2006

Methodology for Quantifying Biomechanical Bone Movement of Transtibial Amputations

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Methodology for Quantifying Biomechanical Bone Movement
of Transtibial Amputations

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Engineering

By

Johanna Claire Bell
B.S., Wright State University, 2005

2006
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Johanna C. Bell ENTITLED Methodology for Quantifying Biomechanical Bone Movement of Transtibial Amputations BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Engineering.

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Abstract
Bell, Johanna Claire. M.S.Egr., Department of Biomedical, Industrial and Human Factors Engineering, Wright State University, 2006.
Methodology for Quantifying Biomechanical Bone Movement of Transtibial Amputations.

A controversy has long existed about an alternate below knee amputation procedure that may be more beneficial than the traditional transtibial amputation. The proponents of this alternate procedure that stabilizes the distal tibia and fibula claim it reduces excessive movement of the fibula relative to the tibia that occurs with common movements, such as walking. The purpose of this study is to develop a methodology for quantifying excessive movement of the fibula bone relative to the tibia bone in traditional below the knee amputations. The methodology will measure the movement and rotation of the fibula relative to the tibia. These results can be compared to the bone movement from below the knee distal tibiofibular fusion procedure in order to observe if the excessive movement has been reduced.

Matlab was used to analyze CT data from a traditional transtibial amputation subject and a distal tibiofibular fusion subject under four loading conditions. Distance and rotation measurements were collected using preexisting and generated Matlab programs. The measurements include locations from several regions on the limb to try to establish a trend for motion. A repeatable methodology with high precision was developed to quantify the movement of the fibula relative to the tibia for both distance and rotation measurements; the average standard deviation for distance measurement is 0.374 mm and the average standard deviation for rotation measurement is 0.131 degrees.
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Acknowledgments

Grants or outside funding were provided from The Wright State University Research Initiation Grant and the Wright State University School of Medicine Seed Grant. In addition, Portal Inc. donated use of the Portal Gravity System for the purposes of this study.

Dedication

This thesis is dedicated to everyone who believed in me and cheered me on throughout my college experience.
1 Introduction

1.1 Transtibial Amputation

In the past, lower-limb amputations were performed for necessity and were often regarded as last resort operations; they were considered destructive. The goal of these amputations was to create a pain-free stump that was muscularly strong and was considered a good shape for carrying prosthesis, not necessarily for ambulation. Post amputation, the patients often suffered from impaired circulation and osteoporosis due to non-use of the limb or misdistribution of the load on the residual limb with poor prosthetic fit, as well as changes in mineral metabolism or degeneration of joints. The present goal of amputation is to maintain functionality. Now the focus is to obtain primary wound healing while avoiding infections, create a well padded residual limb with good shape that can sustain both prosthesis fitting and full weight bearing capabilities in order to achieve a successful interface for ambulation with prosthesis. The hope is that the limb will have end bearing capacity and have a good shape in order to allow rotational stability for prosthesis. Amputations are now considered preventative and constructive as well as function restoring.

1.1.1 Various Techniques Used in Transtibial Amputations

Amputation occurs for numerous reasons, but transtibial amputation usually falls into one of four categories: major trauma, such as high voltage injuries or car accidents, which is usually more prevalent in younger people; infections such as gangrene; general disorders such as diabetes, tumors, ulcers; ischemia from peripheral vascular disease which is more prevailing in older people; severe deformities or limb deficiencies. In the United States, dysvascular limb-loss accounted for 97% of lower limb amputation.
discharged from 1988 to 1996 with 27.6% of those being transtibial amputations amid an upward trend\textsuperscript{19}.

Treatments throughout the different operative stages may vary depending on patient condition, such as preoperative procedure for peripheral vascular disease amputations where the patient is required to undergo clinical observation and evaluation in order to determine the quality level on the tissue on the limb as well as functional abilities\textsuperscript{4}, but the level at which the bones are transected is more or less standard. Most surgeons will leave the bones as long as possible with an ideal tibial bone length between 12.5cm and 17.5cm, or 2.5cm of tibia length for every 30cm of patient height, making sure to remain above the distal third of the tibia due to possible difficulty in prosthesis fit and to maintain soft tissue padding\textsuperscript{4,6,10,11}. The fibula is left shorter than the tibia and is cut between 10mm to 20mm above the distal cut of the tibia bone\textsuperscript{1,3,4,10,11}. For improved prosthetic function and energy conservation with the best chance of ambulation, it is important to try and preserve the knee joint, but tissue viability is always a concern\textsuperscript{6,11}. If the tissue above the level of amputation is compromised, secondary corrective surgery will need to take place and end up further reducing length of the residual limb.

The treatment of the bones and nerves may be similar for most transtibial amputations, but one of the techniques that can be varied is the closing procedure or flap technique used in the closing procedure. The most commonly used “gold standard” technique is the Burgess, also known as the long posterior flap. The flap is comprised of either the soleus or gastrocnemius muscle, which is trimmed and brought up over the beveled distal end of the transected tibia to create a cylindrical shaped residual limb\textsuperscript{1,3,4,11}. This procedure is based on the superior blood supply of the posterior tissues, which is why the flap focuses
on maintaining these tissues\textsuperscript{11}. Some claim the posterior flap technique may have issues with the width of the limb in the transverse diameter direction which may cause delay in prosthetic fitting, so other techniques were created or the posterior flap technique was adapted\textsuperscript{10}.

The Brückner procedure, a modification of the long posterior flap, is used in end-stage occlusive arterial disease and is believed to remove the subjective assessment of muscle viability that surgeons must perform\textsuperscript{1}. The major difference is that the fibula is removed and the medial and lateral parts of the gastrocnemius compose the posterior flap due to restricted blood flow of the other muscles\textsuperscript{1}. The Kendrick is used in place of the Burgess when there is excessive compromised skin and uses the principle of constant geometry; use of anterior and posterior flaps with a 1:2 length ration based on the circumference of the calf\textsuperscript{3}. Equal anterior posterior flaps are used when there is trauma or new tumor growth, but is not recommended for patients with diabetic foot disease or decreased blood flow\textsuperscript{4,11}. Skew flaps and sagittal flaps utilize oblique flaps of equal length that are based on the limb geometry and are approximately one fourth the length of the circumference of the leg\textsuperscript{4,10}.

The different techniques used in treating the limb during amputation may affect shape and axial load bearing capability of residual limb. The techniques discussed are not the only treatments available, however. They affect how the muscle and skin is treated during surgery, but all use similar techniques in bone treatment, save for the removal of the fibula in the Brückner procedure. There are alternatives in how the bone is treated during transtibial amputation.
1.1.2 Ertl/ Distal Tibia-Fibula Fusion (DTFF) Procedure Differs

The Ertl procedure, or osteoperiosteoplasty or osteomyoplasty, differs from other basic transtibial amputation procedures in that it transects the tibia and fibula at the same length and aims to create an osseous bridge between the two distal portions of the tibia and fibula by forming a tube using the osteoperiosteal covering of the bones. Because the outer layer of the bones is where new bone growth occurs, the hope is that the bridge will become permanent bone over time and aid in stabilization of the limb.

The distal tibiofibular fusion (DTFF) is also performed on patients who need a transtibial amputation. The procedure is a modified Ertl procedure, but rather than using the periosteum, the transosseous bridge that spans the gap between the tibia and the fibula is created from a transected portion of the fibula. The length of fibula bone used to bridge the gap varies anywhere from minimum of 1 cm, or 3 cm to 4.5 cm. The bridge is always secured within the gap, though techniques to ensure this vary.

1.1.3 Variations of Ertl and DTFF

While the DTTF differs from the Ertl in that a bone piece is used to bridge the span between the distal tibia and fibula, there are also slight modifications in the DTFF based on how the bone is fixed into place. Some techniques use 3.5cm to 4.5cm screws, one on each bone, to secure the bridge, but it is believed invasive and that there may be cause for removal of the screw due to incompatibility. One article reported modified Ertl in a child where the surgeon creates an incomplete fracture in lateral tibia, then that section of bone is used to bridge gap and secured using a smooth pin, but the pin is slated for eventual removal.
Both techniques commonly use absorbable sutures along with holes drilled in the bridge or periosteum as well as the bones in order to secure the fixture \(^4,14,15,17,18\). In one procedure similar to the Ertl, the surgeon created strips from the periosteum, but it differed when the surgeon included bone fragments. The surgeon then sutured the strips to form a tube and bridge gap between bones; a stipulation for this technique is limb length as patient must have periosteum in good condition 2 cm to 3 cm above the ankle joint for 6 cm to 7 cm of periosteum for use in the bridge\(^{14}\).

### 1.1.4 Beneficial Aspects of the Ertl Procedure

All proponents claim the Ertl procedure is beneficial citing some of the original claims of Ertl himself, such as the improved axial load bearing on distal end, improved stabilization of bones and soft tissues, as well as the concept of decreased formation of bone in abnormal places by closing the intramedullary canal, improving the intramedullary pressure relationship and increased blood flow \(^4,6,7,15,18,20\). The cylindrical shape of the residual limb was mentioned in almost any literature when discussing the procedure or the modification; however, this procedure is not recommended for patients with vascular disease\(^4\). There is high acclaim given to the modified procedure with patients returning to active military duty post amputation\(^{15}\).

The Ertl procedure is performed to reduce pain, aid in stability of the amputated limb, offer a better fit for prosthetics and offer a faster recovery time for the patient all in order to be able to use the residual limb to walk; the DTTF procedure also aims to offer these results. Another key element of the Ertl procedure is to reduce fibular instability or “excessive motion” of the fibula relative to the tibia \(^{13,17,18}\). The key is to be able to
quantify this movement and create a repeatable procedure that can be performed non-
invasively.

1.2 Relevant Research

Research in the area of determining bone location within the limb is vast. In order to
narrow down the relevant research, a few key factors were focused on: basic
methodologies for determining bone location in the limb; methods used to find bone
location or movement under loading conditions, both invasive and non-invasive; and
what research has been done to measure the position, movement and rotation in
transtibial amputees.

1.2.1 Measurement of Bone Location

There was a great deal of research in the area of measuring the location of the bones
relative to the socket in transtibial amputees as well as measurement of bone location
during a gait cycle or a simulated gait cycle. Through use of photoelectric sensor, one
study explores the socket limb interface to determine if there is contact between the limb
and socket, and what the distance between the limb and socket during gait cycle is. A
diffuse reflective sensor is utilized inside the socket to observe the “pistoning” effect
where the socket and limb act like a piston during the gait cycle instead of the socket
remaining taut to the limb. Another roentgenological study of dynamic movement was
to observe the stump-socket, stump-soft-tissue relationship under four different positions
in a simulated gait cycle on below knee amputees; however, the article did a poor job of
defining what methods were physically used on roentgenograms in order to measure
vertical position and angular differences of tibia in the sagittal plane during the gait
cycle. A biomechanical study focused on control of residual tibia in unilateral
transtibial amputees was performed using anterior/posterior and lateral radiographs. Measurements of tibial length, femur-tibial angle, femur-socket angle, and tibia-socket angle were made from lateral radiographs, all apparently by hand\textsuperscript{21}.

There were several articles of interest that failed to mention the techniques they utilized for measuring the internal structures. One such study describes the use of x-rays to investigate the tibial end relative to patella-tendon bearing (PTB) socket during a simulated gait cycle, but there is a lack of description of how the measurements were physically performed\textsuperscript{25}.

A few articles discussed the function of the fibula in the gait cycle and whether it is dynamic or static. One such journal article investigated dynamic fibular function through gait analysis using reflective markers on standard anatomical landmarks and captured time-distance data, kinetic and kinematic data as well as electromyography data from muscular activity using patients with 3 different resections of the fibula to determine fibular function in gait\textsuperscript{22}. The author characterized the fibula as dynamic and important to both knee and ankle joints.

One of the most invasive studies used tantalum markers in bones of the distal tibia, fibula and ankle to observe kinematic properties. Results were captured by x-ray (stereophotogrammetric analysis), markers were identified manually then digitized and fed into a computer\textsuperscript{37}. This technique was uncommon as most of the techniques used were non-invasive.

1.2.2 Techniques Used for Detecting Bones

Many of the techniques focused on image processing or a combination of several techniques. Computed tomography (CT) analysis is a major focus for biomechanical
analysis because it produces highest resolution 3-D images with detailed imagery\textsuperscript{28}. One study focused on the use of digital images, such as magnetic resonance imaging (MRI), for iso-shaping using key points from a partial anatomical structure or object on the image in order to produce structures of a similar shape; the object is defined by distance transformation to analyze the kinematics, manipulated, and “live-wire” method is applied where the user defines a few point which allows the program to snap the wire to the boundary of the object\textsuperscript{23}. CT is thought better than MRI because of image clarity. Ultrasound is discussed to determine if it is a viable option for use in active shape modeling for edge detection in the limb with ultrasound and the feasibility of ultrasound in creating a 3-D model through reconstruction, which could be useful in finite element modeling of the residual limb\textsuperscript{29,30}. Another program exhibited the use of a boundary detection snake program for boundary capture and ultimate use in finite element modeling, but the problem with using ultrasound is a time issue; errors in ultrasound can be attributed to the time allowed for subjects to move\textsuperscript{34}. External evaluation of limb biomechanics was another prevalent theme. One study was assessing efficiency of measuring proximal tibial translations with internally fixed modified halo-pins as well as externally secured retro-reflective tracking targets, which were recorded by video based motion capture system and the results were compared for the most effective method\textsuperscript{32}. The same authors again used a video capture system to analyze gait while the study compared different external attachment methods to determine tibial rotations\textsuperscript{33}. Several studies used motion capture techniques; stereophotogrammetric systems use reflective markers on the skin surface that are recorded and analyzed using a defined coordinate system. The system suffers
inaccuracies due to reconstructive errors based on marker coordinates and movement of skin between marker and bone. One paper discusses error through the use of skin markers as compared to markers on a “bone embedded frame” which was an external fixation device subjects wore due to bone fracture. This technique was invasive, but the invasiveness was not in experimental protocol to be so; subjects had a pre-existing condition\textsuperscript{24}.

A videofluoroscopic technique pilot study was performed to determine if relevant features could be discerned for analysis. The technique was used to analyze dynamic motion using videotape analysis of subjects with transtibial amputation. The study used a videofluoroscopic technique because it reduced radiation exposure, unfortunately the technique yielded poor resolution\textsuperscript{26}.

1.2.3 Techniques used for Measurement of Bone Movement

The techniques discussed above used different techniques for determining relative bone location. One study closely resembles this one in that it uses CT scans to evaluate tibiofibular motion of under different loading conditions\textsuperscript{36}. However, instead of using a computer program, the experimenters matched up film from different loading conditions by matching up the tibias, then measuring the relative change in position by poking holes in approximate centers of fibulas. Issues concerning error in this methodology would be repeatability; it was all done by hand. Computerizing the method reduces the human error aspect and removes the approximation. Another study measures position of anterior margin fibula and tibia using a tape measure on fluoroscopy images\textsuperscript{35}, yielding a similar error.
1.3 Focus of thesis

Up to this point, there is research exploring the motion and direction of the bones relative to the prosthetic and motion of bones in the joint locations of the knee and ankle, but little has been explored about developing a repeatable methodology for measuring the motion of the bones of the residual limb relative to one another in a transtibial amputation patient. Information on how the tibia and fibula react under loading conditions within the gait cycle could provide some insight into how the residual shape of the limb changes or if there is pain associated with this movement which could in turn help in designing more effective prosthetics. Another application is that a consistent methodology could provide some insight as to whether the Ertl or the DTTF procedure is beneficial in reducing bone movement.

In order to gain a better understanding of how the residual limb is affected by different loading conditions, it is important to establish a repeatable methodology for determining the distance and rotation between the tibia and fibula for subsequent study of relative bone movement. This thesis will focus on one such methodology.
2 Methods

2.1 Subjects

Two adult male subjects who had received a unilateral transtibial amputation provided informed consent and voluntarily agreed to participate in this study, which was approved by the institutional review board of both Wright State University and Miami Valley Hospital, Dayton OH. The amputations for both subjects were performed by the same surgeon (R.T.L.) and were from problems secondary to trauma. Subject 1 received a traditional below knee amputation (BKA) on the right side at age 46, while subject 2 was a recipient of a distal tibiofibular fusion procedure (DTFF) of the left side at age 59. The dimensions for the bone bridge of the DTFF, measured from an X-Ray that was taken immediately after surgery on August 2003, are illustrated in Figure 1. The subjects exhibited similar weight, height and build as well as similar post amputation times; at time of study weights of subjects 1 and 2 were 102kg and 105kg, heights were 73 in and 72 in, and their post amputation times were 28 months and 25 months respectively. Both subjects were fitted with patella tendon-bearing prosthesis; during the study subject 1 wore a pin/socket prosthesis and subject 2 wore a Harmony prosthesis (created by Otto Bock, Salt Lake City, Utah)
2.2 Experimental Design for CT Scans

The two subjects chosen each underwent a series of four loading conditions on their residual limb while computed tomography scans were performed over a pre-designated region of their limb for each condition.

2.3 Description of Equipment Used

Computed tomography (CT) imaging was performed at the Miami Valley Hospital, Dayton, OH by the spiral CT scanner (GE LightSpeed 16, GE Medical Systems). Loading conditions on the residual limb were applied by a Portal Gravity System (PGS) (Portal, North Logan, Utah).

2.4 Set up of Equipment and Procedure for Collection of CT data

The scan range was from two inches below the most distal region of the residual limb to five inches above the center of the knee, as shown in Figure 2. In preparation for the CT scan, the subjects lay on their backs with the residual limb under one of four loading conditions.
conditions to simulate stance phase with distributed body weight on residual limb with the use of the PGS force platform:

1.) No prosthetic with no axial load
2.) Prosthetic with no axial load
3.) Prosthetic with 50lbs of axial load applied to the prosthetic foot
4.) Prosthetic with 100lbs of axial load applied to the prosthetic foot

Figure 2: Computed tomography scan region of the residual limb
The load was applied only on the residual limb; the subjects other leg was bent slightly so the applied load was explicitly distributed only to the residual limb with the prosthesis (see Figure 3).

Figure 3: Subject positioning with PGS for the computed tomography imaging

Scan parameters were 120 KVP and 200 mAs, 1 sec. rotation, 1 mm slice width, and pitch of 1 (actual distance between slices is 1.25 mm) in an attempt to reduce the artifacts that would be produced by the metal parts of the PGS (Portable Gravity System).
3  Data Analysis for Measurement of Distance and Rotation

3.1 Use of CT Data in Collecting Distance and Rotational Data

The CT data collected from the two subjects was converted from DICOM format to JPEG format in order to easily access and view the images so that appropriate locations could be chosen for analysis. The images would be used to measure the distance between the tibia and fibula, as well as measure the relative rotation between the bones. In order to perform measurements to determine either the distance or rotation between the tibia and fibula, several issues had to be resolved. The sampling location would need to be chosen and measurements needed to come from the same location on the limb regardless of loading condition.

3.2 Selection of Slices and Sample Locations

In order to clearly determine that the measured change in distance and rotation between the tibia and fibula can be compared for all four conditions, the CT slice chosen must be taken from the same position on the leg under all four loading conditions. Unfortunately, due to change in position of the limb between CT scans and loading conditions, one cannot use the slice number assigned when converting the images to jpeg format as a reference. For a description and explanation on the nomenclature used for the CT data, refer to Figure 4. Figure 4 also illustrates what is referred to as artifacts; the artifacts from the metal portions of the PGS can be seen emanating from below.
3.2.1 Methodology Behind Location on Limb

The determination of how much the leg has shifted when the CT data changes from one condition to the next must be made. For an illustration of how the slice number can be related to the relative location on the limb, refer to Figure 5.
In order to determine that the same position is sampled regardless of loading condition, a landmark must be found that will occur in all four conditions. The landmark must be unique enough to be able to discern from the CT images. This was most easily accomplished by starting at the distal end of the limb. The distal portion, as opposed to the more proximal knee, was chosen because the CT images were more complex around the knee region and the distal images had more obvious landmarks. For the first landmark, the tip of the tibia was chosen. The CT images that had the first appearance of the distal tip of the tibia, seen in Figure 6, were selected from all four loading conditions independently of one another. The images were labeled with their corresponding subject number, condition and CT slice/image number.
The next landmark chosen was the distal tip of the fibula, shown in Figure 7; again, all of the conditions were evaluated separately from one another in order to maintain accuracy and independent results. From this point, the slice numbers between the two positions (tip of fibula and tip of tibia) were subtracted from one another to ascertain what the position on the limb was and to be confident that it correlated for all four loading conditions (table 1).

<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Tip of tibia (slice number)</th>
<th>Tip of fibula (slice number)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>202</td>
<td>189</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>188</td>
<td>176</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>171</td>
<td>158</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>163</td>
<td>150</td>
<td>13</td>
</tr>
</tbody>
</table>
There was a minor difference in number of slices between the two regions for the four loading conditions, specifically for condition 2. There are several possible reasons why there could be slight differences in the level or distance from the first level to the second; when the CT scanner captured images with a pitch of 1, images were captured in 1.25 mm increments, and if the leg had slightly shifted in position in between the capture of images from one loading condition to the next, the location previously defined could be between the images. This is a case where judgment must be used to determine which image best represents the original location. This slight difference is acceptable but can cause a minor error when comparing conditions. This specifically applies to condition two; from the initial image selection for the distal tip of the tibia, condition two increased only twelve slices up to the distal tip of the fibula while the other conditions all increased by thirteen slices. To be sure the slices chosen were the most effective, the slices above and below the level chosen from condition two were compared to the other conditions.

Once the level on the limb has been determined where slices are congruent from all four loading conditions, a distance is selected to move proximally up the limb (4 slices or 5mm), and an initial region of interest location is selected, hereafter referred to as the reference slice or ROI 1 (seen in Figure 8). This is the initial slice that will be used to determine the distance of the fibula relative to the tibia and will serve as a reference location, as illustrated by Figure 9.
Figure 8: ROI 1 CT images for all four loading conditions

Figure 9: Vertical location of the reference ROI 1
An unexpected problem was the noise due to metal in the PGS used to apply the load, which directly affected the issues of finding the sampling location from the same location on the limb regardless of loading condition. To solve this problem, a spreadsheet of the images from each loading condition was created, matching up the image numbers with the appropriate corresponding locations on the limb. Then the entire set of images for each condition were examined for unsuitability and marked as such in the spreadsheet so there was a clear definition of what regions of the limb could be sampled. Once the useable regions were discerned, multiple levels were selected for sampling (see Figure 10).
Table 2 lists the slice locations in reference to one another as well as on the limb itself, which can be seen in Figure 11.

<table>
<thead>
<tr>
<th>Region of Interest on Limb</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between regions</td>
<td>0</td>
<td>10mm</td>
<td>17.5mm</td>
<td>18.75mm</td>
<td>21.25mm</td>
</tr>
<tr>
<td>Distance (distal to proximal)</td>
<td>0</td>
<td>10mm</td>
<td>27.5mm</td>
<td>46.25mm</td>
<td>67.5mm</td>
</tr>
</tbody>
</table>
Figure 11: Sample location regions of interest on limb

Several regions of interest were selected in order to determine whether a linearity of movement could be discerned and if there was a point where movement/rotation is no longer measurable with statistical significance. In this case, only one subject was used, so any results pertaining to these concepts may not be globally applicable.

3.2.2 Methodology of Choosing Landmarks

The next question was how to measure the distance between the tibia and fibula; whether it was center to center, a medial point on the outer edge of each bone, or finding a “landmark” and using it consistently. Another issue was how to keep the consistency of the measurement. One way to achieve this was to repeat the measurement procedure a number of times for reliability and accuracy. The results needed to be dependable and
repeatable regardless of who performed this procedure. The method to find the distance between the bones that had the greatest chance of being repeatable was to use the center of the bone. This was accomplished by finding the centroid of the individual bones, then calculating the distance between them, as in Figure 12. In order to achieve this, a program was written in MATLAB 7.0.4.

![Figure 12: Relative distance between bones found using approximate centroids](image)

3.3 **Program Methodology, Code and Function**

Matlab computational software, version 7.0.4 (The MathWorks, Inc., Natick, Massachusetts) was utilized to create a program that works with the CT images in JPEG format in order to collect distance and rotational data. Code was written to implement a methodology in which to analyze the data with repeatable results (Appendix A).
3.3.1 Program Methodology

The initial part of the program finds the distance between the centers of the tibia and fibula. This is achieved by calculating the centroid of a user defined area for each bone. Finding the approximate centroid of the bone is achieved by calculating the area within the user defined region, then by finding the mean x, y location. The user defines the region of interest by using the mouse to select points around the boundary of each bone one at a time; a line is defined between the user selected points, creating the region of interest in a polygon shape defined as a dotted line illustrated in Figure 13. The program then averages the x and y coordinates of all the pixels within the user defined boundary to find the approximate centroid of the user defined region; the centroid does not depend on the number of points selected for the boundary, only the area within the boundary. The approximate centroid is found for both the tibia and the fibula in the same way and is shown as a plus sign in Figure 13. The centroid locations are used as endpoints of a line spanning the distance between the bones. To quantify the distance between the bones, the length of that line is calculated by the distance formula.
The centroids play a part in the next stage as they are the point that serves as the center of rotation. The next part of the program correlates loading conditions in order to determine the angle of rotation of the fibula relative to the tibia. This is accomplished using a four step process. Before it begins, two loading conditions are chosen, the condition of interest (Figure 14A) and the reference condition (Figure 14B). The reference condition will be used as a reference to determine if there is a change in rotation of the fibula based on the matching of the tibias from both loading conditions.

Step 1: The tibia of interest is shaved down into a template containing only the tibia.
Step 2: The tibia of interest (Figure 14A) is correlated with the reference tibia (Figure 14B) through translation and rotation and the maximum correlation coefficient and the corresponding angle (theta) are found (Figure 14C).
Step 3: The fibula of interest is shaved down into a template containing only the fibula.

Step 4: The fibula of interest has an initial rotation of theta and then goes through a series of translations and rotations and the maximum correlation coefficient and the corresponding angle (alpha) are found (see Figure 15).

Alpha represents the angular rotation of the fibula relative to the tibia based on the initial image rotation of theta found from matching up the tibias (Figure 14C). Figure 15A and 15B illustrate how positive and negative rotation of the fibula relative to the tibia angle $\alpha$ is defined.

Figure 14: (A) Condition of interest, (B) condition of reference and (C) overlaying images to determine tibia rotation $\theta$
Figure 15: Definition of (A) positive and (B) negative rotation $\alpha$ of the fibula relative to the tibia

In order to find the relative rotation, comparisons between loading conditions must be made. The three comparisons are in table 3, where the first loading condition is the reference condition and the next is the condition of interest.

**Table 3: Comparison of loading conditions**

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Reference condition</th>
<th>Condition of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (no socket, no load)</td>
<td>2 (socket, no load)</td>
</tr>
<tr>
<td>2</td>
<td>2 (socket, no load)</td>
<td>3 (socket, 50lb load)</td>
</tr>
<tr>
<td>3</td>
<td>2 (socket, no load)</td>
<td>4 (socket, 100lb load)</td>
</tr>
</tbody>
</table>

The reason for this choice is that no load condition will be compared to one another and the two loads with socket donned will be compared to the socket with no load.

The choice of the centroid for the point of rotation was not of great importance, but a necessary step for rotating the image. Any arbitrary point on the image could have been chosen and the rotation angle would have been the same, as illustrated in Figures 16.1
and 16.2. Figure 16.1 demonstrates two points chosen for rotation of the image, the star represents the centroid, and the circle represents an arbitrary point. Once the original image is rotated some angle $\beta$ about the chosen point as presented Figure 16.1, the original image is matched up with the rotated image using the point of rotation. Both rotated images can be overlaid (Figure 16.2A) in order to observe that the only difference between the two methods is a minor translation of the image rotated about the arbitrary point represented by the circle (figure 16.2B). The centroid was chosen because of its definition early on in the program.

Figure 16.1: Point of rotation illustration
3.3.2 Approach of Code

Figure 17 shows four CT slices, one from each of the four conditions that are taken from the same approximate location on the leg.

P1.1 no prosthetic, no load (slice 185)  P1.2 prosthetic, no load (slice 172)
Two images at a time from Figure 17 will be compared to determine the angle of rotation of the fibula relative to the tibia. As mentioned, comparison 1 will use the second condition (prosthesis, no load) as the condition of interest and the first condition (no prosthesis, no load) as the reference condition. By visually inspecting images P1:1 and P1:2 from Figure 17, there appears to be rotation of the entire image of P1:2 in the counter-clockwise direction when compared to P1:1, the reference. This must be corrected so that the tibias will start at the same position in order to determine if there is rotation of the fibula relative to the tibia. This angle of rotation can be achieved by creating a template of the tibia from the rotated image of interest and using Matlab to correlate the template with the tibia from condition of reference.

Two templates were created, one for the desired size of the template that only includes the tibia (T), and a larger template to use in rotation of the image (Or). Rotation was achieved by finding the centroid of the tibia (mean of the x and y values of user defined
region) and rotating the image about that point. Once the image is rotated, it will be cropped to the size of the initial template; the larger image is needed in rotation because once the image is rotated, MATLAB adds on some excess black border around the image that causes the correlation coefficient to decrease. When the images closely match each other, the correlation coefficient is high, and when there is low matching of the images, the correlation coefficient is low. Due to some slight noise or artifacts in the images, it is difficult to achieve a correlation coefficient of 1, so the highest coefficient and its corresponding angle are selected.

3.3.2.1 Template Creation

Figure 18 illustrates what is meant by template creation. In order to achieve a high level of correlation for the images, it is important to trim the image down to the defining features so that there is no disruption from another well defined feature. Another reason is that when Matlab rotates an object, it rotates the entire object which ends up adding on black space around the edges and ruins the correlation, as seen in Figure 19.

![Original (Or) Template (T)](image)

Figure 18: Template creation of the tibia to use in rotation
3.3.2.1.1 Rotating The Images

Figure 19: The templates for the fibula rotation and correlation

Once the templates are created, the image of the tibia is rotated, and translated across the reference image. Every time the image is rotated, the image template Or is rotated (Tr), then trimmed down to the size of T so that no black border is present; Tn is the image that is used in correlation. Another reason for the additional template creation is to ensure none of the tibia is lost when rotated and trimmed. After all of the pre-specified rotations have taken place, the maximum correlation coefficient and its corresponding angle value are determined. This value is theta, the value accounting for the entire image rotation. Once the angle of correction (theta) is found, the same concept of template creation is applied to the fibula. Once the template is created, an initial rotation of theta (angle for the tibias to match up) is automatically applied so that the rotation and correlation of the fibulas would not need any addition correction. The images for the template creation and rotation are in Figure 20.
3.3.2.2 Method for Finding the Rotation Angle

When the images are correlated, the values of the correlation coefficients and the associated angles of rotation are stored in an array for later analysis. Once the image has been rotated the pre-specified amount (n), then the correlation coefficient array is tested to find its maximum value. Once that value is found, the associated angle of rotation is also found. The actual angle of rotation may be somewhere in between the increments used to rotate the image, so polynomial fitting was utilized in order to get a better approximation.

3.3.2.3 Finding True Rotation Angle using Polynomial Fitting

In order to maximize the efficiency of the program, there were trade-offs. The more angles the program had to run through added time onto the length of program run time. In order to have the code perform in a reasonable amount of time, the number of angles it cycled through was reduced and the data points that were found were fit using a polynomial distribution. The correlation should have something close to a parabolic shape to it; therefore the maximum estimated correlation coefficient from a fit should be close to the actual correlation coefficient. Several runs were completed to test this theory and the results are in Figure 21. Originally, the angle increments were smaller, but with
too many points the plots were rough with multiple local extrema. To fix this problem, the number of angle increments was slightly decreased, and finally the polynomial was used to fit the data and find the maximum value (Figure 21).

![Figure 21: Fibula rotation from -1: 1 degrees in 0.05 degree increments (after image rotation correction) with 3rd and 4th polynomial fit](image)

Both third and fourth order polynomial fits were used because of the sufficient number of points.

### 3.4 Collection of Distance and Rotation Measurements

A Microsoft Excel spreadsheet was created in order to both store the results from the program, but also to randomize the collection process in order to evenly distribute
nuisance factors and the learning curve of measurement collection. Data from all four conditions at all five selected levels were randomized in a spreadsheet using the slice numbers. The data was randomized for collection purposes because there is a learning curve in selecting the boundary points when using the program and the image quality is not consistent for all images. Randomization ensures that the learning curve and the image quality is distributed throughout the measurement process. Once the collection was complete, the measurement results were sorted according to the level and position for graphical analysis and then statistical analysis.

Excel was used to perform some preliminary analysis of the distance and rotation measurement data. The data was plotted to determine if there was a trend and then embedded functions were used to analyze the data based on pre-existing null hypothesis, such as comparison of the means using an F-test.

The design for data collection and analysis was completely randomized with a data collection sample size of 20 distance and rotation measurement data points using genuine replicates. Originally, 20 data point were collected for each distance measurement. Rotation was not statistically analyzed due to the lack of trend in most of the data and the non-normality showing that many of the statistical tests do not apply.
4 Results

4.1 Results of Distance and Rotation Measurements

Before the data collection was underway, some predictions were made about the general movement of the bones. Under the change in conditions, there was anticipated movement of the bones and the change in distance would occur with the increase of load applied, including the donning of the socket. With the knowledge that there is movement of the bones under loading conditions based on previous research, this is a safe assumption. It was anticipated that once the socket was donned, and then when increasing load was applied, the change in distance between the bones would be greater near the distal region of the limb and become less at more proximal levels. Assuming a smaller change of distance closer to the knee joint is based on the concept that there would be less movement near a boney attachment with a greater ability of movement near the distal region of the limb due to lack of a stabilizing component such as the ankle. The behavior concerning rotation of the bones relative to one another was not premeditated as the reaction of the bones under a loading condition was unknown to the experimenters.

After the procedure was performed and the measurement collection was completed, the theory of change in distance between the bones under increasing loading conditions did not necessarily hold true. The distance between the bones did decrease with comparison 1 once the socket was donned and the change in distance between the bones increased for comparison 3 (when the 100 pound load was applied), but there was no apparent significant movement for comparison 2 (as the 50 pound load was applied). There did appear to be a decreasing trend in the change in distance moving from distal to proximal sampling locations on the limb. The rotational data did not exhibit such trends and
generally stayed within 1 degree of rotation in either clockwise or counterclockwise direction.

### 4.2 Preliminary Distance Measurements

In order to simplify the data analysis, preliminary analysis was conducted using both the DTFF subject and the traditional transtibial amputation subject.

![Figure 22: Distance between the tibia and fibula for both subjects under 4 different loading conditions at ROI 1](image)

Figure 22 illustrates the distance between the tibia and fibula for both subjects under 4 different loading conditions at ROI 1.

Figure 22 illustrates the distance between the tibia and fibula for both subjects. With a 20 mm difference in scale for the two results, the change may be more apparent if the change in distance between the different conditions were compared with one another.
The measurement of the mean change in distance was calculated by subtracting the individual comparisons of conditions from Table 3. For example, the first condition comparison would be the average distance between the bones from loading condition 2 (Socket, 0lbs) minus the average distance between the bones from loading condition 1 (No Socket). Figure 23 illustrates the difference in the mean distances between the bones for the three comparisons. There is no apparent significant change in distance between conditions for the DTFF amputation procedure received by subject 2 at the ROI 1 (Table 4). Due to the lack of apparent significant movement between the bones of the DTFF subject at ROI 1, the measurements for different locations on the limb were performed.
solely on subject 1. Although there is no apparent significant difference between conditions 2 and 3 for subject 1, the rest of the results warrant further investigation at other regions of the limb.

### Table 4: Mean change in distance between conditions at ROI 1 for both subjects

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Mean Change in Distance (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>Socket, 0lbs - No Socket</td>
<td>0.137 ± 0.514</td>
</tr>
<tr>
<td></td>
<td>Socket: 50 lbs - 0lbs</td>
<td>1.602 ± 0.497</td>
</tr>
<tr>
<td></td>
<td>Socket: 100lbs - 0lbs</td>
<td></td>
</tr>
<tr>
<td>DTFF</td>
<td>0.340 ± 0.533</td>
<td>0.046 ± 0.445</td>
</tr>
</tbody>
</table>

### 4.3 Distance and Rotation Measurements for Subject 1

Figure 24: Distance between the tibia and fibula at different locations on the limb under 4 different loading conditions for subject 1

Figure 24 illustrates the distance between the tibia and fibula for subject 1 under 4 different loading conditions for 5 different locations on the limb. From visual inspection
of Figure 24, there appears to a trend in the data collected. The result of these measurements is presented in Table 5. Figure 25 will attempt to discern if there is a trend in the distance data collected.

Table 5: Distance Data Collected from all locations on the limb of subject 1 under all loading conditions

<table>
<thead>
<tr>
<th>Region of Interest</th>
<th>Mean Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Socket, 0lbs</td>
</tr>
<tr>
<td>1</td>
<td>60.38 ± 0.401</td>
</tr>
<tr>
<td>2</td>
<td>61.85 ± 0.287</td>
</tr>
<tr>
<td>3</td>
<td>65 ± 0.340</td>
</tr>
<tr>
<td>4</td>
<td>67.29 ± 0.377</td>
</tr>
<tr>
<td>5</td>
<td>71.24 ± 0.399</td>
</tr>
</tbody>
</table>
Figure 25: Trends in distance between the tibia and fibula at different locations on the limb under 4 different loading conditions (with linear fit and the coefficient of correlation) for subject 1.

The coefficient of correlation in Figure 25 ($R^2$) relates to how close the data can be fitted with a straight line, where a coefficient of 1 means a perfect fit. All of the coefficients are close to 1 illustrating a good linear fit. The next focus should be whether there is a trend in the change in distance, as illustrated in Figure 26.
Figure 26: Change in distance between the tibia and fibula at different locations on the limb between different loading conditions for subject 1

Again, the measurement of the mean change in distance was calculated by subtracting the individual comparisons of conditions in Table 3. Figure 26 illustrates the average change in distance between the bones for subject 1 at the 5 region of interest locations on the limb. There appears to be a decrease of the change in distance between the bones as the measurements are taken more proximally up the limb. The difference between the first and second loading condition of comparison 1 causes a decrease in the distance between the bones (they move toward one another) while the difference between the second and fourth loading condition of comparison 3 yields an increase in the change in distance (the bones move away from one another). However, there does not appear to be significance
for the change in distance between the second and third loading condition of comparison 2 (when 50lbs of force is added to the socket with no force applied).

After the distance measurements are performed, the rotational measurements must be collected. Initially the entire image rotation found by matching up the tibias is presented in Figure 27.

![Figure 27: Rotation of entire image based on matching/correlating the tibias between different loading conditions at different locations on the limb for subject 1](image)

The trend for the image rotation should remain very similar regardless of the location on the limb. There are slight variations, most notably from the 4 ROI to the 5 ROI for comparison 3, illustrated in Figure 27. This might be due to more than image rotation and may delve into biomechanics of the limb as the region moves closer to the knee joint.
Figure 28: Rotation of the fibula relative to the tibia between different loading conditions at different locations on the limb for subject 1.

Figure 28 represents the data rotational collected for subject 1. There is no apparent problem with the method, due to the low value of error, but the data seems erratic. Because of the methodology’s high precision and ability to collect any minor movement or rotation of the bones relative to one another, this behavior warrants further study with more subjects and conference with other studies. Figure 28 illustrates that the majority of rotation was within ±1 degree or rotation, excluding comparison 1 at ROI 4, where the rotation was 2.20 ± 0.148 degrees.
4.4 Statistical Methodology

The focus of the statistical testing was to validate the methodology created because there were originally only two subjects in the study. After some preliminary testing, subject 2 was removed due to lack of significance and only subject 1 had extensive measurements made. The statistical analysis is used to prove the low variability in the measurements illustrating the methodology’s high precision. Without comparison with other subjects, it will be difficult to make solid conclusions on the actual results of the measurements made, but not on the precision of the measurements.

4.4.1 Statistical Design

Statistical tests will be run to determine if the distance measurements are significantly different under different loading conditions, when compared from one loading condition to the next. This analysis was completed for validation of the methodology, so sample size was not a focal issue.

With use of a paired t-test and using a 95% confidence level, the determination will be made if there any evidence to support a claim that there is a difference in mean distance of the bones between the two conditions of these three different comparisons from Table 3 at any of the 5 ROI’s for subject 1:

\[ H_0: \mu_1 - \mu_2 = 0 \text{ (no difference)} \]

\[ H_1: \mu_1 - \mu_2 \neq 0 \text{ (difference)} \]

If the null hypothesis is rejected, then accept that there is a difference in the mean distances between the two conditions.
4.4.2 Statistical Results

With a confidence level of 95%, using a students paired t-test to determine if there is a significant difference of mean distance between bones for subject 1. Table 6 illustrates the results of the testing for all measurements at all levels of the limb.

Table 6: Results from Statistical Test

<table>
<thead>
<tr>
<th>ROI</th>
<th>pvalue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 tail</td>
</tr>
<tr>
<td>Compare 1</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.0000</td>
</tr>
<tr>
<td>3</td>
<td>0.0000</td>
</tr>
<tr>
<td>4</td>
<td>0.0000</td>
</tr>
<tr>
<td>5</td>
<td>0.0000</td>
</tr>
<tr>
<td>Compare 2</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0976</td>
</tr>
<tr>
<td>2</td>
<td>0.4446</td>
</tr>
<tr>
<td>3</td>
<td>0.0546</td>
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<tr>
<td>4</td>
<td>0.0086</td>
</tr>
<tr>
<td>5</td>
<td>0.0059</td>
</tr>
<tr>
<td>Compare 3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.0000</td>
</tr>
<tr>
<td>3</td>
<td>0.0000</td>
</tr>
<tr>
<td>4</td>
<td>0.0000</td>
</tr>
<tr>
<td>5</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Table 6 shows that with two-tail t-test at a level of 95%, the difference in comparison 2, between condition 2 and condition 3, is not significant for ROI 1, 2 or 3, but when a one-tail t-test was used, the only non-significant difference occurred during comparison 2, between condition 2 and condition 3, at the lower level, otherwise all of the differences were statistically significant.
5 Discussion

5.1 Methodology

With one subject, a methodology was developed to measure the distance between the tibia and the fibula and rotation of the fibula with respect to the tibia. This measurement technique can be applied to multiple subjects in order to ascertain whether there is bone movement. Figures 22 and 24 for the distance measurements as well as Figures 27 and 28 for rotation measurements illustrate the small standard deviations and highlight the precision of the method. The average standard deviation for distance between the bones is 0.374 mm (range 0.287 – 0.484 mm) and the average standard deviation for rotation measurement is 0.131 degrees (range 0.0748 - 0.1994 degrees). By using all of the pixels within the user defined area for centroid calculation as opposed to using only the boundary points selected, more precision was accomplished in the distance measurements. This precision translated similarly to the rotational measurements as all pixel values within the defined template were used to compare and correlate the images for the maximum correlation coefficient and corresponding angle.

The methodology created and discussed is a basic approach at solving a complex problem with nuisance factors, such as image quality and movement of the subject between loading conditions. The issue of concern with accuracy of the program is mostly due to quality of the images. If this study is to be repeated, the future studies should be careful to ensure that the image quality is uncompromised by any metal in proximity of the spiral CT scanner. Another focus is the program capabilities. Although the application of correlation through the use of Matlab produces a decent estimate of actual bone rotation, the image rotated may end up somewhat skewed based on the method of rotation utilized,
which may over estimate or underestimate the value of the surrounding pixels when interpolating.

Something that was not accounted for in designing the experiment was a physical point of reference in all conditions that would be used to establish what directions of movement occurred and may have made the determination of motion more evident and easily established. A nuisance factor unaccounted for and introduced into the experiment was the movement of the limb in-between computed tomography of each condition and may have moved due to the force exerted on the limb. For a multiple subject study, a frame of reference should be established both on the body for evaluation of the CT scans and for positioning of the subject when the scans are taken, thus more error could be removed from the procedure of determining the motion. Other methodologies exist that have tried to focus on similar aspects using a variety of techniques. Madsen et al discusses issues with current spiral CT methods trying to model loading conditions such as the subject having to lie horizontally which causes loading conditions to be difficult for subject to maintain due to lack of feedback. The device the author designed to correct for this would also allow for consistent positioning. Another study placed a thin steel wire inside patella tendon-bearing socket for reference.

5.1.1 Recommendations

The difficult task is proving this methodology to be sound using data that has artifacts from metal usage while the CT scanning was taking place and having no previous data with which to compare the present results. A 1985 study that used a similar methodology manually overlaid film from different loading conditions, matched up the tibias, and then measured the relative change in position by poking holes in approximate centers of
fibulas\textsuperscript{36}. This method was used on film from subjects with healthy, intact limbs, so the results can not be compared directly. Other studies utilizing CT scans measured movement of the tibia relative to the socket, or the limb relative to the socket, so their results could not be compared, either. The main problem with comparing this methodology to any other pre-existing methodology performed is the technique used in measuring any movement and the repeatability of the performed methodology.

5.1.2 Boundary Detection Programs

Another option of corroborating the distance measurement results would be to utilize a boundary detection program, also known as a snake algorithm. Boundary detection programs work to find the sharp change in pixel values to define the boundary of an object using an initially defined starting location. The metal used in the portal gravity system blurred some of the images from the CT data and made it difficult for a boundary detection program to find the outline of the bones. The prosthesis also had similar density to bone making an automatic boundary detection program difficult to utilize in the entire image. Once some of the issues of image quality are resolved, a snake algorithm can be modified and utilized with the CT images in order to determine the boundary of the bones. The boundary information can then be used with the proposed methodology to find the area within the boundaries, the centroids, and finally the distance between the centroids of those areas.

The snake algorithm could only be used to find the boundary of the bones, but not in analyzing the distance between the two bones or to determine the relative rotation due to the limitation of the program. The snake algorithm could be used for a comparison in boundary determination and centroid location based on the boundary.
5.2 Statistical Results

The statistical results of the study show that, as expected, there is a difference in the bone movement from one loading condition to the next. The only minor discrepancy of the testing of the means is failing to reject that there is no difference in the mean distance from condition 2 to condition 3 for the lower level on the limb after performing a one tailed paired t-test at a 95% confidence level (p = 0.2223). The rest of the mean distances appeared significantly different between conditions.
6 Conclusions

6.1 Conclusion of Methodology

A method to measure the distance between the tibia and fibula and the relative rotation of the fibula to the tibia under different loading conditions was developed and evaluated. This methodology can apply to both healthy and amputated limbs with the use of computed tomography technology. This is a new approach in that it is repeatable and can be applied to a larger number of subjects, which can then be compared in order to determine the true biomechanical behavior of the tibia and fibula in a transtibial amputee. The success of the methodology lies within the precision and ability to detect small amounts of movement; this can be illustrated using the average standard deviation. The average standard deviation for distance between the bones is 0.374 mm (range 0.287 – 0.484 mm) and the average standard deviation for rotation measurement is 0.131 degrees (range 0.0748 - 0.1994 degrees). The collection of the data under genuine replicate conditions was a successful attempt to minimize the level of uncertainty.

6.2 Clinical application

This methodology could be applied to both amputees and non-amputees to determine internal biomechanics during the gait cycle. If coupled with gait analysis, then there is a better chance of understanding what occurs in vivo without invasive procedures. This ultimately can be used to discern whether the Ertl procedure or a modification is truly beneficial in reducing motion, allowing for weight bearing capabilities or has any palpable benefits over a traditional transtibial amputation. If a patient claims there is large or unusual movement of the bones after a transtibial amputation, this methodology can be applied to measure the movement and the results
can be compared to the patient defined movement. Pain can be compared with the measured movement as well to see if there is correlation between the two, and with more subjects, a study may be possible to link movement with pain.

Another application is that this information can also be used in prosthetic fitting techniques to provide an optimal socket in reducing movement or changing the stress distribution on the overall limb. With knowledge of the biomechanics of the residual bones and tissue and the prosthetic, a model can be created and validated in order to aid in proactive individual prosthetic design.

6.3 Future applications

The data analysis of the CT scans from this study will be used to validate a finite element model of the residual limb in order to model the interface of the limb and prosthesis during the gait cycle with the aim of improving prosthesis fitting. As previously mentioned, this could allow for a practical guide for individual prosthetic design and fitting. The CT data can also be used to reconstruct the soft tissue of the limb to observe how the limb changes shape with different loading conditions or to observe a pistoning effect during the gait cycle. This study focused on a preliminary experiment; more subjects would bring significance and relevance to the findings and a model may be created to establish what biomechanically occurs during a simulated gait cycle in either a normal or amputated limb.
References


8 Appendix

8.1 Appendix A: Matlab Code

% added to combine all correlation programs into one for all images 9.14.06
fprintf('n');
comp = input('Please enter the slice number of interest (i.e. 2.172):');
fprintf('n');
These are the files to correlate the images with
% Distal
if comp == 2.172
    compare = ('C:\P1_1_\1 (184).jpg');
elseif comp == 3.154
    compare = ('C:\P1_2\1 (171).jpg');
elseif comp == 4.146
    compare = ('C:\P1_2\1 (171).jpg');
% Lower
elseif comp == 2.165
    compare = ('C:\P1_1_\1 (177).jpg');
elseif comp == 3.147
    compare = ('C:\P1_2\1 (164).jpg');
elseif comp == 4.139
    compare = ('C:\P1_2\1 (164).jpg');
% Mid
elseif comp == 2.152
    compare = ('C:\P1_1_\1 (164).jpg');
elseif comp == 3.134
    compare = ('C:\P1_2\1 (151).jpg');
elseif comp == 4.126
    compare = ('C:\P1_2\1 (151).jpg');
% Upper
elseif comp == 2.138
    compare = ('C:\P1_1_\1 (150).jpg');
elseif comp == 3.120
    compare = ('C:\P1_2\1 (137).jpg');
elseif comp == 4.112
    compare = ('C:\P1_2\1 (137).jpg');
% Mid-Limb
elseif comp == 2.120
    compare = ('C:\P1_1_\1 (132).jpg');
elseif comp == 3.102
    compare = ('C:\P1_2\1 (119).jpg');
elseif comp == 4.94
    compare = ('C:\P1_2\1 (119).jpg');
% Final
elseif comp == 2.102
    compare = ('C:\P1_1_11 (114).jpg');
elseif comp == 3.84
    compare = ('C:\P1_2\1 (101).jpg');
elseif comp == 4.76
    compare = ('C:\P1_2\1 (101).jpg');
else
    fprintf('That slice does not exist.');
    fprintf('

');
    break
end

These are the files to select the image

Distal
if comp == 2.172
    image = ('C:\P1_2\1 (171).jpg');
elseif comp == 3.154
    image = ('C:\P1_3\1 (153).jpg');
elseif comp == 4.146
    image = ('C:\P1_4\1 (145).jpg');

Lower
elseif comp == 2.165
    image = ('C:\P1_2\1 (164).jpg');
elseif comp == 3.147
    image = ('C:\P1_3\1 (146).jpg');
elseif comp == 4.139
    image = ('C:\P1_4\1 (138).jpg');

Mid
elseif comp == 2.152
    image = ('C:\P1_2\1 (151).jpg');
elseif comp == 3.134
    image = ('C:\P1_3\1 (133).jpg');
elseif comp == 4.126
    image = ('C:\P1_4\1 (125).jpg');

Upper
elseif comp == 2.138
    image = ('C:\P1_2\1 (137).jpg');
elseif comp == 3.120
    image = ('C:\P1_3\1 (119).jpg');
elseif comp == 4.112
    image = ('C:\P1_4\1 (111).jpg');

Mid-Limb
elseif comp == 2.120
    image = ('C:\P1_2\1 (119).jpg');
elseif comp == 3.102
    image = ('C:\P1_3\1 (101).jpg');
elseif comp == 4.94
image = ('C:\P1_4\1 (93).jpg');
elseif comp == 2.102
    image = ('C:\P1_2\1 (101).jpg');
elseif comp == 3.84
    image = ('C:\P1_3\1 (83).jpg');
elseif comp == 4.76
    image = ('C:\P1_4\1 (75).jpg');
else
    fprintf('That slice does not exist.
    
    ');break
end

%process.m added on 8.10.06

% [fname,directory]=uigetfile('*.jpg','Choose the file to load:');
% wholename = [directory,fname];
% IM0 = imread(wholename);
% IM = IM0(:,:,1);
IM0 = imread(image);
IM = IM0(:,:,1);
imshow(IM);

% fprintf('

')
% fprintf('Use the mouse to define the area of interest by single \n')
% fprintf('clicking on the boundary of the tibia. Double click to finish.
')
% fprintf('

');BW1 = roipoly;
BW is a 0-1 image. The circled area contains 1s.
% By summing these 1s, s becomes the total number of pixel in the area.
[i1,j1] = find(BW1);

% Centroid Location:
xt = mean(j1);
yt = mean(i1);

% fprintf('Use the mouse to define the second area of interest by single\n')
% fprintf('clicking on the boundary of the fibula. Double click to finish.\n')
% fprintf('

');BW2 = roipoly;
[i2,j2] = find(BW2);

% Centroid Location:
xf = mean(j2);
yf = mean(i2);
distance = sqrt((xf-xt)^2 + (yf - yt)^2);
dist_in_mm = .938*distance

%Rotation creates the template and finds the position of tibia and correlates
%this template to other images. Then the template is rotated to find the
%highest level of correlation for the tibia. This angle will be used as a
%starting point to find the rotation of the fibula

xt = round(mean(j1)); %Get error message when round isn't used
yt = round(mean(i1));

%decide the cropping distance L to use in creating template
Lt1 = max(i1)-min(i1); %max length of y dir
Lt2 = max(j1)-min(j1); %max length of x dir

%if, else, '+2' ensures entire bone would be captured in rotation
%'L/2' needed so that only focal bone is captured
if Lt1 > Lt2
    Lt = round(Lt1/2)+2;
else
    Lt = round(Lt2/2)+2;
end
wt = round(2*Lt);

%define area for template
    xtmin = xt-Lt;
ytmin = yt-Lt;
    xtm = xt-wt;
ytm = yt-wt;

%Create templates, T for initial and Original for rotation
T = IM(ytmin:yt+Lt,xtmin:xt+Lt); %template (T) creation
%imshow(T);
Or = IM(ytm:yt+wt,xtm:xt+wt); %template (Original) creation
%imshow(Or);

IM1 = imread(compare);
IM2 = IM1(:,:,1);

%rotate 0.1 degree, check/store correlation coeff
theta = 0.5; %changed from 0.1 to 0.5 on 9.20.06
Tr = imrotate(Or,theta,'bilinear');
C = round(size(Tr,1)/2);
Tn = Tr(C-Lt:Lt+C,C-Lt:Lt+C);
cc1 = normxcorr2(Tn,IM2);
[max_cc1] = max(abs(cc1(:)));
%%rotate -0.1 degree, check/store correlation coeff
theta = -0.5;  % changed from 0.1 to 0.5 on 9.20.06
Tr = imrotate(Or,theta,'bilinear');
C = round(size(Tr,1)/2);
Tn = Tr(C-Lt:Lt+C,C-Lt:Lt+C);
cc2 = normxcorr2(Tn,IM2);
[max_cc2] = max(abs(cc2(:)));
%imshow(Tn);
corr2 = max_cc2;

if corr1 > corr2
    flag = 1;  % this will determine if the image initially rotates cw
else
    flag =-1;  % this will determine if the image initially rotates ccw
end

%%collect the correlation coefficients by rotating the tibia template image
%%from 1 to 10 degrees in the direction specified by the flag (above)
countn = 0;
anglen = zeros(1,15);
%disp('Starting to find theta');
corr_1 = zeros(1,15);
for n=0:0.5:7 % decided on 7 degrees; all image rotation < 6.5, 9.26.06
    countn = countn+1;
    anglen(countn) = n;
    theta = n*flag;
    Tr = imrotate(Or,theta,'bilinear');
    C = round(size(Tr,1)/2);
    Tn = Tr(C-Lt:Lt+C,C-Lt:Lt+C);
    cct1 = normxcorr2(Tn,IM2);
    [max_cct1] = max(abs(cct1(:)));
    %imshow(Tn);
corr_1(countn) = max_cct1;
end
[c_1, a] = max(corr_1);
A = anglen(a-1)*flag;
%ppi=polyfit(anglen*flag,c_1,3);
%Xi=flag*(0.1:0.0001:7)';
%YYi=[Xi.^3 Xi.^2 Xi ones(size(Xi))]*ppi';
% plot(anglen*flag,c_1,'o',Xi,YYi);
countn = 0;
anglen1 = zeros(1,10);
corr = zeros(1,10);
for n=0.1:0.1:1
    countn = countn+1;
    anglen1(countn) = n;
    theta = A+n*flag;
    Tr = imrotate(Or,theta,'bilinear');
    C = round(size(Tr,1)/2);
    Tn = Tr(C-Lt:Lt+C,C-Lt:Lt+C);
    cct = normxcorr2(Tn,IM2);
    [max_cct] = max(abs(cct(:)));
    imshow(Tn);
    corr(countn) = max_cct;
end
[c1, a1] = max(corr);

% trying to get a polynom fit
pp1=polyfit(anglen1*flag+A,corr,3);
X1=flag*(0.1:0.0001:1)';
X1=X1+A;
YY1=[X1.^3 X1.^2 X1 ones(size(X1))]*pp1';
% plot(anglen1*flag+A,corr,'o',X1,YY1);
% xlabel('Angle Increments');
% ylabel('Correlation Coefficient');
% legend('data','polyfit, 3rd degree',4);
[mm1,xx1]=max(YY1);
mm1;
theta=X1(xx1)

% Centroid Location:
xf = round(mean(j2));
yf = round(mean(i2));

% decide the cropping distance L
Lf1 = max(i2)-min(i2);  %length of x dir
Lf2 = max(j2)-min(j2);  %length of y dir
if $Lf_1 > Lf_2$
    $Lf = \text{round}(Lf_1/2)+2$;
else
    $Lf = \text{round}(Lf_2/2)+2$;
end

$wf = \text{round}(2*Lf)$;

%define area for template
if $Lf < xf$
    $xfmin = xf-Lf$;
    $yfmin = yf-Lf$;
    $xfm = xf-wf$;
    $yfm = yf-wf$;
else
    $xfmin = Lf-xf$;
    $yfmin = Lf-yf$;
    $xfm = wf-xf$;
    $yfm = wf-yf$;
end

%Create templates

$F = \text{IM}(yfmin:yf+Lf,xfmin:xf+Lf)$; %template (F) creation
% imshow(F);
$Or2 = \text{IM}(yfmin:yf+wf,xfmin:xf+wf)$; %template (Or2) creation
% imshow(Or2);

%disp('finding alpha');
%collect the correlation coefficients by rotating the fibula template image
%from 1 to 10 degrees in the direction specified by the flag2 (above)
$\text{countn} = 0$;
$\text{anglen2} = \text{zeros}(1,26)$;
$\text{cor} = \text{zeros}(1,26)$;
for $n=-3:0.2:2$
    $\text{countn} = \text{countn}+1$;
    $\text{anglen2}($countn$) = n$;
    $\text{alpha} = \theta + n$;
    $Fr = \text{imrotate}(Or2,\text{alpha},'\text{bilinear}')$;
    $C = \text{round}(\text{size}(Fr,1)/2)$;
    $Fn = Fr(C-Lf:C,Lf+L+C);$C-Lf);F
    $\text{ccf} = \text{normxcorr2}(Fn,IM2)$;
    $[\text{max}_\text{ccf}] = \text{max}(\text{abs}(\text{ccf}(:)))$;
% imshow(Fn);
    $\text{cor}($countn$) = \text{max}_\text{ccf}$;
end
% find the max correlation coefficient and corresponding angle of rotation
% from the data collected above
[c2, a2] = max(cor);
max_Alpha=anglen2(a2);

% trying to get a polynom fit 9.8.06
pp2=polyfit(anglen2,cor,3);
pp22=polyfit(anglen2,cor,4);
pp25=polyfit(anglen2,cor,5);

X2=(-3:0.0001:2)';
YY2=[X2.^3 X2.^2 X2 ones(size(X2))]*pp2';
YY22=[X2.^4 X2.^3 X2.^2 X2 ones(size(X2))]*pp22';
YY25=[X2.^5 X2.^4 X2.^3 X2.^2 X2 ones(size(X2))]*pp25';

plot(anglen2,cor,'o',X2,YY2,'-.',X2,YY22,':',X2,YY25,'-');
xlabel('Angle Increments');
ylabel('Correlation Coefficient');
legend('data','polyfit 3rd degree','polyfit 4th degree','polyfit 5th degree',4);

[mm2,xx2]=max(YY2);
[mm22,xx22]=max(YY22);
[mm25,xx25]=max(YY25);

% mm2
alpha_3rd=X2(xx2)
alpha_4th=X2(xx22)
alpha_5th=X2(xx25)