming the thermoplastic socket, the prosthetist could attach a lever arm to the distal end of the socket. This lever arm would be mounted between a 45 and 90 degree flexion angle to simulate elbow flexion. The end of the lever arm would include a hook that the amputee could use to pick up a series of weighted objects while the same movement data are collected. The unilateral and bilateral lifting tasks could be the only tasks included during the dynamic socket check, and would provide enough data for the prosthetist to analyze and make adjustments to socket shape from.

The methods of this dissertation used a motion analysis system and Slip Detection Sensor. The slip sensor could easily afforded by local prosthetic clinics, but the motion capture system could be too expensive. Therefore the slip sensor could be used alone, or other hardware could be used to replace the motion capture system. One study found comparable results between accelerometer based sensors and a motion capture system [73]. This may provide a less expensive solution for local prosthetic clinics. The prosthetist could evaluate the skin blanching through the clear thermoplastic socket as they currently do, then analyze the socket movement data and correlations to help determine what changes to make for the next socket iteration.

A number of correlation graphs were presented in the results, but only a few will be needed to analyze the socket. This includes anterior-posterior socket tilt, medial-lateral socket tilt, and vertical socket translation to residual limb RoM during the task. Vertical socket translation and vertical/rotational socket slip to the task weight were also significant correlations that could be used as performance parameters. These outcomes seemed to have the highest correlations and provided the most information for how a socket was performing. Comparing the participants to one another, it was shown that the three participants who were able to complete the entire study protocol also had very significant correlations to each of these comparisons.

7.5 Limitations

The small sample size of the study limits the power of the results and should be addressed in future studies. However, the sample size of seven is greater than most of the upper limb prosthesis studies currently in the literature, particularly for transhumeral prostheses. The motion capture model assumption that the socket anterior-posterior and medial-lateral tilt rotates about the center point of bone inside the socket has not been proven experimentally. Additionally, each participant's socket shape was duplicated, but not the rest of the prosthetic components and harness system. Standard body-powered components and a universal harness were used. The universal harness could easily be adjusted for any size user. This may have created differences in how the participant operated the prosthesis and how the socket movement was influenced by the harness. It was not possible to determine if the difference in socket movement was due to differences in the socket shape and which were due to difference in the prosthesis and harness system. For this reason, the sample was problematic to study. Testing of other amputation levels and prosthetic systems will be needed to further validate the methods.

Another limitation of the study was human error in placing the passive reflective markers on the participants and their prosthesis. While great care was taken to standardize placement procedures, it was not possible to place the markers at exactly the same location. A relatively small sample size was collected, and therefore these results are related to these individuals. More data are needed before general conclusions can be made.

CHAPTER 8: CONTRIBUTIONS AND FUTURE WORK

The motion capture model and Slip Detection Sensor developed in this dissertation allowed for the measurement of socket interface movement during dynamic activity. The data collected on seven transhumeral amputees represents one of the largest sample sizes in the current literature. Additional participants are needed to increase the power of the study. A few conclusions can made based of the results from the study sample. Wearing a prosthesis on the residual limb significantly reduced the shoulder range of motion for flexion/extension and abduction/adduction compared to when the participant was not wearing a prosthesis. The amount of socket anterior-posterior and medial-lateral tilt was not dependent on the task weight as hypothesized, rather was correlated with residual limb movement. The amount of socket slip was more dependent on the task weight. The length of the participants' residual limb also had an impact on the amount of socket interface movement. A multivariate linear regression found a negative correlation value when comparing residual limb length to the different types of socket movement. Therefore shorter residual limbs resulted in more movement at the socket interface.

The magnitude of socket slip was relatively small, but throughout the course of the day, the cumulative effect of the slip motion over hours (rather than minutes or seconds like the tasks in this study) could result in residual limb injury. The Slip Detection Sensor proved to be an efficient and nonintrusive means to quantify the amount of socket slip occurring at the socket interface, which is projected to be easily adaptable for incorporation to adjustable interface systems. Therefore the Slip Detection Sensor will be critical to the advancement of socket comfort and performance.

8.1 Contributions

The work in this dissertation has made several contributions to the areas of basic and applied prosthetic socket interface research.

1) A motion capture model was developed to quantify the amount of prosthetic socket rotations and translation occurring at the interface with the residual limb.
2) A Slip Detection Sensor was designed, prototyped, and validated to experimentally measure the amount of slip between the prosthetic socket and residual limb skin surface.
3) The amount of socket interface movement occurring for body-powered transhumeral prosthesis wearers during common tasks was quantified.
4) Evidence was provided for the tasks that should be included in a dynamic socket fit check that could be used to standardize prosthetic care across the world.
5) Potential socket fit outcomes were discovered that can be used to evaluate the fit of a socket.

The methods developed in this dissertation could be applied in research and clinical settings. Researchers will be able to evaluate the fit and performance of various socket designs/suspension methods, providing clinicians with quantified data on how one socket and suspension option could provide improved comfort and function over another socket and suspension option based off some amputee specific parameters. The development of automatic adjusting socket interfaces will be another avenue for Slip Detection Sensor to positively impact prosthetic comfort. Clinicians can use the data to assist them with the fitting and prescription of prosthetic sockets.

8.2 Future Work

Continued research investigating movements occurring at the prosthetic socket interface is needed. The work presented here indicates other factors that contribute to socket interface movement that could be investigated.

First, the motion capture method for approximating residual limb bone position inside the socket could be compared to fluoroscopy or some type of radiological measurement technique. This will show the accuracy at which the method approximates the bone position inside the socket. The procedures would be limited to static poses where the amputee will hold weighted objects with his prosthesis and the amount of socket tilt and socket translation measured.

Second, additional sensors could be used such as strain gages in the harness suspension system to quantify forces being placed on the socket by the harness straps. The data from the sensor embedded prosthesis showed higher correlations for the three participants who were not able to complete the study protocol than the data from the original prosthesis did. This may be related to additional suspension of the universal harness used with all of the sensor embedded prostheses. Additionally, myoelectric devices could be included in the study to see the difference in socket interface movement with and without a harness suspension system or the need to put tension in the cables to operate the prosthesis.

Third, the simultaneous use of multiple Slip Detection Sensors placed at various positions in the socket would provide an overall slip mapping occurring at the socket interface. The various positions could be compared to see at what point(s) the most amount of slip occurs. This data could be used to optimize the location of the sensor for use in a dynamic interface system. The Slip Detection Sensor can be further reduced in size and operational efficiency for incorporation with a dynamic interface system. The system could be tested to see how it improves residual limb health and socket by managing socket interface movement.

These methods have currently been tested only on one level of upper limb systems, but could easily be expanded to lower limb prostheses. One hot area of research relates to the amount of pistoning in lower limb systems. This would be an excellent application for the Slip Detection Sensor. The sensor could even be used in a study to assess how the Slip Detection Sensor impacts a prosthetists decision making during a fitting for lower limb system. A dynamic socket check can be performed where the slip sensor collects data while the amputee ambulates with a check socket. Additional work pertaining to the slip detection sensor includes simplifying the software outcomes for ease of clinical use.

The methods and devices presented in this study offer an elegant approach to analyze the socket interface movement. The results from this study and related future work hope to improve socket comfort and prosthetic function to meet the needs of an constantly growing amputee population.

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APPENDICES

Appendix A: Data Collection Documents

A.1 Subject Measurement Form

USF RRT Motion Analysis Lab

SUBJECT MEASUREMENT FORM

Study Name ____________________

Subject Identifier ______ Collection Date ________ Researcher ______________

USF UNIVERSITY OF SOUTH FLORIDA COLLEGE OF ENGINEERING

Patient Information

Patient's Name ____________________

Age ______ Sex ______ Weight ______ Height ______

Amputation Cause: ____________________ Date ______

Amputation Level: ____________________ ☐ Right ☐ Left

☐ Caucasian ☐ Brown ☐ Other Previous Prosthesis Worn? ☐ Yes ☐ No Shade# ___

(If this is a Replacement Prosthesis, please include measurments from old prosthesis on a seperate form)

Is the Prosthesis to be shipped Ready for Fitting? ☐ Yes ☐ No Date ______

Socket

☐ Open Socket ☐ End Bearing ☐ Split Socket

Part# ______ Part# ______ Part# ______

Model ______ Model ______ Model ______

☐ Lightweight ☐ Standard Weight ☐ Heavy Duty

Special Inst: ____________________

Joint Type

☐ Wrist ☐ Elbow ☐ Hinge

Part# ______ Part# ______ Part# ______

Model ______ Model ______ Model ______

☐ Check Here for Lift Assist

Special Inst: ____________________

Terminal Device

☐ Hook ☐ Hand ☐ Glove

Part# ______ Part# ______ Part# ______

Model ______ Model ______ Model ______

Special Inst: ____________________

Include

☐ Harness ☐ Cuff ☐ Cables

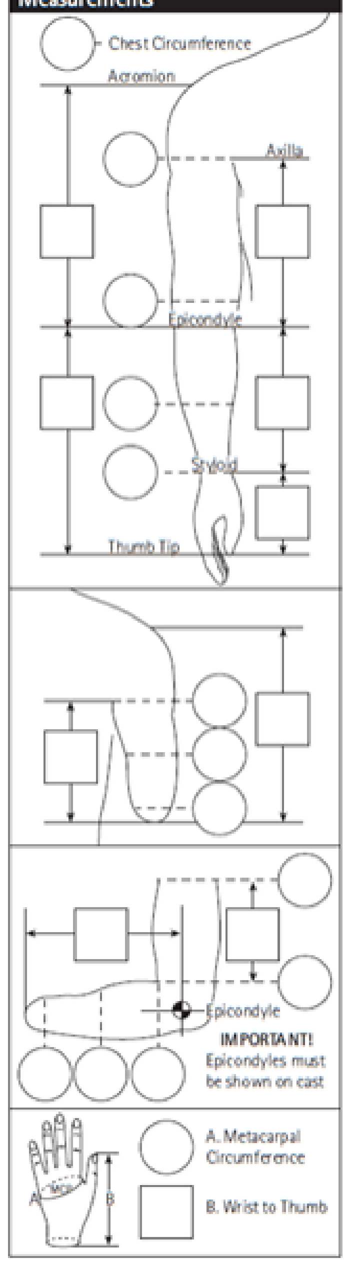
Part# ______ Part# ______ Part# ______

Model ______ Model ______ Model ______

☐ Other Accessories: ____________________

Special Inst: ____________________

Measurements



Appendix A (Continued)

A.2 Day 1 Data Collection Checklist

Data Collection Checklist: Day 1

Subject ID: ______________ **Name:** __________________________ **Date:** ___________

❑ **Subject sign informed consent**

❑ **Subject sign photography release (optional)**

❑ **Prosthetist make positive mold of socket while beginning testing procedures below**

❑ **Measure and record subject parameters**

- ❑ Height = _______________
- ❑ Weight = _______________
- ❑ Residual Limb Measurement Sheet
- ❑ Prosthesis Harness Connection Points
- ❑ Prosthesis Weight = _____________

❑ **Attach markers**

❑ T1	❑ RPSI	❑ LIC	❑ LWRB
❑ T10	❑ LASI	❑ LSHOA	❑ LFIN
❑ CLAV	❑ LPSI	❑ LSHOP	❑ RSLA
❑ STRN	❑ RSHOA	❑ LELB	❑ RSLP
❑ LBAK	❑ RSHOP	❑ LELBM	
❑ RASI	❑ RIC	❑ LWRA	

❑ **Calibrate Cameras**

❑ **Range of motion tasks without prosthesis x 3**

- ❑ Static
- ❑ Shoulder Abduction/Adduction
- ❑ Shoulder Flexion/Extension
- ❑ Shoulder Rotation

❑ **Trinity Amputation and Prosthesis Experience Scales (TAPES)**

Appendix A (Continued)

A.3 Day 2 Data Collection Checklist

Data Collection Checklist: Day 2

Subject ID: ______________ **Name:** __________________________ **Date:** ___________

❑ **Measure and record residual limb volume**

❑ Volume =____________________

❑ **Attach markers**

❑ T1	❑ LASI	❑ RELBM	❑ LELBM
❑ T10	❑ LPSI	❑ RWRA	❑ LWRA
❑ CLAV	❑ RIC	❑ RWRB	❑ LWRB
❑ STRN	❑ LIC	❑ RFIN	❑ LFIN
❑ LBAK	❑ RSHOA	❑ LSHOA	❑ SCKA
❑ RASI	❑ RSHOP	❑ LSHOP	❑ SCKP
❑ RPSI	❑ RELB	❑ LELB	❑ SCKL

❑ **Calibrate Cameras**

❑ **Range of motion tasks with prosthesis A x 3 (check left column)**

❑ Static	❑	❑ Shoulder Rot	❑
❑ Shoulder Flex/Ext	❑	❑ Elbow Flex/Ext	❑
❑ Shoulder Ab/Add	❑		

❑ **Functional Tasks with prosthesis x 3 (check left column)**

❑ Static	❑	❑ Walk and Carry	❑
❑ Unilateral Lift	❑	❑ Fold a Towel	❑
❑ Bilateral Lift	❑	❑ Box and Blocks	❑

❑ **Change prosthesis and Recalibrate Cameras**

❑ **Measure and record residual limb volume**

❑ Volume =____________________

❑ **Repeat collection protocol (check right column)**

❑ **Measure and record residual limb volume**

❑ Volume =____________________

Appendix A (Continued)

A.4 Trinity Amputation and Prosthesis Experience Scales (TAPES)

This is a questionnaire designed to investigate different aspects of having a prosthesis.
Please answer every item as honestly as you can. There are no right or wrong answers.
Your responses will remain confidential.

1. Client Name: ______________________________

2. Client date of birth: _________________________

3. Are you male.... [ ]
   female..[ ]

4. How long ago did you have your amputation?
   _______________ years _______________ months (If you have had more than one amputation surgery please refer to your first amputation surgery).

5. How long have you had a prosthesis?
   _______________ years _______________ months

6. How long have you had the prosthesis that you wear at the moment?
   _______________ years _______________ months

7. What type of prosthesis do you have? *(Please tick the appropriate box)*

Below-Knee	[ ]	Below-elbow	[ ]
Through-Knee	[ ]	Through-elbow	[ ]
Above-Knee	[ ]	Above-elbow	[ ]

   Other (please specify) ________________________________

8. What was your amputation a result of? *(Please tick the appropriate box)*
   Peripheral Vascular Disorder [ ]
   Diabetes [ ]
   Cancer [ ]
   Accident [ ]
   Other (please specify) ________________________________

1

Appendix A (Continued)

Part I

Below are written a series of statements concerning the wearing of a prosthesis. Please read through each statement carefully. Then ***tick the box*** beside each statement, which shows how strongly you agree or disagree with it.

		Strongly disagree	Disagree	Agree	Strongly agree	Not applicable
1.	I have adjusted to having a prosthesis....................	[1]	[2]	[3]	[4]	[ ]
2.	As time goes by, I accept my prosthesis more.........	[1]	[2]	[3]	[4]	[ ]
3.	I feel that I have dealt successfully with this trauma in my life	[1]	[2]	[3]	[4]	[ ]
4.	Although I have a prosthesis, my life is full	[1]	[2]	[3]	[4]	[ ]
5.	I have gotten used to wearing a prosthesis............	[1]	[2]	[3]	[4]	[ ]
6.	I don't care if somebody looks at my prosthesis	[1]	[2]	[3]	[4]	[ ]
7.	I find it easy to talk about my prosthesis	[1]	[2]	[3]	[4]	[ ]
8.	I don't mind people asking about my prosthesis	[1]	[2]	[3]	[4]	[ ]
9.	I find it easy to talk about my limb loss in conversation	[1]	[2]	[3]	[4]	[ ]
10.	I don't care if somebody notices that I am limping ..	[1]	[2]	[3]	[4]	[ ]
11.	A prosthesis interferes with the <u>ability</u> to do my work..	[4]	[3]	[2]	[1]	[ ]
12.	Having a prosthesis makes me more dependent on others than I would like to be	[4]	[3]	[2]	[1]	[ ]
13.	Having a prosthesis limits the <u>kind</u> of work that I can do	[4]	[3]	[2]	[1]	[ ]
14.	Being an amputee means that I can't do what I want to do	[4]	[3]	[2]	[1]	[ ]
15.	Having a prosthesis limits the <u>amount</u> of work that I can do...	[4]	[3]	[2]	[1]	[ ]

2

Appendix A (Continued)

The following questions are about activities you might do during a typical day. Does having a prosthesis limit you in these activities? If so, how much? *Please tick the appropriate box.*

	Yes, limited a lot	Limited a little	No, not limited at all	
(a) Vigorous activities, such as running, lifting heavy objects, participating in strenuous sports..................................	[$_2$]	[$_1$]	[$_0$]	
(b) climbing several flights of stairs	[$_2$]	[$_1$]	[$_0$]	
(c) running for a bus	[$_2$]	[$_1$]	[$_0$]	
(d) sport and recreation	[$_2$]	[$_1$]	[$_0$]	
(e) climbing one flight of stairs	[$_2$]	[$_1$]	[$_0$]	
(f) walking more than a mile...........................	[$_2$]	[$_1$]	[$_0$]	
(g) walking half a mile....................................	[$_2$]	[$_1$]	[$_0$]	
(h) walking 100 metres	[$_2$]	[$_1$]	[$_0$]	
(i) working on hobbies	[$_2$]	[$_1$]	[$_0$]	
(j) going to work..	[$_2$]	[$_1$]	[$_0$]	[Not applicable]

3

Appendix A (Continued)

Please *tick the box* that represents the extent to which you are satisfied or dissatisfied with *each* of the different aspects of your prosthesis mentioned below:

		Not satisfied	Satisfied	Very Satisfied
(i)	Colour.	[₁]	[₂]	[₃]
(ii)	Shape	[₁]	[₂]	[₃]
(iii)	Appearance	[₁]	[₂]	[₃]
(iv)	Weight	[₁]	[₂]	[₃]
(v)	Usefulness	[₁]	[₂]	[₃]
(vi)	Reliability	[₁]	[₂]	[₃]
(vii)	Fit	[₁]	[₂]	[₃]
(viii)	Comfort	[₁]	[₂]	[₃]

Please circle the number (0-10) that best describes how satisfied you are with your prosthesis?

0 1 2 3 4 5 6 7 8 9 10

Not at all Satisfied — Very Satisfied

4

Appendix A (Continued)

Part II

(For the following questions, please tick the appropriate boxes)

1. On average, how many hours a day do you wear your prosthesis? __________ **hours**

2. In general, would you say your health is:

Very Poor [1] Poor [2] Fair [3] Good [4] Very Good [5]

3. In general, would you say your physical capabilities are:

Very Poor [1] Poor [2] Fair [3] Good [4] Very Good [5]

4(a) Do you experience **residual limb (stump) pain** (pain in the remaining part of your amputated limb)?

No [0] .... (If no, go to question 5)

Yes [1] .... (If yes, answer part (b), (c), (d) and (e))

(b) During the last week, how many times have you experienced stump pain? __________

(c) How long, on average, did each episode of pain last? __________

(d) Please indicate, the average level of stump pain experienced during the last week on the scale below by ticking the appropriate box:

Excruciating	Horrible	Distressing	Discomforting	Mild
[5]	[4]	[3]	[2]	[1]

(e) How much did stump pain interfere with your normal lifestyle (eg. work, social and family activities) during the last week?

A Lot	Quite a Bit	Moderately	A Little Bit	Not at All
[5]	[4]	[3]	[2]	[1]

5

5. (a) Do you experience **phantom limb pain** (pain in the part of the limb which was amputated)?

No [$_0$] .... (if no, go to question 6)

Yes [$_1$] .... (If yes, answer part (b), (c), (d), and (e))

(b) During the last week, how many times have you experienced phantom limb pain? ___________

(c) How long, on average, did each episode of pain last? __________

(d) Please indicate the average level of phantom limb pain experienced during the last week on the scale below by ticking the appropriate box:

Excruciating	Horrible	Distressing	Discomforting	Mild
[$_5$]	[$_4$]	[$_3$]	[$_2$]	[$_1$]

(e) How much did phantom limb pain interfere with your normal lifestyle (e.g. work, social and family activities) during the last week?

A Lot	Quite a Bit	Moderately	A Little Bit	Not at All
[$_5$]	[$_4$]	[$_3$]	[$_2$]	[$_1$]

6. (a) Do you experience any **other medical problems** apart from stump pain or phantom limb pain?

No [$_0$]

Yes [$_1$] (If yes, answer part (b), (c), (d), (e),(f) and (g))

(b) Please specify what problems you experience ________________________________

(c) During the last week, how many times have you suffered from these medical problems? ___________

(d) How long, on average, did each problem last? __________

(e) Please indicate the level of pain experienced as a result of these problems during the last week on the scale below by ticking the appropriate box:

Excruciating	Horrible	Distressing	Discomforting	Mild
[$_5$]	[$_4$]	[$_3$]	[$_2$]	[$_1$]

6

Appendix A (Continued)

(f) How much did these medical problems interfere with your normal lifestyle (e.g. work, social and family activities) during the last week?

A Lot	Quite a Bit	Moderately	A Little Bit	Not at All
[5]	[4]	[3]	[2]	[1]

(g) Do you experience **any other pain** that you have not previously mentioned?

No [0]
Yes [1]
If yes, please specify ______________________________

7. Did you complete this questionnaire: (please tick the appropriate box)

on your own? [ ]
with assistance? [ ]

8. Date of Completion: ______________________

Please check that you have answered all the questions.
Thank you for all your help.

7

Appendix B: Matlab Code

B.1 SRiM.m

```
% Socket Model creation algorithm for the "Socket Residual Limb Interface Model" (SRiM)
% Written by Matthew M. Wernke 3/31/2011
% Requires the Robotics Toolbox (Peter Corke) and the c3d wrapper (Matthew
% R. Walker)

% Process the data for the No prosthesis trials

%Change cd to dissertation files
cd ('C:\Users\mwernke\Documents\MATLAB\Dissertation Files')

% Include c3d files at this location
path ([cd,'\SubFunctions'], path)
% Clear variables fADL the current workspace
clear all
% Close all open figure windows (plots)
close all

% Define the subject side of amputation to set up coordinate frames
% H01=R; H02=R; H03=L; H04=R; H05=R; H06=L; H07
amputation = 'R';

% Change directory to the ROMNP with NP folder of subjects(s)
cd ('C:\Users\mwernke\Documents\MATLAB\Dissertation Files\H07_DS\ROMNP')
% Load all of the *.c3d (motion trails) files
foldernfo = dir('*.c3d');
% Create the field for subject, in structure ROMNP, set the feild filenames
% to the names of the files in the folder.
ROMNP.filenames = char(foldernfo.name);
% Create a varible for the number of .c3d files in the folder
ROMNP.nfiles = size(ROMNP.filenames,1);

%Create empty arrays to be filled later with RoM data
ROMNP.RLMaxCompiled = [];
ROMNP.RLMinCompiled = [];
ROMNP.CLMaxCompiled = [];
ROMNP.CLMinCompiled = [];
ROMNP.RLThetaRoMCompiled = [];
ROMNP.CLThetaRoMCompiled = [];

% For all files in ROMNPNP of subject
for i=1:ROMNP.nfiles;
   % Load c3d server.
   newServer = c3dserver;
```

Appendix B (Continued)

```
% Open the c3d files
openc3d(newServer,0,ROMNP.filenames(i,:));
% Set variable name to name of current file
name = removewhite(ROMNP.filenames(i,:));
% Get all of the targets (makers) fROMNP the c3d server
newtarget = get3dtargets(newServer,1);
% Assign the targets to the trial feild
ROMNP.(name) = newtarget;
% Set the variable markers to all of the marker names
markers = fieldnames(ROMNP.(name));
% Set Nmarkers equal to the number of markers in the trial.
Nmarker = size(markers,1);
% Set Nsamples equal to the number of samples in the trial.
Nsamples = size(ROMNP.(name).T1,1);

% Filter the marker data
for j=1:Nmarker
   if ~strcmpi(markers(j), 'units')
      ROMNP.(name).(char(markers(j))) = ...
         WMAfilter(21,getfield(ROMNP.(name), char(markers(j)), {1:Nsamples,1:3}));
   end
end

% Create virtual points based on marker positions.
ROMNP.(name).UTOR = (ROMNP.(name).CLAV+ROMNP.(name).T1)/2;
ROMNP.(name).LTOR = (ROMNP.(name).STRN+ROMNP.(name).T10)/2;
ROMNP.(name).rSHO = (ROMNP.(name).RSHOA+ROMNP.(name).RSHOP)/2;
ROMNP.(name).lSHO = (ROMNP.(name).LSHOA+ROMNP.(name).LSHOP)/2;
ROMNP.(name).RSL = (ROMNP.(name).RSLA+ROMNP.(name).RSLP)/2;

% Create the segment frames that do not change using createSegment.m
ROMNP.(name).Torso = createSegment(ROMNP.(name).UTOR,(ROMNP.(name).UTOR-
ROMNP.(name).LTOR),(ROMNP.(name).T1-ROMNP.(name).CLAV), 'yzx');
ROMNP.(name).RShoulder = createSegment(ROMNP.(name).rSHO,(ROMNP.(name).rSHO-
ROMNP.(name).UTOR),(ROMNP.(name).RSHOA-ROMNP.(name).RSHOP), 'zyx');
ROMNP.(name).LShoulder = createSegment(ROMNP.(name).lSHO,(ROMNP.(name).lSHO-
ROMNP.(name).UTOR),(ROMNP.(name).LSHOP-ROMNP.(name).LSHOA), 'zyx');

% Create the segment frames that do change using createSegment.m
if amputation == 'R'
   ROMNP.(name).lELB = (ROMNP.(name).LELB+ROMNP.(name).LELBM)/2;
   ROMNP.(name).RLimb = createSegment(ROMNP.(name).rSHO,(ROMNP.(name).rSHO-
ROMNP.(name).RSL),(ROMNP.(name).RSLP-ROMNP.(name).RSLA), 'yzx');
   ROMNP.(name).LUArm = createSegment(ROMNP.(name).lSHO,(ROMNP.(name).lSHO-
ROMNP.(name).lELB),(ROMNP.(name).LELB-ROMNP.(name).LELBM), 'yxz');
```

Appendix B (Continued)

```
    else
        ROMNP.(name).rELB = (ROMNP.(name).RELB+ROMNP.(name).RELBM)/2;
        ROMNP.(name).RLimb = createSegment(ROMNP.(name).lSHO,(ROMNP.(name).lSHO-
ROMNP.(name).RSL),(ROMNP.(name).RSLA-ROMNP.(name).RSLP), 'yzx');
        ROMNP.(name).RUArm = createSegment(ROMNP.(name).rSHO,(ROMNP.(name).rSHO-
ROMNP.(name).rELB),(ROMNP.(name).RELB-ROMNP.(name).RELBM), 'yxz');
    end

    % Multiply the Homogeneous transfroms to find the transformation
    % matrices between segments
    for k=1:Nsamples
        ROMNP.(name).RShoMotion(:,:,k) = (ROMNP.(name).Torso.HT(:,:,k))^-
1*ROMNP.(name).RShoulder.HT(:,:,k);
        ROMNP.(name).LShoMotion(:,:,k) = (ROMNP.(name).Torso.HT(:,:,k))^-
1*ROMNP.(name).LShoulder.HT(:,:,k);
        if amputation == 'R'
            ROMNP.(name).RLMotion(:,:,k) = (ROMNP.(name).RShoulder.HT(:,:,k))^-
1*ROMNP.(name).RLimb.HT(:,:,k);
            ROMNP.(name).CLMotion(:,:,k) = (ROMNP.(name).LShoulder.HT(:,:,k))^-
1*ROMNP.(name).LUArm.HT(:,:,k);
        else
            ROMNP.(name).RLMotion(:,:,k) = (ROMNP.(name).LShoulder.HT(:,:,k))^-
1*ROMNP.(name).RLimb.HT(:,:,k);
            ROMNP.(name).CLMotion(:,:,k) = (ROMNP.(name).RShoulder.HT(:,:,k))^-
1*ROMNP.(name).RUArm.HT(:,:,k);
        end
    end

    %Use the transformation matrices to calculate the Euler angle rotations
    for k=1:Nsamples
        ROMNP.(name).RShoAngle(:,k) = findTheta('zxy',
ROMNP.(name).RShoMotion(1:3,1:3,k));
        ROMNP.(name).RShoRotation(:,k) = ROMNP.(name).RShoAngle(:,k).*(180/pi);
        ROMNP.(name).LShoAngle(:,k) = findTheta('zxy',
ROMNP.(name).LShoMotion(1:3,1:3,k));
        ROMNP.(name).LShoRotation(:,k) = ROMNP.(name).LShoAngle(:,k).*(180/pi);
        if amputation == 'R'
            ROMNP.(name).RLAngle(:,k) = findTheta('zxy', ROMNP.(name).RLMotion(1:3,1:3,k));
            ROMNP.(name).RLRotation(:,k) = ROMNP.(name).RLAngle(:,k).*(180/pi);
            ROMNP.(name).CLAngle(:,k) = findTheta('zxy', ROMNP.(name).CLMotion(1:3,1:3,k));
            ROMNP.(name).CLRotation(:,k) = ROMNP.(name).CLAngle(:,k).*(180/pi);
            ROMNP.(name).CLRotation(1,k) = ROMNP.(name).CLRotation(1,k).*-1;
            ROMNP.(name).CLRotation(3,k) = ROMNP.(name).CLRotation(3,k).*-1;
        else
            ROMNP.(name).RLAngle(:,k) = findTheta('zxy', ROMNP.(name).RLMotion(1:3,1:3,k));
```

```
        ROMNP.(name).RLRotation(:,k) = ROMNP.(name).RLAngle(:,k).*(180/pi);
        ROMNP.(name).RLRotation(1,k) = ROMNP.(name).RLRotation(1,k).*-1;
        ROMNP.(name).RLRotation(3,k) = ROMNP.(name).RLRotation(3,k).*-1;
        ROMNP.(name).CLAngle(:,k) = findTheta('zxy', ROMNP.(name).CLMotion(1:3,1:3,k));
        ROMNP.(name).CLRotation(:,k) = ROMNP.(name).CLAngle(:,k).*(180/pi);
    end
end

%Find the maximum and minimum values
if amputation == 'R'
    ROMNP.(name).RLMax = max(ROMNP.(name).RLRotation,[],2);
    ROMNP.(name).RLMin = min(ROMNP.(name).RLRotation,[],2);
    ROMNP.(name).CLMax = max(ROMNP.(name).CLRotation,[],2);
    ROMNP.(name).CLMin = min(ROMNP.(name).CLRotation,[],2);
else
    ROMNP.(name).RLMax = max(ROMNP.(name).RLRotation,[],2);
    ROMNP.(name).RLMin = min(ROMNP.(name).RLRotation,[],2);
    ROMNP.(name).CLMax = max(ROMNP.(name).CLRotation,[],2);
    ROMNP.(name).CLMin = min(ROMNP.(name).CLRotation,[],2);
end

% Equivalent axis rotation calculation
ROMNP.(name).RLTheta(:,:) =
(acos((ROMNP.(name).RLMotion(1,1,:)+ROMNP.(name).RLMotion(2,2,:)+ROMNP.(name).R
LMotion(3,3,:)-1)/2))*(180/pi);
ROMNP.(name).CLTheta(:,:) =
(acos((ROMNP.(name).CLMotion(1,1,:)+ROMNP.(name).CLMotion(2,2,:)+ROMNP.(name).C
LMotion(3,3,:)-1)/2))*(180/pi);

ROMNP.(name).time = cumsum(ones(Nsamples,1))/120;

ROMNP.(name).RLThetaRoM(:,:) = max(ROMNP.(name).RLTheta,[],1)-
min(ROMNP.(name).RLTheta,[],1);
ROMNP.(name).CLThetaRoM(:,:) = max(ROMNP.(name).CLTheta,[],1)-
min(ROMNP.(name).CLTheta,[],1);

if ~strcmp('Static', name)
    ROMNP.RLMaxCompiled = [ROMNP.RLMaxCompiled, ROMNP.(name).RLMax];
    ROMNP.RLMinCompiled = [ROMNP.RLMinCompiled, ROMNP.(name).RLMin];
    ROMNP.CLMaxCompiled = [ROMNP.CLMaxCompiled, ROMNP.(name).CLMax];
    ROMNP.CLMinCompiled = [ROMNP.CLMinCompiled, ROMNP.(name).CLMin];
    ROMNP.RLThetaRoMCompiled = [ROMNP.RLThetaRoMCompiled,
ROMNP.(name).RLThetaRoM];
    ROMNP.CLThetaRoMCompiled = [ROMNP.CLThetaRoMCompiled,
ROMNP.(name).CLThetaRoM];
```

```
    end
end

%%
%Change cd to dissertation files
cd ('C:\Users\mwernke\Documents\MATLAB\Dissertation Files')
% Include c3d files at this location
path ([cd,'\SubFunctions'], path)

% Define the subjects side of amputation to set up coordinate frames
amputation = 'R';

% Change directory to the ROM with NP folder of subjects(s)
cd ('C:\Users\mwernke\Documents\MATLAB\Dissertation Files\H07_DS\OriginalArm')
% Load all of the *.c3d (motion trails) files
foldernfo = dir('*.c3d');
% Create the field for subject, in structure Original, set the feild filenames
% to the names of the files in the folder.
Original.filenames = char(foldernfo.name);
% Create a varible for the number of .c3d files in the folder
Original.nfiles = size(Original.filenames,1);

%Create empty arrays to be filled later with RoM data
Original.RLMaxCompiled = [];
Original.RLMinCompiled = [];
Original.RLThetaMaxCompiled = [];
Original.RLThetaMinCompiled = [];
Original.SCKMaxCompiled = [];
Original.SCKMinCompiled = [];
Original.SCKTRANMaxCompiled = [];
Original.SCKTRANMinCompiled = [];
Original.SCKThetaMaxCompiled = [];
Original.SCKThetaMinCompiled = [];

% For all files in Original of subject
for i=1:Original.nfiles;
    % Load c3d server.
    newServer = c3dserver;
    % Open the c3d files
    openc3d(newServer,0,Original.filenames(i,:));
    % Set variable name to name of current file
    name = removewhite(Original.filenames(i,:));
    % Get all of the targets (makers) from the c3d server
    newtarget = get3dtargets(newServer,1);
    % Assign the targets to the trial field
```

Appendix B (Continued)

```
    Original.(name) = newtarget;
    % Set the variable markers to all of the marker names
    markers = fieldnames(Original.(name));
    % Set Nmarkers equal to the number of markers in the trial.
    Nmarker = size(markers,1);
    % Set Nsamples equal to the number of samples in the trial.
    Nsamples = size(Original.(name).T1,1);

    % Filter the marker data
    for j=1:Nmarker
        if ~strcmpi(markers(j), 'units')
            Original.(name).(char(markers(j))) = ...
                WMAfilter(21,getfield(Original.(name), char(markers(j)), {1:Nsamples,1:3}));
        end
    end
    %if the RELBM marker is missing, create an empty array the size of another
    %marker so that the missing RELBM marker can be reconrtucte
    if ~isfield(Original.(name), 'RELBM')
        Original.(name).RELBM = nan(size(Original.(name).LBAK));
    end
end

% Define Static postions for cluster reconstruction of the torso
Original.Static.UTOR = (Original.Static.CLAV+Original.Static.T1)/2;
Original.Static.LTOR = (Original.Static.STRN+Original.Static.T10)/2;
Original.Static.Torso = createSegment(Original.Static.UTOR,(Original.Static.UTOR-
Original.Static.LTOR),(Original.Static.T1-Original.Static.CLAV), 'yzx');
Original.Static.Torso = addPoint2(Original.Static.Torso, Original.Static.CLAV);
Original.Static.Torso = addPoint2(Original.Static.Torso, Original.Static.STRN);
Original.Static.Torso = addPoint2(Original.Static.Torso, Original.Static.T1);
Original.Static.Torso = addPoint2(Original.Static.Torso, Original.Static.T10);
Original.Static.Torso = addPoint2(Original.Static.Torso, Original.Static.LBAK);
% Calculate the mean relative position of pelvis markers (for cluster reconstruction).
Original.X(:,:) = nanmean(Original.Static.Torso.Point);

% Define Static positions for cluster reconstruction of the socket
if amputation == 'R'
    Original.Static.SCKT = (Original.Static.SCKA+Original.Static.SCKP)/2;
    Original.Static.ELBR = (Original.Static.RELB+Original.Static.RELBM)/2;
    Original.Static.Socket = createSegment(Original.Static.SCKT,(Original.Static.SCKT-
Original.Static.ELBR),(Original.Static.SCKP-Original.Static.SCKA), 'yzx');
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.SCKA);
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.SCKP);
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.SCKL);
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.RELB);
```

```
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.RELBM);
else
    Original.Static.SCKT = (Original.Static.SCKA+Original.Static.SCKP)/2;
    Original.Static.ELBL = (Original.Static.LELB+Original.Static.LELBM)/2;
    Original.Static.Socket = createSegment(Original.Static.SCKT,(Original.Static.SCKT-
Original.Static.ELBL),(Original.Static.SCKP-Original.Static.SCKA), 'yzx');
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.SCKA);
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.SCKP);
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.SCKL);
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.LELB);
    Original.Static.Socket = addPoint2(Original.Static.Socket, Original.Static.LELBM);
end
% Calculate the mean relative position of pelvis markers (for cluster reconstruction).
Original.SX(:,:) = nanmean(Original.Static.Socket.Point);

% Define Static positions for cluster reconstruction of the socket
if amputation == 'R'
    Original.Static.RWR = (Original.Static.RWRA+Original.Static.RWRB)/2;
    Original.Static.ELBR = (Original.Static.RELB+Original.Static.RELBM)/2;
    Original.Static.Forearm = createSegment(Original.Static.ELBR,(Original.Static.ELBR-
Original.Static.RWR),(Original.Static.RELB-Original.Static.RELBM), 'yzx');
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.RWRA);
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.RWRB);
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.RFIN);
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.RELB);
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.RELBM);
else
    Original.Static.LWR = (Original.Static.LWRA+Original.Static.LWRB)/2;
    Original.Static.ELBL = (Original.Static.LELB+Original.Static.LELBM)/2;
    Original.Static.Forearm = createSegment(Original.Static.ELBL,(Original.Static.ELBL-
Original.Static.LWR),(Original.Static.LELB-Original.Static.LELBM), 'yzx');
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.LWRA);
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.LWRB);
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.LFIN);
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.LELB);
    Original.Static.Forearm = addPoint2(Original.Static.Forearm, Original.Static.LELBM);
end
% Calculate the mean relative position of pelvis markers (for cluster reconstruction).
Original.FX(:,:) = nanmean(Original.Static.Forearm.Point);

for i=1:Original.nfiles;
    % Set variable name to name of current file
    name = removewhite(Original.filenames(i,:));
```

Appendix B (Continued)

```
    [Original.(name).CLAV, Original.(name).STRN,  Original.(name).T1, Original.(name).T10] = ...
        clusterReconstruct(Original.X, Original.(name).CLAV, Original.(name).STRN, Original.(name).T1, Original.(name).T10, Original.(name).LBAK);

    if amputation == 'R'
        [Original.(name).SCKA, Original.(name).SCKP,  Original.(name).SCKL, Original.(name).RELB] = ...
            clusterReconstruct(Original.SX, Original.(name).SCKA, Original.(name).SCKP, Original.(name).SCKL, Original.(name).RELB, Original.(name).RELBM);
    else
        [Original.(name).SCKA, Original.(name).SCKP,  Original.(name).SCKL, Original.(name).LELB] = ...
            clusterReconstruct(Original.SX, Original.(name).SCKA, Original.(name).SCKP, Original.(name).SCKL, Original.(name).LELB, Original.(name).LELBM);
    end

    if amputation == 'R'
        [Original.(name).RELB, Original.(name).RELBM,  Original.(name).RWRA, Original.(name).RWRB] = ...
            clusterReconstruct(Original.FX, Original.(name).RELB, Original.(name).RELBM, Original.(name).RWRA, Original.(name).RWRB, Original.(name).RFIN);
    else
        [Original.(name).LELB, Original.(name).LELBM,  Original.(name).LWRA, Original.(name).LWRB] = ...
            clusterReconstruct(Original.FX, Original.(name).LELB, Original.(name).LELBM, Original.(name).LWRA, Original.(name).LWRB, Original.(name).LFIN);
    end



    %OFFSETS NEED TO BE CHANGED FOR EACH SUBJECT AS FOLLOWS:
    %H01_LS: RL Length = 220mm;    SCKOffset = 180mm
    %H02_RC: RL Length = 260mm;    SCKOffset = 150mm
    %H03_MA: RL Length = 420mm;    SCKOffset = 150mm
    %H04_RG_NP: RL Length = 310mm;    SCKOffset = 150mm
    %H05_RG_WP: RL Length = 310mm;    SCKOffset = 150mm
    %H06_JW: RL Length = 230mm;    SCKOffset = 150mm
    %H07_DS: RL Length = 350mm;    SCKOffset = 150mm

    %Define residual limb length; used to calculate virtual point of RL
    Original.(name).RLLength = ones(size(Original.(name).T1,1),1)*220;

    %Define offset for how far SCK markers are from trim lines
    Original.(name).SCKMarkerOffset = ones(size(Original.(name).T1,1),1)*180;
```

Appendix B (Continued)

```
    % Create virtual points based on marker positions.
    % Calcualte Pelvis, Shoulders, Residual Limb, Socket, Elbow and Wrist center points
    Original.(name).UTOR = (Original.(name).CLAV+Original.(name).T1)/2;
    Original.(name).LTOR = (Original.(name).STRN+Original.(name).T10)/2;
    Original.(name).rSHO = (Original.(name).RSHOA+Original.(name).RSHOP)/2;
    Original.(name).lSHO = (Original.(name).LSHOA+Original.(name).LSHOP)/2;
    Original.(name).SCKT = (Original.(name).SCKA+Original.(name).SCKP)/2;

    %Create the segment frames that do not change using createSegment.m
    Original.(name).Torso = createSegment(Original.(name).UTOR,(Original.(name).UTOR-
Original.(name).LTOR),(Original.(name).T1-Original.(name).CLAV), 'yzx');
    Original.(name).RShoulder = createSegment(Original.(name).rSHO,(Original.(name).rSHO-
Original.(name).UTOR),(Original.(name).RSHOA-Original.(name).RSHOP), 'zyx');
    Original.(name).LShoulder = createSegment(Original.(name).lSHO,(Original.(name).lSHO-
Original.(name).UTOR),(Original.(name).LSHOP-Original.(name).LSHOA), 'zyx');

    % Create the segment frames that do change using createSegment.m
    if amputation == 'R'
        Original.(name).ELBR = (Original.(name).RELB+Original.(name).RELBM)/2;
        Original.(name).RWR = (Original.(name).RWRA+Original.(name).RWRB)/2;
        Original.(name).RLimb = createSegment(Original.(name).rSHO,(Original.(name).rSHO-
Original.(name).ELBR),(Original.(name).SCKP-Original.(name).SCKA), 'yzx');
        Original.(name).SCK = createSegment(Original.(name).SCKT, (Original.(name).SCKT-
Original.(name).ELBR), (Original.(name).SCKP-Original.(name).SCKA), 'yzx');
        Original.(name).FARM = createSegment(Original.(name).ELBR, (Original.(name).ELBR-
Original.(name).RWR), (Original.(name).SCK.Zaxis), 'yxz');
    else
        Original.(name).ELBL = (Original.(name).LELB+Original.(name).LELBM)/2;
        Original.(name).LWR = (Original.(name).LWRA+Original.(name).LWRB)/2;
        Original.(name).RLimb = createSegment(Original.(name).lSHO,(Original.(name).lSHO-
Original.(name).ELBL),(Original.(name).SCKA-Original.(name).SCKP), 'yzx');
        Original.(name).SCK = createSegment(Original.(name).SCKT, (Original.(name).SCKT-
Original.(name).ELBL), (Original.(name).SCKA-Original.(name).SCKP), 'yzx');
        Original.(name).FARM = createSegment(Original.(name).ELBL, (Original.(name).ELBL-
Original.(name).LWR), (Original.(name).SCK.Zaxis), 'yxz');
    end

    % Calculate Motion of the Residual limb, Socket, and Forearm
    for k=1:size(Original.(name).T1,1);
        if amputation == 'R'
            Original.(name).RShoMotion(:,:,k) = (Original.(name).Torso.HT(:,:,k))^-
1*Original.(name).RShoulder.HT(:,:,k);
            Original.(name).RLMotion2(:,:,k) = (Original.(name).RShoulder.HT(:,:,k))^-
1*Original.(name).RLimb.HT(:,:,k);
        else
```

Appendix B (Continued)

```
            Original.(name).LShoMotion(:,:,k) = (Original.(name).Torso.HT(:,:,k))^-
1*Original.(name).LShoulder.HT(:,:,k);
            Original.(name).RLMotion2(:,:,k) = (Original.(name).LShoulder.HT(:,:,k))^-
1*Original.(name).RLimb.HT(:,:,k);
        end
        Original.(name).SCKMotion2(:,:,k) = (Original.(name).RLimb.HT(:,:,k))^-
1*Original.(name).SCK.HT(:,:,k);
        Original.(name).SCKMarkDist(:,k) =
sqrt(Original.(name).SCKMotion2(1,4,k)^2+Original.(name).SCKMotion2(2,4,k)^2+Original.(n
ame).SCKMotion2(3,4,k)^2);

        Original.(name).ELBMotion(:,:,k) = (Original.(name).SCK.HT(:,:,k))^-
1*Original.(name).FARM.HT(:,:,k);
    end

    %Caluclate the amount of bone inside the socket and find center point
    Original.(name).BoneInCenter = (Original.(name).RLLength -
(Original.(name).SCKMarkDist'-Original.(name).SCKMarkerOffset))/2;

    % Create new point to represent RL bone position
    for k=1:size(Original.(name).T1,1);
        Original.(name).RLBone(k,:) = Original.(name).SCK.HT(1:3,:,k)*([0;
Original.(name).SCKMarkerOffset(k) - Original.(name).BoneInCenter(k); 0; 1]);
    end

    % Create segment for residual limb bone posistion
    if amputation == 'R'
        Original.(name).ResidualBone =
createSegment(Original.(name).rSHO,(Original.(name).rSHO-Original.(name).RLBone),(-
Original.(name).SCK.Xaxis), 'yzx');
    else
        Original.(name).ResidualBone =
createSegment(Original.(name).lSHO,(Original.(name).lSHO-Original.(name).RLBone),(-
Original.(name).SCK.Xaxis), 'yzx');
    end

    % Calculate Motion of the Residual limb using new bone position
    for k=1:size(Original.(name).T1,1);
        if amputation == 'R'
            Original.(name).RLMotion(:,:,k) = (Original.(name).RShoulder.HT(:,:,k))^-
1*Original.(name).ResidualBone.HT(:,:,k);
        else
            Original.(name).RLMotion(:,:,k) = (Original.(name).LShoulder.HT(:,:,k))^-
1*Original.(name).ResidualBone.HT(:,:,k);
        end
```

Appendix B (Continued)

```
        Original.(name).SCKMotion(:,:,k) = (Original.(name).ResidualBone.HT(:,:,k))^-
1*Original.(name).SCK.HT(:,:,k);
    end

    % Calculate Angles for Residual limb, Socket, and Elbow as well as the
    % translation of the socket
    for k=1:size(Original.(name).T1,1);
        if amputation == 'R'
            Original.(name).RShoAngle(:,k) = findTheta('zxy',
Original.(name).RShoMotion(1:3,1:3,k));
            Original.(name).RShoRotation(:,k) = Original.(name).RShoAngle(:,k).*(180/pi);
        else
            Original.(name).LShoAngle(:,k) = findTheta('zxy',
Original.(name).LShoMotion(1:3,1:3,k));
            Original.(name).LShoRotation(:,k) = Original.(name).LShoAngle(:,k).*(180/pi);
        end

        Original.(name).RLAngle(:,k) = findTheta('zxy', Original.(name).RLMotion(1:3,1:3,k));
        Original.(name).RLRotation(:,k) = Original.(name).RLAngle(:,k).*(180/pi);

        if ~(amputation == 'R')
            Original.(name).RLRotation(1,k) = Original.(name).RLRotation(1,k).*-1;
            Original.(name).RLRotation(3,k) = Original.(name).RLRotation(3,k).*-1;
        end

        Original.(name).SCKTranslation(:,k) = Original.(name).SCKMotion(2,4,k)-
nanmean(Original.(name).SCKMotion(2,4,1:5),3);
        Original.(name).SCKAngle(:,k) = findTheta('zxy', Original.(name).SCKMotion(1:3,1:3,k));
        Original.(name).SCKRotation(:,k) = Original.(name).SCKAngle(:,k).*(180/pi)-
Original.(name).SCKAngle(:,1).*(180/pi);

        Original.(name).ELBAngle(:,k) = findTheta('zxy', Original.(name).ELBMotion(1:3,1:3,k));
        Original.(name).ELBRotation(:,k) = Original.(name).ELBAngle(:,k).*(180/pi)-
Original.(name).ELBAngle(:,1).*(180/pi);

        if ~(amputation == 'R')
            Original.(name).SCKRotation(1,k) = Original.(name).SCKRotation(1,k).*-1;
            Original.(name).SCKRotation(3,k) = Original.(name).SCKRotation(3,k).*-1;
        end

        % Equivalent axis rotation calculation
        Original.(name).RLTheta(:,:) =
(acos((Original.(name).RLMotion(1,1,:)+Original.(name).RLMotion(2,2,:)+Original.(name).RL
Motion(3,3,:)-1)/2))*(180/pi);
```

Appendix B (Continued)

```
        Original.(name).SCKTheta(:,:) = 
(acos((Original.(name).SCKMotion(1,1,:)+Original.(name).SCKMotion(2,2,:)+Original.(name).
SCKMotion(3,3,:)-1)/2))*(180/pi);
        Original.(name).ELBTheta(:,:) = 
(acos((Original.(name).ELBMotion(1,1,:)+Original.(name).ELBMotion(2,2,:)+Original.(name).
ELBMotion(3,3,:)-1)/2))*(180/pi);
    end

    %Find the maximum and minimum values
    Original.(name).RLMax = max(Original.(name).RLRotation,[],2);
    Original.(name).RLMin = min(Original.(name).RLRotation,[],2);
    Original.(name).RLThetaMax = max(Original.(name).RLTheta,[],1);
    Original.(name).RLThetaMin = min(Original.(name).RLTheta,[],1);
    Original.(name).SCKMax = max(Original.(name).SCKRotation,[],2);
    Original.(name).SCKMin = min(Original.(name).SCKRotation,[],2);
    Original.(name).SCKTRANMax = max(Original.(name).SCKTranslation,[],2);
    Original.(name).SCKTRANMin = min(Original.(name).SCKTranslation,[],2);
    Original.(name).SCKThetaMax = max(Original.(name).SCKTheta,[],1);
    Original.(name).SCKThetaMin = min(Original.(name).SCKTheta,[],1);

    Original.(name).time = cumsum(ones(Nsamples,1))/120;

    %Compile the data for export into Excel
    if ~strcmp('Static', name)
        Original.RLMaxCompiled =  [Original.RLMaxCompiled, Original.(name).RLMax];
        Original.RLMinCompiled =  [Original.RLMinCompiled, Original.(name).RLMin];
        Original.RLThetaMaxCompiled = [Original.RLThetaMaxCompiled, 
Original.(name).RLThetaMax];
        Original.RLThetaMinCompiled = [Original.RLThetaMinCompiled, 
Original.(name).RLThetaMin];
        Original.SCKMaxCompiled = [Original.SCKMaxCompiled, Original.(name).SCKMax];
        Original.SCKMinCompiled = [Original.SCKMinCompiled, Original.(name).SCKMin];
        Original.SCKTRANMaxCompiled = [Original.SCKTRANMaxCompiled, 
Original.(name).SCKTRANMax];
        Original.SCKTRANMinCompiled = [Original.SCKTRANMinCompiled, 
Original.(name).SCKTRANMin];
        Original.SCKThetaMaxCompiled = [Original.SCKThetaMaxCompiled, 
Original.(name).SCKThetaMax];
        Original.SCKThetaMinCompiled = [Original.SCKThetaMinCompiled, 
Original.(name).SCKThetaMin];
    end
end

%Find the range of motion based off the max and min values
Original.RLRoM = Original.RLMaxCompiled - Original.RLMinCompiled;
```

Appendix B (Continued)

```
Original.RLThetaRoM = Original.RLThetaMaxCompiled - Original.RLThetaMinCompiled;
Original.SCKRoM = Original.SCKMaxCompiled - Original.SCKMinCompiled;
Original.SCKTRANRoM = Original.SCKTRANMaxCompiled -
Original.SCKTRANMinCompiled;
Original.SCKThetaRoM = Original.SCKThetaMaxCompiled -
Original.SCKThetaMinCompiled;

%%
%Change cd to dissertation files
cd ('C:\Users\mwernke\Documents\MATLAB\Dissertation Files')
% Include c3d files at this location
path ([cd,'\SubFunctions'], path)

% Define the subjects side of amputation to set up coordinate frames
amputation = 'R';

% Change directory to the ROM with NP folder of subjects(s)
cd ('C:\Users\mwernke\Documents\MATLAB\Dissertation Files\H07_DS\SensorArm')
% Load all of the *.c3d (motion trails) files
foldernfo = dir('*.c3d');
% Create the field for subject, in structure Sensor, set the feild filenames
% to the names of the files in the folder.
Sensor.filenames = char(foldernfo.name);
% Create a varible for the number of .c3d files in the folder
Sensor.nfiles = size(Sensor.filenames,1);

%Create empty arrays to be filled later with RoM data
Sensor.RLMaxCompiled = [];
Sensor.RLMinCompiled = [];
Sensor.RLThetaMaxCompiled = [];
Sensor.RLThetaMinCompiled = [];
Sensor.SCKMaxCompiled = [];
Sensor.SCKMinCompiled = [];
Sensor.SCKTRANMaxCompiled = [];
Sensor.SCKTRANMinCompiled = [];
Sensor.SCKThetaMaxCompiled = [];
Sensor.SCKThetaMinCompiled = [];
Sensor.MouseMaxCompiled = [];
Sensor.MouseMinCompiled = [];

% For all files in Sensor of subject
for i=1:Sensor.nfiles;
    % Load c3d server.
    newServer = c3dserver;
    % Open the c3d files
```

```
    openc3d(newServer,0,Sensor.filenames(i,:));
    % Set variable name to name of current file
    name = removewhite(Sensor.filenames(i,:));
    % Get all of the targets (makers) from the c3d server
    newtarget = get3dtargets(newServer,1);
    % Assign the targets to the trial feild
    Sensor.(name) = newtarget;
    % Set the variable markers to all of the marker names
    markers = fieldnames(Sensor.(name));
    % Set Nmarkers equal to the number of markers in the trial.
    Nmarker = size(markers,1);
    % Set Nsamples equal to the number of samples in the trial.
    Nsamples = size(Sensor.(name).LBAK,1);

    % Filter the marker data
    for j=1:Nmarker
        if ~strcmpi(markers(j), 'units')
            Sensor.(name).(char(markers(j))) = ...
                WMAfilter(21,getfield(Sensor.(name), char(markers(j)), {1:Nsamples,1:3}));
        end
    end
    %if the T1 marker is missing, create an empty array the size of another
    %marker so that the missing T1 marker can be reconrtucted
    if ~isfield(Sensor.(name), 'T1')
        Sensor.(name).T1 = nan(size(Sensor.(name).LBAK));
    end
end

% Define Static postions for cluster reconstruction of the torso
Sensor.Static.UTOR = (Sensor.Static.CLAV+Sensor.Static.T1)/2;
Sensor.Static.LTOR = (Sensor.Static.STRN+Sensor.Static.T10)/2;
Sensor.Static.Torso = createSegment(Sensor.Static.UTOR,(Sensor.Static.UTOR-
Sensor.Static.LTOR),(Sensor.Static.T1-Sensor.Static.CLAV), 'yzx');
Sensor.Static.Torso = addPoint2(Sensor.Static.Torso, Sensor.Static.CLAV);
Sensor.Static.Torso = addPoint2(Sensor.Static.Torso, Sensor.Static.STRN);
Sensor.Static.Torso = addPoint2(Sensor.Static.Torso, Sensor.Static.T1);
Sensor.Static.Torso = addPoint2(Sensor.Static.Torso, Sensor.Static.T10);
Sensor.Static.Torso = addPoint2(Sensor.Static.Torso, Sensor.Static.LBAK);
% Calculate the mean relative position of pelvis markers (for cluster reconstruction).
Sensor.X(:,:) = nanmean(Sensor.Static.Torso.Point);

% Define Static positions for cluster reconstruction of the socket
if amputation == 'R'
    Sensor.Static.SCKT = (Sensor.Static.SCKA+Sensor.Static.SCKP)/2;
    Sensor.Static.ELBR = (Sensor.Static.RELB+Sensor.Static.RELBM)/2;
```

Appendix B (Continued)

```
   Sensor.Static.Socket = createSegment(Sensor.Static.SCKT,(Sensor.Static.SCKT-
Sensor.Static.ELBR),(Sensor.Static.SCKP-Sensor.Static.SCKA), 'yzx');
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.SCKA);
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.SCKP);
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.SCKL);
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.RELB);
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.RELBM);
else
   Sensor.Static.SCKT = (Sensor.Static.SCKA+Sensor.Static.SCKP)/2;
   Sensor.Static.ELBL = (Sensor.Static.LELB+Sensor.Static.LELBM)/2;
   Sensor.Static.Socket = createSegment(Sensor.Static.SCKT,(Sensor.Static.SCKT-
Sensor.Static.ELBL),(Sensor.Static.SCKP-Sensor.Static.SCKA), 'yzx');
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.SCKA);
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.SCKP);
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.SCKL);
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.LELB);
   Sensor.Static.Socket = addPoint2(Sensor.Static.Socket, Sensor.Static.LELBM);
end
% Calculate the mean relative position of pelvis markers (for cluster reconstruction).
Sensor.Z(:,:) = nanmean(Sensor.Static.Socket.Point);

for i=1:Sensor.nfiles;
   % Set variable name to name of current file
   name = removewhite(Sensor.filenames(i,:));

   [Sensor.(name).CLAV, Sensor.(name).STRN,  Sensor.(name).T1, Sensor.(name).T10] = ...
      clusterReconstruct(Sensor.X, Sensor.(name).CLAV, Sensor.(name).STRN,
Sensor.(name).T1, Sensor.(name).T10, Sensor.(name).LBAK);

   if amputation == 'R'
      [Sensor.(name).SCKA, Sensor.(name).SCKP,  Sensor.(name).SCKL, Sensor.(name).RELB]
= ...
         clusterReconstruct(Sensor.Z, Sensor.(name).SCKA, Sensor.(name).SCKP,
Sensor.(name).SCKL, Sensor.(name).RELB, Sensor.(name).RELBM);
   else
      [Sensor.(name).SCKA, Sensor.(name).SCKP,  Sensor.(name).SCKL, Sensor.(name).LELB]
= ...
         clusterReconstruct(Sensor.Z, Sensor.(name).SCKA, Sensor.(name).SCKP,
Sensor.(name).SCKL, Sensor.(name).LELB, Sensor.(name).LELBM);
   end

   %OFFSETS NEED TO BE CHANGED FOR EACH SUBJECT AS FOLLOWS:
   %H01_LS: RL Length = 220mm;    SCKOffset = Sensor 110mm
   %H02_RC: RL Length = 260mm;    SCKOffset = 150mm
   %H03_MA: RL Length = 420mm;    SCKOffset = 150mm
```

Appendix B (Continued)

```
   %H04_RG_NP: RL Length = 310mm;    SCKOffset = 150mm
   %H05_RG_WP: RL Length = 310mm;    SCKOffset = 150mm
   %H06_JW: RL Length = 230mm;    SCKOffset = 150mm
   %H07_DS: RL Length = 350mm;    SCKOffset = 150mm

   %Define residual limb length; used to calculate virtual point of RL
   Sensor.(name).RLLength = ones(size(Sensor.(name).T1,1),1)*310;

   %Define offset for how far SCK markers are from trim lines
   Sensor.(name).SCKMarkerOffset = ones(size(Sensor.(name).T1,1),1)*150;

   % Create virtual points based on marker positions.
   % Calcualte Pelvis, Shoulders, Residual Limb, Socket, Elbow and Wrist center points
   Sensor.(name).UTOR = (Sensor.(name).CLAV+Sensor.(name).T1)/2;
   Sensor.(name).LTOR = (Sensor.(name).STRN+Sensor.(name).T10)/2;
   Sensor.(name).rSHO = (Sensor.(name).RSHOA+Sensor.(name).RSHOP)/2;
   Sensor.(name).lSHO = (Sensor.(name).LSHOA+Sensor.(name).LSHOP)/2;
   Sensor.(name).SCKT = (Sensor.(name).SCKA+Sensor.(name).SCKP)/2;

   %Create the segment frames that do not change using createSegment.m
   Sensor.(name).Torso = createSegment(Sensor.(name).UTOR,(Sensor.(name).UTOR-
Sensor.(name).LTOR),(Sensor.(name).T1-Sensor.(name).CLAV), 'yzx');
   Sensor.(name).RShoulder = createSegment(Sensor.(name).rSHO,(Sensor.(name).rSHO-
Sensor.(name).UTOR),(Sensor.(name).RSHOA-Sensor.(name).RSHOP), 'zyx');
   Sensor.(name).LShoulder = createSegment(Sensor.(name).lSHO,(Sensor.(name).lSHO-
Sensor.(name).UTOR),(Sensor.(name).LSHOP-Sensor.(name).LSHOA), 'zyx');

   % Create the segment frames that do change using createSegment.m
   if amputation == 'R'
      Sensor.(name).ELBR = (Sensor.(name).RELB+Sensor.(name).RELBM)/2;
      Sensor.(name).RWR = (Sensor.(name).RWRA+Sensor.(name).RWRB)/2;
      Sensor.(name).RLimb = createSegment(Sensor.(name).rSHO,(Sensor.(name).rSHO-
Sensor.(name).ELBR),(Sensor.(name).SCKP-Sensor.(name).SCKA), 'yzx');
      Sensor.(name).SCK = createSegment(Sensor.(name).SCKT, (Sensor.(name).SCKT-
Sensor.(name).ELBR), (Sensor.(name).SCKP-Sensor.(name).SCKA), 'yzx');
      Sensor.(name).FARM = createSegment(Sensor.(name).ELBR, (Sensor.(name).ELBR-
Sensor.(name).RWR), (Sensor.(name).SCK.Zaxis), 'yxz');
   else
      Sensor.(name).ELBL = (Sensor.(name).LELB+Sensor.(name).LELBM)/2;
      Sensor.(name).LWR = (Sensor.(name).LWRA+Sensor.(name).LWRB)/2;
      Sensor.(name).RLimb = createSegment(Sensor.(name).lSHO,(Sensor.(name).lSHO-
Sensor.(name).ELBL),(Sensor.(name).SCKA-Sensor.(name).SCKP), 'yzx');
      Sensor.(name).SCK = createSegment(Sensor.(name).SCKT, (Sensor.(name).SCKT-
Sensor.(name).ELBL), (Sensor.(name).SCKA-Sensor.(name).SCKP), 'yzx');
```

Appendix B (Continued)

```
        Sensor.(name).FARM = createSegment(Sensor.(name).ELBL, (Sensor.(name).ELBL-
Sensor.(name).LWR), (Sensor.(name).SCK.Zaxis), 'yxz');
    end

    % Calculate Motion of the Residual limb, Socket, and Forearm
    for k=1:size(Sensor.(name).T1,1);
        if amputation == 'R'
            Sensor.(name).RShoMotion(:,:,k) = (Sensor.(name).Torso.HT(:,:,k))^-
1*Sensor.(name).RShoulder.HT(:,:,k);
            Sensor.(name).RLMotion2(:,:,k) = (Sensor.(name).RShoulder.HT(:,:,k))^-
1*Sensor.(name).RLimb.HT(:,:,k);
        else
            Sensor.(name).LShoMotion(:,:,k) = (Sensor.(name).Torso.HT(:,:,k))^-
1*Sensor.(name).LShoulder.HT(:,:,k);
            Sensor.(name).RLMotion2(:,:,k) = (Sensor.(name).LShoulder.HT(:,:,k))^-
1*Sensor.(name).RLimb.HT(:,:,k);
        end
        Sensor.(name).SCKMotion2(:,:,k) = (Sensor.(name).RLimb.HT(:,:,k))^-
1*Sensor.(name).SCK.HT(:,:,k);
        Sensor.(name).SCKMarkDist(:,k) =
sqrt(Sensor.(name).SCKMotion2(1,4,k)^2+Sensor.(name).SCKMotion2(2,4,k)^2+Sensor.(name)
.SCKMotion2(3,4,k)^2);

        Sensor.(name).ELBMotion(:,:,k) = (Sensor.(name).SCK.HT(:,:,k))^-
1*Sensor.(name).FARM.HT(:,:,k);
    end

    %Caluclate the amount of bone inside the socket and find center point
    Sensor.(name).BoneInCenter = (Sensor.(name).RLLength - (Sensor.(name).SCKMarkDist'-
Sensor.(name).SCKMarkerOffset))/2;

    % Create new point to represent RL bone position
    for k=1:size(Sensor.(name).T1,1);
        Sensor.(name).RLBone(k,:) = Sensor.(name).SCK.HT(1:3,:,k)*([0;
Sensor.(name).SCKMarkerOffset(k) - Sensor.(name).BoneInCenter(k); 0; 1]);
    end

    % Create segment fo residual limb bone posistion
    if amputation == 'R'
        Sensor.(name).ResidualBone = createSegment(Sensor.(name).rSHO,(Sensor.(name).rSHO-
Sensor.(name).RLBone),(-Sensor.(name).SCK.Xaxis), 'yzx');
    else
        Sensor.(name).ResidualBone = createSegment(Sensor.(name).lSHO,(Sensor.(name).lSHO-
Sensor.(name).RLBone),(-Sensor.(name).SCK.Xaxis), 'yzx');
    end
```

Appendix B (Continued)

```
    % Calculate Motion of the Residual limb using new bone position
    for k=1:size(Sensor.(name).T1,1);
        if amputation == 'R'
            Sensor.(name).RLMotion(:,:,k) = (Sensor.(name).RShoulder.HT(:,:,k))^-
1*Sensor.(name).ResidualBone.HT(:,:,k);
        else
            Sensor.(name).RLMotion(:,:,k) = (Sensor.(name).LShoulder.HT(:,:,k))^-
1*Sensor.(name).ResidualBone.HT(:,:,k);
        end
        Sensor.(name).SCKMotion(:,:,k) = (Sensor.(name).ResidualBone.HT(:,:,k))^-
1*Sensor.(name).SCK.HT(:,:,k);
    end

    % Calculate Angles for Residual limb, Socket, and Elbow
    for k=1:size(Sensor.(name).T1,1);
        if amputation == 'R'
            Sensor.(name).RShoAngle(:,k) = findTheta('zxy',
Sensor.(name).RShoMotion(1:3,1:3,k));
            Sensor.(name).RShoRotation(:,k) = Sensor.(name).RShoAngle(:,k).*(180/pi);
        else
            Sensor.(name).LShoAngle(:,k) = findTheta('zxy', Sensor.(name).LShoMotion(1:3,1:3,k));
            Sensor.(name).LShoRotation(:,k) = Sensor.(name).LShoAngle(:,k).*(180/pi);
        end

        Sensor.(name).RLAngle(:,k) = findTheta('zxy', Sensor.(name).RLMotion(1:3,1:3,k));
        Sensor.(name).RLRotation(:,k) = ((Sensor.(name).RLAngle(:,k)).*(180/pi));

        if ~(amputation == 'R')
            Sensor.(name).RLRotation(1,k) = Sensor.(name).RLRotation(1,k).*-1;
            Sensor.(name).RLRotation(3,k) = Sensor.(name).RLRotation(3,k).*-1;
        end

        Sensor.(name).SCKOffset(:,k) = nanmean(Sensor.(name).SCKMotion(2,4,1:5),3);
        Sensor.(name).SCKTranslation(:,k) = Sensor.(name).SCKMotion(2,4,k)-
nanmean(Sensor.(name).SCKMotion(2,4,1:5),3);
        Sensor.(name).SCKAngle(:,k) = findTheta('zxy', Sensor.(name).SCKMotion(1:3,1:3,k));
        Sensor.(name).SCKRotation(:,k) = Sensor.(name).SCKAngle(:,k).*(180/pi)-
Sensor.(name).SCKAngle(:,1).*(180/pi);

        Sensor.(name).ELBAngle(:,k) = findTheta('zxy', Sensor.(name).ELBMotion(1:3,1:3,k));
        Sensor.(name).ELBRotation(:,k) = Sensor.(name).ELBAngle(:,k).*(180/pi)-
Sensor.(name).ELBAngle(:,1).*(180/pi);

        if ~(amputation == 'R')
            Sensor.(name).SCKRotation(1,k) = Sensor.(name).SCKRotation(1,k).*-1;
```

Appendix B (Continued)

```
            Sensor.(name).SCKRotation(3,k) = Sensor.(name).SCKRotation(3,k).*-1;
        end

        % Equivalent axis rotation
        Sensor.(name).RLTheta(:,:) =
(acos((Sensor.(name).RLMotion(1,1,:)+Sensor.(name).RLMotion(2,2,:)+Sensor.(name).RLMoti
on(3,3,:)-1)/2))*(180/pi);
        Sensor.(name).SCKTheta(:,:) =
(acos((Sensor.(name).SCKMotion(1,1,:)+Sensor.(name).SCKMotion(2,2,:)+Sensor.(name).SCK
Motion(3,3,:)-1)/2))*(180/pi);
        Sensor.(name).ELBTheta(:,:) =
(acos((Sensor.(name).ELBMotion(1,1,:)+Sensor.(name).ELBMotion(2,2,:)+Sensor.(name).ELB
Motion(3,3,:)-1)/2))*(180/pi);
    end

    Sensor.(name).RLMax = max(Sensor.(name).RLRotation,[],2);
    Sensor.(name).RLMin = min(Sensor.(name).RLRotation,[],2);
    Sensor.(name).RLThetaMax = max(Sensor.(name).RLTheta,[],1);
    Sensor.(name).RLThetaMin = min(Sensor.(name).RLTheta,[],1);
    Sensor.(name).SCKMax = max(Sensor.(name).SCKRotation,[],2);
    Sensor.(name).SCKMin = min(Sensor.(name).SCKRotation,[],2);
    Sensor.(name).SCKTRANMax = max(Sensor.(name).SCKTranslation,[],2);
    Sensor.(name).SCKTRANMin = min(Sensor.(name).SCKTranslation,[],2);
    Sensor.(name).SCKThetaMax = max(Sensor.(name).SCKTheta,[],1);
    Sensor.(name).SCKThetaMin = min(Sensor.(name).SCKTheta,[],1);

    Sensor.(name).time = cumsum(ones(size(Sensor.(name).T1,1)))/120;

    if ~strcmp('Static', name)
        Sensor.(name).Mouse = dlmread([name,'.txt']);
        Sensor.(name).Mouse(:,1) = (Sensor.(name).Mouse(:,1)-Sensor.(name).Mouse(1,1));
        Sensor.(name).Mouse(:,2) = (Sensor.(name).Mouse(:,2)-Sensor.(name).Mouse(1,2));
        Sensor.(name).MouseMax = max(Sensor.(name).Mouse(:,(1:2)),[],1)';
        Sensor.(name).MouseMin = min(Sensor.(name).Mouse(:,(1:2)),[],1)';
    end

    if ~strcmp('Static', name)
        Sensor.RLMaxCompiled =  [Sensor.RLMaxCompiled, Sensor.(name).RLMax];
        Sensor.RLMinCompiled =  [Sensor.RLMinCompiled, Sensor.(name).RLMin];
        Sensor.RLThetaMaxCompiled = [Sensor.RLThetaMaxCompiled,
Sensor.(name).RLThetaMax];
        Sensor.RLThetaMinCompiled = [Sensor.RLThetaMinCompiled,
Sensor.(name).RLThetaMin];
        Sensor.SCKMaxCompiled = [Sensor.SCKMaxCompiled, Sensor.(name).SCKMax];
        Sensor.SCKMinCompiled = [Sensor.SCKMinCompiled, Sensor.(name).SCKMin];
```

```
        Sensor.SCKTRANMaxCompiled = [Sensor.SCKTRANMaxCompiled,
Sensor.(name).SCKTRANMax];
        Sensor.SCKTRANMinCompiled = [Sensor.SCKTRANMinCompiled,
Sensor.(name).SCKTRANMin];
        Sensor.SCKThetaMaxCompiled = [Sensor.SCKThetaMaxCompiled,
Sensor.(name).SCKThetaMax];
        Sensor.SCKThetaMinCompiled = [Sensor.SCKThetaMinCompiled,
Sensor.(name).SCKThetaMin];
        Sensor.MouseMaxCompiled = [Sensor.MouseMaxCompiled, Sensor.(name).MouseMax];
        Sensor.MouseMinCompiled = [Sensor.MouseMinCompiled, Sensor.(name).MouseMin];
    end
end

Sensor.RLRoM = Sensor.RLMaxCompiled - Sensor.RLMinCompiled;
Sensor.RLThetaRoM = Sensor.RLThetaMaxCompiled - Sensor.RLThetaMinCompiled;
Sensor.SCKRoM = Sensor.SCKMaxCompiled - Sensor.SCKMinCompiled;
Sensor.SCKTRANRoM = Sensor.SCKTRANMaxCompiled - Sensor.SCKTRANMinCompiled;
Sensor.SCKThetaRoM = Sensor.SCKThetaMaxCompiled - Sensor.SCKThetaMinCompiled;
```

B.2 SRiM\Subfunctions\removewhite.m

```
% White Space Remover
function string2 = removewhite(string1)
spacemat = isspace(string1);
i = 1;
while i<=size(string1,2)
    if (spacemat(i)==1)
        string1(i) = [];
        spacemat(i) = [];
    else
        i=i+1;
    end
end

string2 = string1;

if (size(string1,2)>=4)
    if strcmp(string1(1,(size(string1,2)-3):(size(string1,2))),'.c3d')
        string2 = string1(1,1:(size(string1,2)-4));
    end
end
end
```

Appendix B (Continued)

B.3 SRiM\Subfunctions\WMAfilter.m

```
%better filter
function [xfil] = WMAfilter(n, x)
% Moving average filter
% x = Array of points to be filtered.
% n = Width of the filter.
% xfil = Filtered array of input array x.
% Define weighting array
WA = [];
for i = 1:n
   if i<=floor(n/2)
      WA = [WA,i];
   else
      WA = [WA,n-i+1];
   end
end
WA = WA/sum(WA);

xfil = zeros(size(x));
% defining a zero matrix, of the same size as array x.

xnew = x;
for i=1:floor(n/2)
   xnew = cat(1, x(i+1,:,:), xnew);
   xnew = cat(1, xnew, x(size(x,1)-i,:,:));
end

for i=1:size(x,1)
   % iterations, from 1 to number of rows of the array x.
   for j = 1:n
      xfil(i,:,:) = xfil(i,:,:) + WA(j)*xnew((i+j-1),:,:);
   end

end

end
%repeat until size (x,1) has been reached
```

B.4 SRiM\Subfunctions\createSegment.m

```
classdef createSegment
% Creates a segment frame for a set of marker positions using an origin
% point, two defining lines and an order.
```

Appendix B (Continued)

```
% The Segment Frame is centered at the Origin.
% The first axis lies along the first defining line.
% The second axis is the cross product of the first and second defining
% lines.
% The thrid axis is the cross of the two first axes.
    properties
        Origin;
        Xaxis;
        Yaxis;
        Zaxis;
        HT;
        Point = [];
        DistalPoint = [];
    end
    methods
        function seg = createSegment(origin, Line1, Line2, Order)
            if(nargin <= 2)
                'Segment must contain at least an origin and 2 defining lines'
            end
            seg.Origin = origin;

            e2preunit = cross(Line1, Line2);
            e3preunit = cross(Line1, e2preunit);

            e1 = vec2unit(Line1);
            e2 = vec2unit(e2preunit);
            e3 = vec2unit(e3preunit);
            if ((nargin == 3)||strcmpi(Order, 'xyz'))
                seg.Xaxis = e1;
                seg.Yaxis = e2;
                seg.Zaxis = e3;
            elseif strcmpi(Order, 'xzy')
                seg.Xaxis = e1;
                seg.Yaxis = -e3;
                seg.Zaxis = e2;
            elseif strcmpi(Order, 'yxz')
                seg.Xaxis = e2;
                seg.Yaxis = e1;
                seg.Zaxis = -e3;
            elseif strcmpi(Order, 'yzx')
                seg.Xaxis = e3;
                seg.Yaxis = e1;
                seg.Zaxis = e2;
            elseif strcmpi(Order, 'zxy')
                seg.Xaxis = e2;
```

```
            seg.Yaxis = e3;
            seg.Zaxis = e1;
         elseif strcmpi(Order, 'zyx')
            seg.Xaxis = -e3;
            seg.Yaxis = e2;
            seg.Zaxis = e1;
         end
         for i=1:size(seg.Xaxis,1)
            seg.HT(:,:,i) = cat(2, seg.Xaxis(i,:)', seg.Yaxis(i,:)', seg.Zaxis(i,:)', origin(i,:)');
         end
         seg.HT(4,4,:) = 1;
      end % Function Create Segment


   end % Methods
end % Class Def
```

B.5 SRiM\Subfunctions\findTheta.m

```
% Calculates the euler angles given a rotation order and a rotation matrix.
% Derek Lura, University of South Florida 2011
function theta = findTheta(order, R)

if strcmp(order,'zxy')
   x = asin(R(3,2));
   y = acos(R(3,3)/cos(x));
   y2 = asin(-R(3,1)/cos(x));
   z = acos(R(2,2)/cos(x));
   z2 = asin(-R(1,2)/cos(x));

   if y2<=0
      y= -y;
   end
   if z2<=0
      z= -z;
   end

   Rzxy = [ cos(z)*cos(y)-sin(z)*sin(x)*sin(y),                  -sin(z)*cos(x),
cos(z)*sin(y)+sin(z)*sin(x)*cos(y);
           sin(z)*cos(y)+cos(z)*sin(x)*sin(y),                  cos(z)*cos(x), sin(z)*sin(y)-
cos(z)*sin(x)*cos(y);
                          -cos(x)*sin(y),                          sin(x),                  cos(x)*cos(y)];

   test = R-Rzxy;
```

Appendix B (Continued)

```
    if sum(sum(test.^2))>=0.001
        'Error in angle calculation zxy'
    end
    theta = real([z, x, y]);

elseif strcmp(order,'yxz')
    x = asin(-R(2,3)); %returns x from -pi/2 to pi/2
    y = acos(R(3,3)/cos(x)); %returns y from 0 to pi
    y2 = asin(R(1,3)/cos(x)); %returns y from -pi/2 to pi/2
    z = acos(R(2,2)/cos(x)); %returns z from 0 to pi
    z2 = asin(R(2,1)/cos(x)); %returns z from -pi/2 to pi/2

    if y2<=0
        y= -y;
    end
    if z2<=0
        z= -z;
    end

    Ryxz = [ sin(z)*sin(x)*sin(y)+cos(z)*cos(y), cos(z)*sin(x)*sin(y)-sin(z)*cos(y),cos(x)*sin(y);
              sin(z)*cos(x), cos(z)*cos(x), -sin(x);
           sin(z)*sin(x)*cos(y)-cos(z)*sin(y), cos(z)*sin(x)*cos(y)+sin(z)*sin(y), cos(x)*cos(y)];
    test = R-Ryxz;
    if sum(sum(test.^2))>=0.001
        'Error in angle calculation yxz'
    end
    theta = real([y,x,z]);

elseif strcmp(order,'xyz')
    y = asin(R(1,3)); %returns x from -pi/2 to pi/2
    x = acos(R(3,3)/cos(y)); %returns x from 0 to pi
    x2 = asin(-R(2,3)/cos(y)); %returns x from -pi/2 to pi/2
    z = acos(R(1,1)/cos(y)); %returns z from 0 to pi
    z2 = asin(-R(1,2)/cos(y)); %returns z from -pi/2 to pi/2

    if x2<=0
        x= -x;
    end
    if z2<=0
        z= -z;
    end

    Rxyz =  [cos(y)*cos(z),-cos(y)*sin(z),sin(y);
            sin(x)*sin(y)*cos(z)+cos(x)*sin(z), -sin(x)*sin(y)*sin(z)+cos(x)*cos(z),-sin(x)*cos(y);
           -cos(x)*sin(y)*cos(z)+sin(x)*sin(z),  cos(x)*sin(y)*sin(z)+sin(x)*cos(z),cos(x)*cos(y)];
```

Appendix B (Continued)

```
   test = R-Rxyz;
   if sum(sum(test.^2))>=0.001
      'Error in angle calculation xyz'
   end
   theta = real([x,y,z]);

elseif strcmp(order,'zyx')
   y = asin(-R(3,1)); %returns x from -pi/2 to pi/2
   x = acos(R(3,3)/cos(y)); %returns x from 0 to pi
   x2 = asin(R(3,2)/cos(y)); %returns x from -pi/2 to pi/2
   z = acos(R(1,1)/cos(y)); %returns z from 0 to pi
   z2 = asin(R(2,1)/cos(y)); %returns z from -pi/2 to pi/2

   if x2<=0
      x= -x;
   end
   if z2<=0
      z= -z;
   end

   Rzyx =  [ cos(z)*cos(y), -sin(z)*cos(x)+cos(z)*sin(y)*sin(x),
sin(z)*sin(x)+cos(z)*sin(y)*cos(x);
           sin(z)*cos(y),  cos(z)*cos(x)+sin(z)*sin(y)*sin(x), -cos(z)*sin(x)+sin(z)*sin(y)*cos(x);
               -sin(y),                cos(y)*sin(x),                cos(y)*cos(x)];
   test = R-Rzyx;
   if sum(sum(test.^2))>=0.001
      'Error in angle calculation zyx'
   end
   theta = real([z,y,x]);

elseif strcmp(order,'xzy')
   z = asin(-R(1,2)); %returns x from -pi/2 to pi/2
   x = acos(R(2,2)/cos(z)); %returns x from 0 to pi
   x2 = asin(R(3,2)/cos(z)); %returns x from -pi/2 to pi/2
   y = acos(R(1,1)/cos(z)); %returns z from 0 to pi
   y2 = asin(R(1,3)/cos(y)); %returns z from -pi/2 to pi/2

   if x2<=0
      x= -x;
   end
   if y2<=0
      z= -z;
   end

   Rxzy =  [              cos(z)*cos(y),              -sin(z),            cos(z)*sin(y);
```

Appendix B (Continued)

```
            sin(z)*cos(x)*cos(y)+sin(x)*sin(y),                 cos(z)*cos(x), sin(z)*sin(y)*cos(x)-
cos(y)*sin(x);
            sin(z)*sin(x)*cos(y)-cos(x)*sin(y),                 cos(z)*sin(x),
sin(z)*sin(y)*sin(x)+cos(y)*cos(x)];
   test = R-Rxzy;
   if sum(sum(test.^2))>=0.001
      'Error in angle calculation Rxzy'
   end
   theta = real([x,z,y]);

elseif strcmp(order,'yzx')
   z = asin(R(2,1)); %returns x from -pi/2 to pi/2
   x = acos(R(2,2)/cos(z)); %returns x from 0 to pi
   x2 = asin(-R(2,3)/cos(z)); %returns x from -pi/2 to pi/2
   y = acos(R(1,1)/cos(z)); %returns z from 0 to pi
   y2 = asin(-R(3,1)/cos(z)); %returns z from -pi/2 to pi/2

   if x2<=0
      x= -x;
   end
   if y2<=0
      z= -z;
   end

   Ryzx = [  cos(z)*cos(y), -sin(z)*cos(x)*cos(y)+sin(x)*sin(y),
sin(z)*sin(x)*cos(y)+cos(x)*sin(y);
                 sin(z),                cos(z)*cos(x),                -cos(z)*sin(x);
           -cos(z)*sin(y),  sin(z)*sin(y)*cos(x)+cos(y)*sin(x), -
sin(z)*sin(y)*sin(x)+cos(y)*cos(x)];
   test = R-Ryzx;
   if sum(sum(test.^2))>=0.001
      'Error in angle calculation zyx'
   end
   theta = real([y,z,x]);

end

%    Rx = [1,      0,     0;
%          0, cos(x), -sin(x);
%          0, sin(x), cos(x)];
%
%    Ry = [cos(y), 0, sin(y);
%            0,    1,  0;
%          -sin(y), 0, cos(y)];
%
```

```
%     Rz = [cos(z), -sin(z), 0;
%           sin(z), cos(z),  0;
%           0,       0,     1];

end
```

B.6 SRiM\Subfunctions\addPoint2.m

```
function seg = addPoint2(seg, point) % Add a point to the current segment
newpoint = 1;
point = point(:,1:3);
segPoint(:,:) = point - seg.Origin;
for i=1:size(point,1)
    segPoint(i,:) = [dot(segPoint(i,:),seg.Xaxis(i,:)), dot(segPoint(i,:),seg.Yaxis(i,:)),
dot(segPoint(i,:),seg.Zaxis(i,:))];
end

PN = 1;
if size(seg.Point,1)>0;
    PN = size(seg.Point,3) + 1;
%     for i=1:size(seg.Point,3)
%         if all(all(seg.Point(:,:,i)==segPoint))
%             disp('Point is already added to position :')
%             disp(i)
%             newpoint = 0;
%         end
%
%     end
end

if newpoint
    seg.Point(:,:,PN) = segPoint;
end

end
```

B.7 SRiM\Subfunctions\clusterReconstruct.m

```
% Create segment from cluster tracking points
% Derek Lura 04/23/12
function [Pta, Ptb, Ptc, Ptd] = clusterReconstruct(X, varargin)

%function Pt1 = bestPoint(Pt1, Pt2, Pt3)
```

```
for j=1:size(varargin{1},1)
    y = [];
    xt = [];
    Y = [];
    Xt = [];
    for i=1:nargin-1
        if ~(isnan(varargin{i}(j,1)))
            y = [y, varargin{i}(j,:)'];
            xt = [xt, X(:,i)];
        end
    end
    yb = mean(y,2);
    xb = mean(xt,2);
    for i=1:size(y,2)
        Y(:,i) = y(:,i)-yb;
        Xt(:,i) = xt(:,i)-xb;
    end
    Z = Y*Xt';
    [U,~,V] = svd(Z);
    R = U*diag([1,1,det(U*V')])*V';
    p = mean((y - R*xt),2);
    for i=1:4
        if (isnan(varargin{i}(j,1)))
            varargin{i}(j,:) = R*X(:,i) + p;

        end
    end

end

Pta = varargin{1};
Ptb = varargin{2};
Ptc = varargin{3};
Ptd = varargin{4};
end
```

B.8 SkinMotion.m

```
% SkinMotion
% Create a figure and specify a callback function to be added into the
% windowbuttonmotionfcn cell in the callback window; then maximize the
% graph to fill up the screen
% written by Matt Wernke on June 1, 2009
global fid
```

Appendix B (Continued)

```
Key = input('Input Filename & Press Enter to Start and Stop Trial: ', 's');

fid = fopen([Key,'.txt'], 'a');
tic
h = figure('WindowButtonMotionFcn', 'gpos(gca)', 'CloseRequestFcn', @my_closereq);
maximize(h);
%Change axis dimensions. This is done by taking the ratio of the actual
%movement over the recorded. This number was then multiplied by the
%previous scaling factor to get the new one. The settings for the mouse
%were no pointer enhancement and speed at the 4th notch.

% %Notch at 4th position
xDim = 80;
yDim = 42;
axis([0 xDim 0 yDim])

% %Notch at 6th position
% xDim = 39.7;
% yDim = 18.9;
% axis([0 xDim 0 yDim])
```

B.9 SkinMotion\Subfunctions\maximize.m

```
function maximize(h)

% MAXIMIZE   maximize figure windows
%
==================================================================
%
%       Berne University of Applied Sciences
%
%       School of Engineering and Information Technology
%       Division of Electrical- and Communication Engineering
%
%
==================================================================
%                    maximize figure windows
%
==================================================================
%
% Author:    Alain Trostel
% e-mail:    alain.trostel@bfh.ch
% Date:      June 2007
% Version:   4.1
```

```
%
%
==========================================================================
%
% function maximize(h)
%
% Input parameters
% -----------------
%   h           handle(s) of the figure window
%
%
% Output parameters
% ------------------
%   The function has no output parameters.
%
%
% Used files
% -----------
%   - windowMaximize.dll
%
%
% Examples
% ---------
%   % maximize the current figure
%   ------------------------------
%   maximize;
%
%
%   % maximize the current figure
%   ------------------------------
%   maximize(gcf);
%
%
%   % maximize the specified figure
%   --------------------------------
%   h = figure;
%   maximize(h);
%
%
%   % maximize the application window
%   ----------------------------------
%   maximize(0);
%
%
%   % maximize more than one figure
```

```
%   -------------------------------
%   h(1) = figure;
%   h(2) = figure;
%   maximize(h);
%
%
%   % maximize all figures
%   ----------------------
%   maximize('all');
%
%
%   % maximize a GUI in the OpeningFcn
%   ----------------------------------
%
%   % --- Executes just before untitled is made visible.
%   function untitled_OpeningFcn(hObject, eventdata, handles, varargin)
%   % This function has no output args, see OutputFcn.
%   % hObject    handle to figure
%   % eventdata  reserved - to be defined in a future version of MATLAB
%   % handles    structure with handles and user data (see GUIDATA)
%   % varargin   command line arguments to untitled (see VARARGIN)
%
%   % Choose default command line output for untitled
%   handles.output = hObject;
%
%   % Update handles structure
%   guidata(hObject, handles);
%
%   % UIWAIT makes untitled wait for user response (see UIRESUME)
%   % uiwait(handles.figure1);
%
%   % maximize the GUI
%   set(hObject,'Visible','on');
%   maximize(hObject);



% check if dll-file exists
if ~exist('windowMaximize.dll','file')
    error('windowMaximize.dll not found.');
end

% if no input parameters, get handle of the current figure
if nargin == 0
    h = gcf;
```

Appendix B (Continued)

```
end

% if one input parameter, check the input parameter
if ischar(h)
   % check the string
   if strcmpi(h,'all')
      % get all figure handles
      h = findobj('Type','figure');
   else
      % incorrect string argument
      error('Argument must be the correct string.');
   end
else
   % check each handle
   for n=1:length(h)
      % it must be a handle and of type 'root' or 'figure'
      if ~ishandle(h(n)) || (~strcmp(get(h(n),'Type'),'root') && ...
                        ~strcmp(get(h(n),'Type'),'figure'))
         % incorrect handle
         error('Argument(s) must be a correct handle(s).');
      end
   end
end

% if handle is not the root
if h ~= 0
   % for each handle
   for n=length(h):-1:1
      % create the temporary window name
      windowname = ['maximize_',num2str(h(n))];

      % save current window name
      numTitle = get(h(n),'NumberTitle');
      figName = get(h(n),'Name');

      % set the temporary window name
      set(h(n),'Name',windowname,'NumberTitle','off');

      % draw figure now
      drawnow;
      % maximize the window with the C function
      windowMaximize(windowname,get(h(n),'Resize'));

      % reset the window name
      set(h(n),'Name',figName,'NumberTitle',numTitle);
```

```
   end
else
   % maximize the application window "MATLAB"
   windowMaximize('MATLAB');
end
```

B.10 SkinMotion\Subfunctions\myclosereq.m

```
%Closes the current figure
function my_closereq (src, evnt)
global fid
fclose(fid)
delete(gcf)
end
```

B.11 SkinMotion\Subfunctions\gpos.m

```
%GPOS Get current position of cusor and return its coordinates in axes with handle h_axes
% h_axes - handle of specified axes
% [x,y]  - cursor coordinates in axes h_axes
%
% -----------------------------------------------------------------------
% Note:
%  1. This function should be called in the figure callback WindowButtonMotionFcn.
%  2. It works like GINPUT provided by Matlab,but it traces the position
%      of cursor without click and is designed for 2-D axes.
%  3. It can also work even if the units of figure and axes are inconsistent,
%      or the direction of axes is reversed.
% -----------------------------------------------------------------------

% Written by Kang Zhao,DLUT,Dalian,CHINA. 2003-11-19
% E-mail:kangzhao@student.dlut.edu.cn

function [x,y]=gpos(h_axes)

h_figure=gcf;

units_figure = get(h_figure,'units');
units_axes   = get(h_axes,'units');

if_units_consistent = 1;
```

Appendix B (Continued)

```
if ~strcmp(units_figure,units_axes)
    if_units_consistent=0;
    set(h_axes,'units',units_figure); % To be sure that units of figure and axes are consistent
end

% Position of origin in figure [left bottom]
pos_axes_unitfig    = get(h_axes,'position');
width_axes_unitfig  = pos_axes_unitfig(3);
height_axes_unitfig = pos_axes_unitfig(4);

xDir_axes=get(h_axes,'XDir');
yDir_axes=get(h_axes,'YDir');

% Cursor position in figure
pos_cursor_unitfig = get( h_figure, 'currentpoint'); % [left bottom]

if strcmp(xDir_axes,'normal')
    left_origin_unitfig = pos_axes_unitfig(1);
    x_cursor2origin_unitfig = pos_cursor_unitfig(1) - left_origin_unitfig;
else
    left_origin_unitfig = pos_axes_unitfig(1) + width_axes_unitfig;
    x_cursor2origin_unitfig = -( pos_cursor_unitfig(1) - left_origin_unitfig );
end

if strcmp(yDir_axes,'normal')
    bottom_origin_unitfig     = pos_axes_unitfig(2);
    y_cursor2origin_unitfig = pos_cursor_unitfig(2) - bottom_origin_unitfig;
else
    bottom_origin_unitfig = pos_axes_unitfig(2) + height_axes_unitfig;
    y_cursor2origin_unitfig = -( pos_cursor_unitfig(2) - bottom_origin_unitfig );
end

xlim_axes=get(h_axes,'XLim');
width_axes_unitaxes=xlim_axes(2)-xlim_axes(1);

ylim_axes=get(h_axes,'YLim');
height_axes_unitaxes=ylim_axes(2)-ylim_axes(1);

x = xlim_axes(1) + x_cursor2origin_unitfig / width_axes_unitfig * width_axes_unitaxes;
y = ylim_axes(1) + y_cursor2origin_unitfig / height_axes_unitfig * height_axes_unitaxes;

% Recover units of axes,if original units of figure and axes are not consistent.
if ~if_units_consistent
    set(h_axes,'units',units_axes);
```

```
end
%[t] = sprintf(' %1.7f ',now());
global fid
%display(fid)
fprintf(fid, '%g\t%g\t%1.7f\r\n', x, y, toc);
```

B.12 SkinMotion\Subfunctions\windowMaximize.m

```
/*
|==========================================================================
====|
|                                                          |
|      Berne University of Applied Sciences                           |
|                                                          |
|      School of Engineering and Information Technology               |
|      Division of Electrical- and Communication Engineering           |
|                                                          |
|==========================================================================
====|
|                     maximize the window                        |
|==========================================================================
====|
|                                                          |
| Author:    Alain Trostel                                  |
| e-mail:    alain.trostel@bfh.ch                             |
| Date:      April 2007                                     |
| Version:   2.0                                            |
|                                                          |
|==========================================================================
====|
|                                                          |
| windowMaximize(windowname,resizeState)                          |
|                                                          |
| input parameters:                                         |
| -----------------                                         |
| windowname    string with the window name                       |
| resizeState   string with the resize state                   |
|             "on":   window is resizable                     |
|             "off":  window is not resizable                  |
|                                                          |
|                                                          |
| output parameters:                                         |
| ------------------                                        |
| The function has no output parameters.                        |
```

Appendix B (Continued)

```
|                                                   |
|                                                   |
| used files:                                       |
| -----------                                       |
| The function doesn't use additional files.        |
|                                                   |
|                                                   |
| compilation:                                      |
| ------------                                      |
| mex windowMaximize.c -output windowMaximize.dll   |
|                                                   |
|==================================================================
====|
*/

/* include header files */
#include <windows.h>
#include "mex.h"


/* interface between MATLAB and the C function */
void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray *prhs[])
{
   /* declare variables */
   HWND hWnd;
   long nStyle;
   int strLength;
   char *windowname, *resizeState;

   /* length of the string */
   strLength = mxGetN(prhs[0])+1;
   /* allocate memory for the window name */
   /* MATLAB frees the allocated memory automatically */
   windowname = mxCalloc(strLength, sizeof(char));
   /* copy the variable from MATLAB */
   mxGetString(prhs[0],windowname,strLength);

   /* length of the string */
   strLength = mxGetN(prhs[1])+1;
   /* allocate memory for the resize state */
   /* MATLAB frees the allocated memory automatically */
   resizeState = mxCalloc(strLength, sizeof(char));
   /* copy the variable from MATLAB */
   mxGetString(prhs[1],resizeState,strLength);
```

Appendix B (Continued)

```
    /* handle of the window */
    hWnd = FindWindow(NULL,windowname);

    /* get current window style */
    nStyle = GetWindowLong(hWnd,GWL_STYLE);

    /* make sure that the window can be resized */
    SetWindowLong(hWnd,GWL_STYLE,nStyle | WS_MAXIMIZEBOX);

    /* maximize window */
    ShowWindow(hWnd,SW_MAXIMIZE);

    /* window is not resizable */
    if(strcmp(resizeState,"off") == 0)
    {
        /* restore the settings */
        SetWindowLong(hWnd,GWL_STYLE,nStyle);
    }

    /* redraw the menu bar */
    DrawMenuBar(hWnd);
}
```