ACCURACY OF PRODUCING 3D PRINTED MODELS FROM CT SEGMENTATION RENDERINGS OF CADAVERIC ANKLE AND FOOT BONES AND THE KINEMATICS OF LOADED JOINTS IN THE ANKLE AND FOOT

By
Bonnie Sze Pui Lee

A thesis submitted to the Department of Biomedical and Molecular Sciences in conformity with the requirements for the degree of Master of Science

Queen’s University
Kingston, Ontario, Canada
(December, 2011)

Copyright © Bonnie Sze Pui Lee, 2011
Abstract

Introduction and Purpose: Total ankle arthroplasty is a relatively new and underdeveloped treatment for ankle arthritis that has shown disappointing results due to complications from malpositioning and improper sizing of the prosthesis during surgery as well as a lack of knowledge on the kinematics of the ankle and foot. The purpose of this study was two-fold: Part 1 analyzed the accuracy of producing three-dimensional (3D) printed models from computed tomography (CT) segmentation renderings and Part 2 examined the kinematics of the loaded joints in the ankle and foot.

Part 1:

Methods: CT images were taken from four cadaveric lower limbs and the ankle and foot bones were segmented into 3D virtual models and printed plastic models. A three-way analysis was performed between the CT segmentations, printed models and cadaveric bones.

Results: Sub-millimetre accuracy was achieved for all aspects of the analysis although the CT segmentations were consistently slightly larger than the printed models or cadaveric bones.

Part 2:

Methods: 3D fluoroscopic images were taken of four loaded cadaveric lower limbs in the plantarflexed, neutral and dorsiflexed positions. The images were
Segmented to produce 3D virtual models and the translation as well as rotation of the ankle, subtalar and talonavicular joints were analyzed.

**Results:** The ankle joint had little translation (0.4mm-2.5mm) but rotation of the tibiofibular mortise was great in the anterior/posterior (7.2°-51.9°), internal/external (2.1°-24.8°) and medial/lateral (2.2°-31.9°) directions. The talonavicular joint displayed the most translation (0.2mm-7.4mm) and had moderate rotation. The subtalar and talonavicular joints translated and rotated the most during loading of a foot in neutral position indicating that loading induces a significant amount of movement between bones.

**Conclusions:** This study found that 3D models of the ankle and foot bones could be successfully produced from their CT images with sub-millimetre accuracy and should be used for pre-operative planning and during surgeries. This study also reported more translation and rotation in the ankle and foot joints than allowed in current total ankle arthroplasties. As well, the simple action of loading a foot induces a lot of movement in the joints. This kinematic data is valuable to future revisions and designs of total ankle arthroplasty implants.
Acknowledgements

This thesis could not have been completed without the love, support and help from those whom I have been blessed to have in my life. I can never express just how thankful I am for all of your encouraging words and presence!

**To God:** First, I want to acknowledge my never ending thanks to my heavenly Father who has been there with me every step of the way. I cannot do anything without Him and I am so grateful for His love.

**To my family:** Mom and Dad, I want to thank you for your love, care and support through every stage of my life. Thank you for your prayers and for bringing me up in such a wonderful family. I love you both! To my sister Fiona, thank you for being my role model and best friend. I know I don’t have to say anything else for you to know how much I love you! To my brother-in-law Davin, thanks for all your care and encouragements. You’re just like a brother to me! To my grandmother, I want to thank you for bringing me up, for your prayers and unconditional love. To my grandfather, although you are a man of few words, I want to thank you for supporting me!

**To my friends:** I want to thank all my friends for their encouragements, care and support. Thanks for all your prayers and for your undying friendship no matter how far apart we are. I am so blessed to have you all in my life!

**To my classmates:** To the P2 class of 2011 (Hanin Abdullah, Alexandra Boasie, Drew Countryman, Emma Dowds, Dora Habib, Maria Komisarenko, Stephanie Reiter, Trish Scribbans, Gabriel Venne and Nicole Ventura), I want to say that I will miss you all! It’s been such a great 16 months and I wish that we had more time together. I hope that
we will always stay close and I wish for all the best with your careers!

**To my supervisors:** To Dr. Ron Easteal, Dr. Les MacKenzie, Dr. Stephen Pang, and Dr. Conrad Reifel, thank you so much for giving me this opportunity. I have never met teachers as passionate about anatomy and genuinely caring for their students! You are all truly inspirations to me! Thank you for your guidance, wisdom and for the time you took to invest in our lives. To Dr. Randy Ellis, thank you so much for being such a great supervisor. You were so patient and encouraging and I admire how you always made time for me amidst your busy schedule. I learned so much working with you!

**To my co-workers in Dr. Ellis’ Lab:** I am so thankful to have had the opportunity to work with all of you (Brian, Erin, Fiona, Gab, Greg, Joey, and Paul). You have all spent so much time helping me with my thesis and I cannot express just how grateful I am. To Erin, thank you for your patience and for all the hard work that you put into analyzing my data. You’ve sacrificed so much of your time for me and I definitely could not have finished my thesis without you! To Joey, thanks for always being there to answer any questions that I had and for all the work you’ve done for me.

**To the staff in the Human Mobility Resource Centre:** Thank you so much for all of your uplifting smiles and help throughout my thesis! I especially want to thank Carolyn Heymans for helping me out with printing all of my plastic models.

**To the staff in the Department of Biomedical and Molecular Sciences and Queen’s University:** I want to thank you all for your undivided attention and the resources and financial support you’ve provided me with. Thanks for running this program so smoothly and I appreciate all of your help! I want to especially thank Rick and Earl for all the advice that they’ve given me!
# Table of Contents

Abstract ......................................................................................................................................................... ii  
Acknowledgements ........................................................................................................................................ iv  
Table of Contents .......................................................................................................................................... vi  
List of Figures ................................................................................................................................................ xi  
List of Tables ................................................................................................................................................ xiii  
List of Abbreviations .................................................................................................................................... xiv  
Chapter 1 - Introduction .............................................................................................................................. 1  
1.1 - Anatomy and Biomechanics of the Ankle and Foot .............................................................................. 3  
1.1.1 - Kinematics of the Foot ..................................................................................................................... 5  
1.1.2 - Anatomy of the Middle and Distal Tibiofibular Joints ..................................................................... 7  
1.1.2.1 - Tibia ........................................................................................................................................ 9  
1.1.2.2 - Fibula ......................................................................................................................................... 9  
1.1.2.3 - Interosseous Membrane ........................................................................................................... 11  
1.1.2.4 - Middle Tibiofibular Joint .......................................................................................................... 13  
1.1.2.5 - Distal Tibiofibular Joint ............................................................................................................ 13  
1.1.2.6 - Movement at the Tibiofibular Joints and Function ..................................................................... 15  
1.1.3 - Anatomy of the Ankle (Talocrural) Joint ........................................................................................ 15  
1.1.3.1 - Tibia and Fibula ......................................................................................................................... 15  
1.1.3.2 - Talus ......................................................................................................................................... 15  
1.1.3.3 - The Ankle Joint ......................................................................................................................... 19  
1.1.3.4 - Movement at the Ankle Joint .................................................................................................. 20  
1.1.4 - Anatomy of the Subtalar (Talocalcaneal) Joint ................................................................................ 23  
1.1.4.1 - Talus ......................................................................................................................................... 23  
1.1.4.2 - Calcaneus ................................................................................................................................. 23  
1.1.4.3 - Subtalar Joint ............................................................................................................................ 26  
1.1.4.4 - Movements at the Subtalar Joint ............................................................................................. 28  
1.1.5 - Anatomy of the Talocalcaneonavicular Joint .................................................................................. 29  
1.1.5.1 - Talus ......................................................................................................................................... 29  
1.1.5.2 - Calcaneus ................................................................................................................................ 29
1.1.5.3 - Navicular .................................................................29
1.1.5.4 - The Talocalcaneonavicular Joint ................................30
1.1.5.5 - Movements at the Talocalcaneonavicular Joint ........32
1.1.6 - Interplay between the Subtalar and Talocalcaneonavicular Joints ....33
1.1.7 - Cuboid .................................................................33
1.1.8 - Muscles and their Functions in the Ankle and Foot Joints ....34
   1.1.8.1 - Anterior Compartment ......................................34
   1.1.8.2 - Lateral Compartment ........................................37
   1.1.8.3 - Posterior Compartment ......................................37
1.2 - History of Total Ankle Arthroplasty..............................38
1.3 - Current Total Ankle Arthroplasty Designs .....................42
1.4 - Complications of Total Ankle Arthroplasty ....................45
1.5 - Purpose of Thesis ....................................................48
1.6 - Hypotheses of Thesis .................................................49

Chapter 2 - PART 1: Analyzing the Accuracy of Producing 3D Printed Models from CT Segmentation Renderings of Cadaveric Ankle and Foot Bones ........50

2.1 - Experimental Design ..................................................50
2.2 - Materials and Methods ...............................................51
   2.2.1 - Materials ..........................................................52
   2.2.2 - CT Scan Acquisition ............................................54
      2.2.2.1 - CT Scan Parameters ......................................54
      2.2.2.2 - Leg Positioning ..............................................54
      2.2.2.3 - Export CT Image Data ....................................54
   2.2.3 - Protocol for the 3D Model Rendering Process (CT Segmentation) ....54
      2.2.3.1 - Import CT Image Data ....................................54
      2.2.3.2 - Thresholding ...............................................55
      2.2.3.3 - Editing Masks ..............................................55
      2.2.3.4 - Region Growing ............................................57
      2.2.3.5 - Calculate Polylines and Cavity Fill from Polylines ............59
      2.2.3.6 - Calculate 3D from Mask ..................................61
      2.2.3.7 - Exporting Files and Printing of the Plastic Models ............61
3.2.3 - Jig Design and Construction .................................................................101
3.2.4 - 3D Fluoroscopic Image Acquisition ..................................................103
  3.2.4.1 - Jig Set-Up ..................................................................................103
  3.2.4.2 - Leg Positioning .........................................................................104
    3.2.4.2.1 - Neutral Position .................................................................104
    3.2.4.2.2 - Dorsiflexion Position .........................................................104
    3.2.4.2.3 - Plantarflexion Position ......................................................104
  3.2.4.3 - Load Set-Up ..............................................................................107
  3.2.4.4 - 3D Fluoroscopic Image Parameters .........................................109
  3.2.4.5 - Export 3D Fluoroscopic Image Data ............................................109
3.2.5 - Protocol for 3D Model Rendering Process (CT Segmentation).........109
  3.2.5.1 - Import 3D Fluoroscopic Image Data ..........................................109
  3.2.5.2 - Thresholding ............................................................................110
  3.2.5.3 - Editing Masks ..........................................................................110
  3.2.5.4 - Region Growing .......................................................................110
  3.2.5.5 - Calculate Polylines and Cavity Fill from Polylines ......................110
  3.2.5.6 - Calculate 3D from Mask ............................................................110
  3.2.5.7 - Exporting Files ........................................................................110
3.2.6 - Quantitative Analysis of the Kinematics .........................................110
  3.2.6.1 - Kinematics of Tibia and Fibula with Talus .................................111
  3.2.6.2 - Kinematics of Talus with Calcaneus ..........................................114
  3.2.6.3 - Kinematics of Talus with Navicular ..........................................117
3.3 - Results ...............................................................................................119
  3.3.1 - Movement from Neutral Unloaded to Neutral Loaded Position ......119
    3.3.1.1 - Ankle Joint ............................................................................119
    3.3.1.2 - Subtalar Joint ........................................................................123
    3.3.1.3 - Talonavicular (of Talocalcaneonavicular) Joint ........................123
  3.3.2 - Neutral Loaded to Dorsiflex Loaded Position .................................124
    3.3.2.1 - Ankle Joint ............................................................................124
    3.3.2.2 - Subtalar Joint ........................................................................124
    3.3.2.3 - Talonavicular (of Talocalcaneonavicular) Joint ........................124
List of Figures

Figure 1.1 - Bones of the Foot ........................................................................................................4
Figure 1.2 - Foot Motion Around Three Axes .................................................................................6
Figure 1.3 - Tibia and Fibula ...........................................................................................................8
Figure 1.4 - Tibia .............................................................................................................................10
Figure 1.5 - Fibula ..........................................................................................................................12
Figure 1.6 - The Ankle Joint ...........................................................................................................14
Figure 1.7 - Talus ............................................................................................................................17
Figure 1.8 - Ankle Joint Capsule ...................................................................................................21
Figure 1.9 - Medial Ligaments of the Ankle and Foot .................................................................21
Figure 1.10 - Lateral Ligaments of the Ankle and Foot ............................................................22
Figure 1.11 - Calcaneus ..................................................................................................................25
Figure 1.12 - Tarsal Sinus ..............................................................................................................27
Figure 1.13 - Navicular ...................................................................................................................31
Figure 1.14 - Cuboid .......................................................................................................................35
Figure 1.15 - Anterior Compartment Muscles of the Leg ...........................................................36
Figure 1.16 - Posterior (Deep Layer) and Lateral Compartment Muscles of the Leg .................39
Figure 1.17 - Posterior (Superficial Layer) Compartment Muscles of the Leg ..........................39
Figure 1.18 - Current Total Ankle Arthroplasty Designs .............................................................43
Figure 2.1 - Mimics Workspace with Imported CT Images ..........................................................56
Figure 2.2 - Thresholding for Bony Material ..................................................................................56
Figure 2.3 - Edit Masks ..................................................................................................................58
Figure 2.4 - Region Growing ..........................................................................................................60
Figure 2.5 - Calculate Polylines and Cavity Fill from Polylines ...................................................60
Figure 2.6 - 3D Virtual Model ........................................................................................................62
Figure 2.7 - Printed 3D Plastic Models ...........................................................................................62
Figure 2.8 - Removing Extraneous Data from a Laser Scan Patch ..............................................66
Figure 2.9 - Stitching Laser Scan Patches ......................................................................................66
Figure 2.10 - Completed Laser Scan Models ................................................................................69
Figure 2.11 - Aligning Laser Scan Patches with the CT Segmentation.............................71
Figure 2.12 - Topographical Colourmap of the Talus .......................................................80
Figure 2.13 - Topographical Colourmap of the Calcaneus................................................80
Figure 2.14 - Topographical Colourmap of the Navicular ................................................81
Figure 2.15 - Topographical Colourmap of the Cuboid ....................................................81
Figure 2.16 - Topographical Colourmap of the Tibia........................................................83
Figure 2.17 - Topographical Colourmap of the Fibula......................................................83
Figure 2.18 - Qualitative Comparisons Between the Cadaveric Bones with their CT Segmentations and 3D Plastic Models .............................................................84

Figure 3.1 - Dissected Lower Limbs..................................................................................96
Figure 3.2 - Dissected Lower Limbs with Muscles Partially Detached ............................97
Figure 3.3 - Custom Jig....................................................................................................102
Figure 3.4 - Leg Positioning and Load Set-Up - Neutral Position..................................105
Figure 3.5 - Leg Positioning and Load Set-Up - Dorsiflexion Position ..........................106
Figure 3.6 - Leg Positioning and Load Set-Up - Plantarflexion Position .......................108
Figure 3.7 - Coordinate Frame for Tibia and Fibula with Talus......................................113
Figure 3.8 - Calculating Kinematics for Ankle Joint (Neutral Loaded to Neutral Unloaded Position)........................................................................................................113
Figure 3.9 - Coordinate Frame and Calculating Kinematics for Talus with Calcaneus (Neutral Loaded to Neutral Unloaded Position) .......................................................115
Figure 3.10 - Coordinate Frame for Talus with Navicular .............................................118
Figure 3.11 - Calculating Kinematics for Talonavicular Joint (Neutral Loaded to Neutral Unloaded Position) .................................................................118
Figure 3.12 - Kinematics from Neutral Unloaded to Neutral Loaded ..............................122
Figure 3.13 - Kinematics from Neutral Loaded to Dorsiflex Loaded .............................125
Figure 3.14 - Kinematics from Neutral Loaded to Plantarflex Loaded ...........................127
Figure 3.15 - Distortion in the 3D Fluoroscopic Images ..................................................135
List of Tables

Table 2.1 - CT Segmentation to 3D Plastic Model Match.................................................75
Table 2.2 - CT Segmentation to Cadaveric Bone Match...................................................76
Table 2.3 - 3D Plastic Model to Cadaveric Bone Match ...................................................77
Table 3.1 - Kinematics of the Tibia and Fibula with Talus .............................................120
Table 3.2 - Kinematics of the Talus with Calcaneus .......................................................120
Table 3.3 - Kinematics of the Talus with Navicular ........................................................121
List of Abbreviations

#1 Male Cadaver, Left Lower Limb
#2 Male Cadaver, Right Lower Limb
#3 Female Cadaver, Left Lower Limb
#4 Female Cadaver, Right Lower Limb

*.mcs Map Cycle Set

*.pf Prefetch

*.stl Stereolithography

2D Two-Dimensional

3D Three-Dimensional

ABS Acrylonitrile Butadiene Styrene

ASCII American Standard Code for Information Interchange

AVE Average Deviation

AVE_SIGN Average Deviation (Signed)

CT Computed Tomography

DICOM Digital Imaging and Communications in Medicine

HU Hounsfield Units

ICP Iterative Closest Point

ISB International Society of Biomechanics

JCS Joint Coordinate System

LM Lateral Malleolus

MAX_D Maximum Deviation
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM</td>
<td>Medial Malleolus</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>MSE</td>
<td>Mean Square Error</td>
</tr>
<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root-Mean Square Error</td>
</tr>
<tr>
<td>S.T.A.R.</td>
<td>Scandinavian Total Ankle Replacement</td>
</tr>
<tr>
<td>STC</td>
<td>Standardization and Terminology Committee</td>
</tr>
<tr>
<td>TAA</td>
<td>Total Ankle Arthroplasty</td>
</tr>
<tr>
<td>TNK</td>
<td>Takakura Nara Kyocera</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Ankle arthritis is a painful type of degenerative joint disease that has recently increased in incidences. Unlike hip and knee arthritis which is mainly caused by wear-and-tear, 70-80% of ankle arthritis is of post-traumatic etiology (Conti & Wong, 2001; Saltzman et al., 2005). During a traumatic event, the cartilage matrix and cells of the articular surfaces can become damaged as a result of the force from trauma alone. In addition, the damaged soft tissue in the vicinity such as torn ligaments frequently becomes scarred or inelastic. These damages are often exacerbated by inflammation which results from infections or malalignment and destabilization of the ankle joint complex due to fractured or dislocated bones. Aside from progressive cartilage degeneration, ankle arthritis is also characterized by joint deformity, osteophyte growth, decrease in joint space, reduction in range of motion, chronic pain and consequently gait abnormality. Unfortunately, due to its association with traumatic events, the incidence of ankle arthritis has dramatically increased and is expected to continue to rise in the future due to longer life expectancy and a higher volume of trauma and sports-related injuries. Therefore, this debilitating disease greatly affects individuals of all ages (Hintermann & Valderrabano, 2003).

The current treatments for ankle arthritis include ankle arthrodesis, an option involving fusion of the affected bones, and total ankle arthroplasty (TAA), a procedure where the joint is replaced with prosthesis. Ankle arthrodesis was first introduced to make paralytic limbs useful by stabilizing the affected joints with fusion so that the foot
could be better controlled with more proximal, less affected muscles. As the procedure improved and success rates increased, indications for ankle arthrodesis expanded to include treatment of other foot deformities, injuries and post-traumatic arthritis. Currently, ankle arthrodesis is still the standard treatment and an orthopaedic surgeon’s preferred choice for ankle arthritis. It does moderately reduce pain levels and allow patients to ease performance of daily activities but longer studies have shown that these benefits are short-lived (Coester et al., 2001). Instead, because the surgery alters and limits the movements between bones, transfer of body weight and articular stresses are directed to neighbouring joints, forcing them to provide movements which they were not purposed for. This unnatural change leads to early degeneration of midfoot joints and exacerbates arthritis in the region. A long-term study with a maximum follow-up of 25 years found breakdown of tarsal joints in 22 of the 37 patients and stiff subtalar joints in all 37 patients (Jackson & Glasgow, 1979). These results were confirmed by another study that found progressive osteoarthrosis in 16% and 33% of the tarsal joints and subtalar joint of their patients, respectively (Takakura, 1999). Patients complained of persistent pain (Hefti et al., 1980; Alvine, 2000) and had an overall 10% decrease in gait efficiency (Cook et al., 1923). Finally, other complications included difficulties climbing stairs, getting up from a chair, walking or running on uneven surfaces (Lance et al., 1979; Lynch et al., 1988; Mazur et al., 1979; Morgan et al., 1985) and the need for ambulatory aids or permanent shoe modifications (Mazur et al., 1979; Boobbyer, 1981; Hefti et al., 1980).

When it was first introduced in the 1970s, early attempts of TAA were met with poor success rates and many investigators doubted whether the ankle joint could be
replaced at all (Hamblen, 1985). Due to several obstacles that made investigations futile, research into TAA dissipated. It was only within the past decade that the interest in TAA was reignited due to the growing dissatisfaction and concern for the poor long-term results for ankle arthrodeses as well as the recent successes of hip and knee arthroplasties. Although long-term results are just starting to surface and seem to produce moderate but not ideal results (Hintermann, 2005), the field of TAA still requires a lot of growth and investigations.

1.1 – Anatomy and Biomechanics of the Ankle and Foot

In order to participate in studies on TAA, it is important to first understand the complex anatomy and biomechanics of the ankle and foot. In addition to the tibia and fibula, there are altogether 27 bones (not including any sesamoid bones) in the ankle and foot (Figure 1.1). The bones in the foot are divided into three groups:

1) Tarsal bones: Talus, calcaneus, navicular, cuboid, and three cuneiform bones (medial, intermediate, and lateral)

2) Metatarsals: Metatarsals I to V

3) Phalanges: Proximal phalanges I to V, middle phalanges II to V, and distal phalanges I to V

These bones are closely associated with one another and their motions inter-relate and influence each other. The ankle and foot complex are integral in acting as a structural support platform and capable of withstanding body weight and extra repetitive loads. The ankle does so by effectively transferring the load from the lower extremity to the foot.
Figure 1.1 - Bones of the Foot

*Left foot, dorsal surface.* Figure shows the tarsals, metatarsals, and phalangeal bones of the foot.
The ankle complex is also an important mechanical structure that allows for complicated movements such as a smooth and stable gait by constantly adjusting to the unstable ground. It is due to the wonderful design of the foot that allows it to become a rigid structure such as when an individual plantarflexes to reach an object on a shelf or become a flexible structure when an individual is walking on a rocky path.

In order to understand the biomechanics at the ankle and foot, it is important to first acquire a good understanding of the anatomy. This thesis will focus on the tibia, fibula, talus, calcaneus, navicular and cuboid bones as well as the ankle (talocrural), subtalar (talocalcaneal) and talocalcaneonavicular joints. The following descriptions have been adapted from four textbooks (Perrott, 1970; Nordin & Frankel, 2001; Drake et al., 2005; Moore & Dalley, 2006).

1.1.1 – Kinematics of the Foot

Before the anatomy of the joints is considered in detail, it is important to recognize the possible motions that can occur at the foot, all of which are produced by the collaborative movement of the bones in the ankle and foot. Although the kinematics of the foot is extremely complex, its gross movements are usually described around three axes on three planes (Figure 1.2). An axis running along the sagittal plane produces flexion (plantarflexion) and extension (dorsiflexion) of the foot. Plantarflexion of the foot is anatomically defined as the motion in which the angle between the anterior side of the tibia and dorsal part of the foot increases from 90°. This is generally described as the foot and its toes moving downwards towards the sole of the foot. Dorsiflexion is the opposite of plantarflexion and is defined as the motion in which the angle between the front of the
Figure 1.2 - Foot Motion Around Three Axes

*Right lower limb, anterior view.* Dorsiflexion/plantarflexion in the sagittal plane, eversion/inversion in the frontal, and abduction/adduction of the foot in the transverse (horizontal) plane.
tibia and dorsal part of the foot decreases from 90°. In other words, the dorsum of the foot and its toes are moving upwards towards the tibia.

An axis running along the transverse (horizontal) plane produces adduction and abduction of the foot. Adduction of the foot occurs when the foot is medially rotated towards the midline of the body and the toes end up pointing medially. Abduction of the foot occurs when the foot is laterally rotated and the toes end up pointing laterally.

An axis running along the frontal (coronal) plane produces inversion and eversion of the foot. Inversion is defined by the medial rotation of the plantar surface of the foot whereas eversion is described as the lateral rotation of this same surface.

Finally, two special triplanar motions known as pronation and supination can also occur in the foot. Pronation of the foot is a combination of eversion, dorsiflexion, and abduction as opposed to supination of the foot which is a combination of inversion, plantarflexion, and adduction.

1.1.2 – Anatomy of the Middle and Distal Tibiofibular Joints

The bony framework of the leg consists of two bones arranged in parallel: the tibia and fibula (Figure 1.3). The bones are connected together by muscles, ligaments and an interosseous membrane. The middle and distal tibiofibular joints are articulations between the tibia and fibula which are located along the middle shaft and distal end of the bones respectively. The proximal tibiofibular joint will not be examined as it does not play a major role in the ankle and foot joints.
Figure 1.3 - Tibia and Fibula

*Right lower limb, anterior surface.* Tibiofibular joints (middle and distal) and the ankle joint are shown here. The interosseous membrane was removed in this image.
1.1.2.1 – Tibia

The tibia (Figure 1.3), otherwise known as the shin bone, is much larger than the fibula and located on the antero-medial aspect of the fibula. This is attributed by its role as the main weight-bearing bone of the leg since it forms the knee joint at its proximal end.

The distal end of the tibia (Figure 1.4a) is much broader than the shaft of the bone and has a rectangular shape. There is a strong, flattened pyramidal-shaped bony protuberance known as the medial malleolus projecting medially and downwards. It can be easily palpated as a prominent bony bump on the medial side of the ankle. The medial malleolus and distal end of the tibia articulate with the talus to form the majority of the ankle joint while articulation with the fibula completes the rest of the ankle joint. The posterior surface of the distal tibia (Figure 1.4b) is marked by a vertical groove which travels inferiorly and medially, terminating at the posterior side of the medial malleolus. This groove provides a path for the tendon of the tibialis posterior muscle. The lateral surface of the distal tibia (Figure 1.4c) includes the fibular notch, a deep triangular notch where the distal fibular head would be anchored to the tibia with the assistance of a thickened portion of the interosseous membrane.

1.1.2.2 – Fibula

The fibula is a long, slender bone that is located postero-laterally to the tibia. It plays a minimal role in weight bearing and assists in only 6.4% of the load in a neutral position (Takebe et al., 1984). The main role of the fibula is to serve
Figure 1.4 - Tibia

_Distal end of the right tibia._ (A) Anterior view; (B) Posterior view; (C) Lateral view; (D) Inferior surface of the tibia that articulates with the talus.
as an attachment site for muscles in the leg, support the tibia and form the ankle joint together with the tibia.

Proximally, the fibular head articulates superomedially with the tibia whereas distally, the fibula has a triangular, convex area that articulates with the concave fibular notch on the tibia (Figure 1.5a). At the most distal end, the fibula expands and forms a spade-shaped structure known as the lateral malleolus (Figure 1.5b). At the anterior portion of the lateral malleolus’ medial side (Figure 1.5a) is a small articular surface for interaction with the talus. Postero-inferior to this facet for articulation with the talus is a small fossa known as the malleolar fossa which is a site for attachment of the posterior talofibular ligament found in the ankle joint. On the posterior aspect of the lateral malleolus (Figure 1.5c) is a vertical groove which provides a path for the tendons of the peroneus longus and peroneus brevis muscles.

1.1.2.3 – Interosseous Membrane

The interosseous membrane is a strong, fibrous sheet of connective tissue that travels along the medial and lateral border of the fibula and tibia respectively and connects the two bones together (Figure 1.6). The collagen fibers in the membrane run obliquely from the tibia to the fibula. Aside from connecting bones together, it also serves to support and strengthen the leg, divide anterior and posterior compartments of muscles in the leg and acts as an important surface for muscle attachment. There is a small aperture at the proximal and distal end of the interosseous membrane where blood vessels can pass through. At the most distal
Figure 1.5 - Fibula

*Distal end of the right fibula.* (A) Medial view; (B) Lateral view; (C) Posterior view.
end of the interosseous membrane, the membrane thickens to form the interosseous ligament.

1.1.2.4 – Middle Tibiofibular Joint

The middle tibiofibular joint is the joint where the tibia and fibula shafts are joined together by the interosseous membrane.

1.1.2.5 – Distal Tibiofibular Joint

The distal tibiofibular joint is characterized by the articulation between the fibular notch on the tibia and the corresponding articulating surface on the medial side of the fibula’s lateral malleolus. The interosseous ligament of the interosseous membrane spans the space in the distal tibiofibular joint and joins the two bones together. The joint is reinforced by an anterior tibiofibular ligament (Figure 1.6) and a stronger posterior tibiofibular ligament, both of which run infero-laterally from the tibia to the fibula and overlies the interosseous membrane. These ligaments are continuous with the fibrous capsule of the ankle joint (described in section 1.1.3.3). At the inferior aspect of the posterior tibiofibular ligament is another strong ligament known as the inferior transverse ligament which travels from the malleolus fossa nearly to the medial malleolus. The inferior transverse ligament also forms the posterior aspect of the ankle joint capsule and interacts with the postero-lateral side of the talus.
Figure 1.6 - The Ankle Joint

Anterior View of Left Ankle. Showing the talus within the tibiofibular mortise as well as the anterior tibiofibular ligament.
1.1.2.6 – Movement at the Tibiofibular Joints and Function

The middle tibiofibular joint is a fibrous joint and is considered immovable whereas the distal tibiofibular joint is a syndesmosis joint which allows for some slight movement. The function of these joints is mainly to join the tibia and fibula together and provide support for the leg and the ankle joint. This requires a strong connection between the tibia and fibula in order to firmly articulate with the talus.

1.1.3 – Anatomy of the Ankle (Talocrural) Joint

The ankle joint is formed by three bones: the tibia, fibula and talus. The tibia and fibula together form the superior, medial and lateral aspects of the joint while the talus forms the inferior aspect.

1.1.3.1 – Tibia and Fibula

The tibia and fibula, which were described in sections 1.1.2.1 and 1.1.2.2 respectively, are tightly bound together by their tibiofibular joints. Although the distal tibiofibular joint is a syndesmosis joint, the limited amount of movement at the joint allows it to form a strong tibiofibular mortise that fits over the talus like a cap.

1.1.3.2 – Talus

The talus is the second largest tarsal bone and is the only one that receives direct body weight from the tibia. From the medial and lateral side, the talus has a
snail-shaped appearance (Figure 1.7a, Figure 1.7b). It has a rounded head that is projected anteriorly and medially from a short neck. The neck connects the head with a broad, expanded body.

The articular surface of the talus’ head is domed shaped and articulates with a corresponding concave region in the posterior aspect of the navicular bone. Inferiorly, this articular surface continues into three articular facets (Figure 1.7c): anterior calcaneal surface, middle calcaneal surface, and the articular surface for the plantar calcaneonavicular ligament which is located in between and medially to the other two facets. The anterior and middle calcaneal surfaces articulate with the inferiorly located calcaneus while the plantar calcaneonavicular (spring) ligament, which connects the calcaneus to the navicular, travels inferiorly to the talus. At the posterior aspect of the talus’ inferior side is a large, oval shaped facet known as the posterior calcaneal surface which as its name implies, articulates with the calcaneus. In between the posterior calcaneal surface and middle calcaneal surface is the sulcus tali, a deep groove that travels obliquely and anteriorly from the medial to lateral side of the talus.

Superiorly (Figure 1.7d), the body of the talus is known as the trochlear surface which articulates with the tibia and shaped to acquire a better fit into the tibiofibular mortise. The articular surface continues medially to articulate with the medial malleolus of the tibia. It also continues laterally to form a larger and more inferior articular surface to articulate with the expanded and more inferiorly located lateral malleolus of the fibula. A bony projection known as the lateral process is apparent at the inferior portion of the lateral body of the talus and
Figure 1.7 - Talus

*Right Talus.* (A) Medial view; (B) Lateral view.
Figure 1.7 continued - Talus

*Right Talus.* (C) Inferior view; (D) Superior view; (E) Posterior view.
functions to support the articulation with the fibula.

The back of the talus’ body tapers inferiorly into a posterior and medially projecting posterior process (Figure 1.7e). This process is marked by a medial and lateral tubercle and the groove in between them provides a passageway for the tendon of the flexor hallucis longus. This groove continues to the inferior aspect of the talus and travels medial to the posterior calcaneal surface.

1.1.3.3 – The Ankle Joint

The ankle joint is characterized by the articulation of the strong tibiofibular mortise with the body of the talus (Figure 1.6). As described in sections 1.1.2.1 and 1.1.2.2, the talus interacts superiorly with the inferior portion of the tibia, medially with the medial malleolus and laterally with the lateral malleolus. All articular surfaces are lined by hyaline cartilage. The ankle joint is enclosed by a synovial membrane that attaches to the margins of all the articular surfaces. A fibrous membrane overlies the synovial membrane and also attaches to the same margins to form the joint capsule (Figure 1.8).

The ankle joint is stabilized by both medial and lateral ligaments. The medial (deltoid) ligament is a large, strong ligament stretching in a triangular fashion (Figure 1.9). It is separated into four parts which all attach superiorly at the medial malleolus to form the apex of the triangle. These ligaments each attach inferiorly to a different site along the medial edge of the navicular to the talus to form the base of the triangle. The four parts of the medial ligament are the anterior tibiotalar, tibionavicular, tibiocalcaneal, and posterior tibiotalar which
attach to the anterior and medial aspect of the talus, medial aspect of the navicular in front of the navicular tuberosity (described in section 1.1.5.3), sustenaculum tali (described in section 1.1.4.2) of the calcaneus and the medial tubercle of the talus respectively.

The lateral ligament is composed of three bands of fibers (Figure 1.10). The first is the anterior talofibular ligament, a short ligament attaching the anterior margin of the lateral malleolus to the neck of the lateral aspect of the talus. The posterior talofibular ligament runs backward and medially from the malleolar fossa to the posterior process of the talus. Finally, the calcaneofibular ligament extends postero-inferiorly from the malleolar fossa to a tubercle on the lateral surface of the calcaneus.

1.1.3.4 – Movement at the Ankle Joint

The ankle joint is a synovial joint and is often described as the talus being a half-cylinder tipped onto its flat side with the top of the cylinder facing a malleolus and the bottom of the cylinder facing the other malleolus. The rounded portion of the cylinder is the superior body of the talus. Thus, because of the tight tibiofibular mortise, the motion at the ankle joint has mainly been described as a simple hinge joint allowing flexion (plantarflexion) and extension (dorsiflexion) of the foot about a transverse axis passing through the talus.

Superiorly, the trochlea of the talus body is wider anteriorly than posteriorly (Figure 1.7d). As a result, the talus fits more tightly in the tibiofibular mortise when the ankle is in dorsiflexion since the trochlea of the talus is moved
Figure 1.8 - Ankle Joint Capsule (Gray, 1918)  
(With permission from Bartleby.com, New York, USA © 2000)

Left lower limb, lateral view. Showing the joint capsule of the ankle joint.

Figure 1.9 - Medial Ligaments of the Ankle and Foot (Gray, 1918)  
(With permission from Bartleby.com, New York, USA © 2000)

Right lower limb, medial view. Figure showing medial ligaments supporting the ankle and foot joints.
Figure 1.10 - Lateral Ligaments of the Ankle and Foot (Gray, 1918)
(With permission from Bartleby.com, New York, USA © 2000)

Right lower limb, lateral view. Figure showing lateral ligaments supporting the ankle and foot joints.
into the mortise and slightly spreads apart the tibia and fibula. This leads to a more stable ankle joint in the dorsiflexed position. In addition, the motion of dorsiflexion is limited by the stretching of the medial and lateral ligaments. On the other hand, the narrower posterior aspect of the talus’ trochlea does not limit the range of flexion and plantarflexion can occur until the posterior and inferior margin of the tibia comes into contact with the talus’ posterior process. Thus, the range of motion in plantarflexion is nearly twice as much of dorsiflexion. Altogether, the ankle joint has been described to have a total range of movement of approximately 50° to 70° (Perrott, 1970).

1.1.4 – Anatomy of the Subtalar (Talocalcaneal) Joint

The subtalar joint is formed by articulations between articular facets on the talus’ inferior aspect with corresponding articular facets on the superior aspect of the calcaneus.

1.1.4.1 – Talus

The anatomy of the talus has been thoroughly described in section 1.1.3.2.

1.1.4.2 – Calcaneus

The calcaneus, otherwise known as the heel bone, is the largest tarsal bone and is situated inferior to the talus. It is elongated with compressed lateral sides and an enlarged, rounded posterior. The calcaneus’ long axis is oriented slightly lateral to the midline of the foot.

The calcaneus projects a rounded posterior where the strongest tendon in
the body, the Achilles (calcaneal) tendon attaches (Figure 1.11a). Slightly below this insertion site is the calcaneal tuberosity which continues onto the plantar surface of the calcaneus and is the main weight-bearing surface.

On the plantar aspect of the calcaneus, the calcaneal tuberosity projects slightly anteriorly as a medial and lateral process with a V-shaped notch separating between the two (Figure 1.11b). At the most anterior portion of the calcaneus’ plantar aspect is a raised bump known as the calcaneal tubercle where a short ligament joins the calcaneus with the cuboid.

The calcaneus’ lateral side is quite smooth except for two small bumps (Figure 1.11a). The more anterior bump is known as the fibular trochlea and is often made of two shallow grooves, one lying right on top of the other. This bump is where the tendons of the peroneus brevis and longus muscles pass over as they travel lateral to the calcaneus. The posterior bump is the attachment site of the calcaneofibular ligament which is part of the lateral ligament of the ankle.

The medial side of the calcaneus only has one prominent feature. Near the anterior aspect and associated with the upper margin is a medially projecting shelf of bone that can be easily palpated just inferior to the medial malleolus. This is known as the sustenaculum tali and it functions to support the posterior part of the talus’ head. The inferior side of the sustenaculum tali is marked by a groove in the anterior-posterior direction where the tendon of the flexor hallucis longus travels through (Figure 1.11b).

The calcaneus articulates with the cuboid at its anterior articular surface (Figure 1.11b). It has a triangular shape and is slightly concave from above.
Figure 1.11 - Calcaneus

*Right Calcaneus.* (A) Antero-lateral view; (B) Inferior view.
downward and laterally.

Finally, the superior surface of the calcaneus has three prominent articular surfaces, all of which articulate with the inferior portion of the talus (Figure 1.11a). The anterior talar articular surface is the smallest of the three and is located most anteriorly and medially, articulating with the corresponding anterior calcaneal surface on the head of the talus. The middle talar articular surface is located on the superior aspect of the sustenaculum tali and articulates with the middle calcaneal surface on the head of the talus. The posterior talar articular surface is the largest of the three and located in the middle of the calcaneus’ superior surface. It has a slanted surface and articulates with the large posterior calcaneal surface on the body of the talus. In between the posterior talar articular surface and the middle and anterior talar articular surface is a deep groove known as the calcaneal sulcus. Together, the calcaneal sulcus of the calcaneus and the sulcus tali of the talus’ inferior side form a large canal known as the tarsal sinus (Figure 1.12).

1.1.4.3 – Subtalar Joint

The anatomical definition of the subtalar joint is the articulation between the posterior calcaneal surface on the talus’ inferior surface and the posterior talar articular surface on the calcaneus’ superior surface. The subtalar joint has its own synovial membrane and overlying fibrous membrane which are attached to the margins of the articular surface. Although this joint capsule is relatively weak, it
Figure 1.12 - Tarsal Sinus

*Right Talus and Calcaneus.* (A) Postero-medial view; (B) Antero-lateral view.
is stabilized by medial, lateral, posterior and interosseous talocalcaneal ligaments (Figure 1.9, Figure 1.10). The interosseous talocalcaneal ligament is a strong ligament that lies in the tarsal sinus.

Contrary to anatomists, orthopaedic surgeons normally refer to the subtalar joint as including the talocalcaneal articulations of the talocalcaneonavicular joint which are the interactions between the anterior and middle calcaneal surfaces on the inferior aspect of the talus with the anterior and middle talar articular surfaces on the superior surface of the calcaneus. Structurally, the anatomical subtalar joint is correct because it has its own joint capsule and articular cavity. At the same time, the orthopaedic’s surgeon definition of the subtalar joint is functionally correct because all three articular surfaces of the talus work together to articulate with the calcaneus’ articular surfaces and allow for movements at the subtalar joint.

1.1.4.4 – Movements at the Subtalar Joint

The subtalar joint is anatomically described to be a synovial, gliding (planar) joint that allows for sliding movements. Specifically, the main motions produced at the subtalar joint are inversion and eversion of the foot. The axis of rotation at the subtalar joint was defined to be oriented anteriorly at 42° from the horizontal and medially at 16° from the midline (Manter, 1941). The movements of the calcaneus with respect to the talus are described to be similar to a right-handed screw at the right foot. During subtalar inversion, the calcaneus is said to
rotate slightly in a clockwise direction. Overall, the subtalar joint allows an average of 20° to 30° of inversion and 5° to 10° of eversion (Sarrafian, 1993).

1.1.5 – Anatomy of the Talocalcaneonavicular Joint

The talocalcaneonavicular joint is one of the two transverse tarsal joints. The other joint is the calcaneocuboid joint which will not be covered in this thesis. The talocalcaneonavicular is a complex joint including the inferior articulations between the head of the talus with the antero-superior aspect of the calcaneus and plantar calcaneonavicular (spring) ligament as well as the anterior articulation with the navicular.

1.1.5.1 – Talus

The anatomy of the talus has been thoroughly described in section 1.1.3.2.

1.1.5.2 – Calcaneus

The anatomy of the calcaneus has been described in section 1.1.4.2.

1.1.5.3 – Navicular

The navicular is an intermediate tarsal bone. It is located immediately anterior of the talus and posterior to a row of three cuneiform bones which will not be discussed in this thesis. Due to the way that the head of the talus is medially directed, the navicular is also found on the medial side of the foot.

The entire anterior surface of the navicular bone is convex in shape from side to side (Figure 1.13a). This surface is divided by two ridges into three facets.
that articulate with the three cuneiform bones in front. Posteriorly, the navicular bone has an oval surface that is concave in correspondence to its articulation with the rounded talus head (Figure 1.13b). The posterior surface is also broader more laterally.

The superior (dorsal) surface is also convex in shape from side to side whereas the inferior (plantar) surface has a very irregular contour. Both the superior and inferior surfaces are rough for the attachment of ligaments.

Protruding medially and inferiorly from the medial surface of the navicular bone is a prominent rounded tuberosity which can be palpated on the medial aspect of the foot. This tuberosity is the site for the attachment the tibialis posterior muscle’s tendon (Figure 1.13a and Figure 1.13b). The lateral surface interacts with the cuboid bone, a distal tarsal bone, and often has a small facet for this articulation. It is also rough and irregular for the attachment of ligaments.

1.1.5.4 – The Talocalcaneonavicular Joint

The talocalcaneonavicular joint is composed of articulations between the talus with two other bones and a ligament. First, the rounded head of the talus articulates anteriorly with the concave posterior surface of the navicular. Second, the anterior and middle calcaneal surfaces of the talus articulate with the anterior and middle talar surfaces on the superior aspect of the calcaneus respectively. Third, the head of the talus articulates medially and inferiorly with the plantar calcaneonavicular ligament which joins the medial surface of the navicular bone with the calcaneus’ sustenaculum tali. This broad and thick ligament supports
Figure 1.13 - Navicular

*Right Navicular.* (A) Anterior view; (B) Posterior view.
the head of the talus, helps to transfer weight from the talus and maintains the medial longitudinal arch of the foot.

Aside from the plantar calcaneonavicular ligament, the talocalcaneonavicular joint is enclosed by an incomplete joint capsule and supported by three other ligaments. Posteriorly, the interosseous talocalcaneal ligament in the tarsal sinus joins the talus and calcaneus together. Superiorly, a (dorsal) talonavicular ligament connects the neck of the talus with the superior surface of the navicular (Figure 1.9). The final additional ligament is the calcaneonavicular part of the bifurcate ligament (Figure 1.10). This Y-shaped ligament is attached to the anterior portion of the calcaneus and the calcaneonavicular part attaches to the lateral aspect of the navicular while the calcaneocuboid part attaches to the cuboid.

1.1.5.5 – Movements at the Talocalcaneonavicular Joint

The talocalcaneonavicular joint is a synovial, modified ball-and-socket joint with the rounded head of the talus as the ball and the socket of the joint comprised of the concave articulating surface of the navicular, the superior aspect of the sustentaculum tali and the plantar calcaneonavicular ligament. This joint offers gliding and rotatory movements and thus provides inversion and eversion of the foot. This joint also participates in pronation and supination of the foot.
1.1.6 – Interplay between the Subtalar and Talocalcaneonavicular Joints

An interesting experiment showed how inter-related the joints in the ankle and foot are in terms of producing movement for the foot and transfer of weight. In the study, the authors performed selective fusion of joints in cadavers and measured the movement following the fusions (Aston et al., 1997). After fusion of the subtalar joint, the motion at the talocalcaneonavicular joint reduced to only 26% of its normal motion. When the talonavicular joint of the talocalcaneonavicular joint was fused, the motion of the subtalar joint reduced so significantly that only 2° of motion remained. In another cadaveric study, fusion of the subtalar joint also reduced the articulations between the bones in both the talocalcaneonavicular and ankle joint (Beaudoin et al., 1991). These results show that the joints have a substantial influence on each other and thus emphasize the importance of considering all the joints in the ankle and foot when studying their kinematics and weight transfer.

1.1.7 – Cuboid

The cuboid is not part of the three joints that will be discussed in chapter 3 of this thesis. It is part of the distal group of tarsal bones along with the three cuneiform bones. The cuboid is located directly anterior to the calcaneus and articulates posteriorly with its smooth, triangular surface that is mainly concave with some convex areas near the superior margin (Figure 1.14a). The inferior aspect of the posterior surface forms a medially directed angle that helps to support the anterior end of the calcaneus.

The lateral surface is mainly flat except for the inferior aspect which begins to form a deep groove known as the peroneal sulcus (Figure 1.14b). The superior surface is
quite rough for attachment of ligaments. The same characteristic is found for the medial surface which is also broad and very irregularly shaped (Figure 1.14c). It is on this surface that the cuboid articulates with the lateral cuneiform and sometimes with the navicular bone.

The plantar surface has the peroneal sulcus running obliquely forward and medially (Figure 1.14d). This deep groove is a passageway for the peroneus longus tendon and is bound by a ridge that ends as a tuberosity on the posterior surface of the cuboid. Sometimes there is an oval facet at this tuberosity for articulation with the sesamoid bone.

Anteriorly, the cuboid has an irregular triangular surface which is divided into two facets by a vertical ridge (Figure 1.14e). Here, the cuboid articulates with the 4th and 5th metatarsals.

1.1.8 – Muscles and their Functions in the Ankle and Foot Joints

The motions at the ankle, subtalar and talocalcaneonavicular joints are produced by contractions of muscles located in the leg. The muscles in the leg are categorized in three compartments: anterior, lateral, and posterior.

1.1.8.1 – Anterior Compartment

The four muscles in the anterior compartment are located anterior to the tibia, fibula and interosseous membrane (Figure 1.15). These muscles all originate from the leg, cross the ankle joint and insert into the foot, thus producing the motion of dorsiflexion of the foot. In addition to this movement, these muscles are
Figure 1.14 - Cuboid

Right Cuboid. (A) Posterior view; (B) Lateral view; (C) Medial view; (D) Plantar view; (E) Anterior view.
Figure 1.15 - Anterior Compartment Muscles of the Leg (Gray, 1918)  
(With permission from Bartleby.com, New York, USA © 2000)

Right lower limb, anterior view. Figure showing the tibialis anterior, extensor digitorum longus, extensor hallucis longus and peroneus tertius of the anterior compartment muscles of the leg.
all capable of producing other motions in the foot as a result of their different insertion sites. The tibialis anterior is a muscle that also produces inversion of the foot whereas peroneus tertius has an opposite effect in inducing eversion of the foot. Extensor hallucis longus travels only to the great toe and is also able to extend it whereas the extensor digitorum longus has a tendon that separates into four tendons which insert into and extend the lateral four toes of the foot.

1.1.8.2 – Lateral Compartment

The lateral compartment only has two muscles: peroneus longus and peroneus brevis (Figure 1.16). Both of these muscles originate from the proximal fibula, travel along the shaft of the bone, curve postero-anteriorly under the lateral malleolus and insert into the foot. In fact, these are the same muscles with tendons that pass over the fibular trochlea on the lateral surface of the calcaneus (as described in section 1.1.4.2). The peroneus longus and brevis muscles both cause eversion of the foot and also aids in plantarflexion of the foot.

1.1.8.3 – Posterior Compartment

There are altogether seven muscles in the posterior compartment, three of which are located in the more superficial layer of muscles while the other four are in the deeper group of muscles. The muscles in this compartment are generally muscles that plantarflex the foot.

The muscles in the superficial group are gastrocnemius, plantaris and soleus (Figure 1.17). These muscles originate from the anterior aspects of the
proximal tibia, fibula or the distal femur and they all insert into the posterior aspect of the calcaneus via an extremely strong and thick Achilles tendon. These muscles work together in a powerful manner as they are responsible for pushing against the ground to propel the body forward during walking and upward when an individual stands on their toes.

The muscles in the deep group are popliteus, flexor hallucis longus, flexor digitorum longus and tibialis posterior (Figure 1.16). Since the popliteus muscle is not involved in the movements of the ankle and foot, it will not be discussed. The other three muscles originate from the posterior aspect of the proximal tibia, fibula or adjacent interosseous membrane. In addition to plantarflexion, these muscles are all capable of producing other motions in the foot as a result of their different insertion sites. Flexor hallucis longus travels only to the great toe and is able to flex it while the tendon of flexor digitorum longus divides into four tendons that insert into the lateral four toes and flexes them. Tibialis posterior inserts into the rounded tuberosity on the medial aspect of the navicular and thus causes inversion of the foot as well.

1.2 – History of Total Ankle Arthroplasty

The development of TAA first began in the 1970s and initial interest was high with over 25 different designs (Hintermann, 2005). Most of the first generation TAA had a basic two component design that required the resection of more bone. For
Figure 1.16 - Posterior (Deep Layer) and Lateral Compartment Muscles of the Leg (Gray, 1918)  
(With permission from Bartleby.com, New York, USA © 2000)

Left lower limb, posterior view. Figure showing the popliteus, tibialis posterior, flexor hallucis longus and flexor digitorum longus muscles and the peroneus longus and peroneus brevis muscles.

Figure 1.17 - Posterior (Superficial Layer) Compartment Muscles of the Leg (Gray, 1918)  
(With permission from Bartleby.com, New York, USA © 2000)

Left lower limb, posterior view. Figure showing the gastrocnemius, soleus and plantaris muscles.
example, one of the earliest designs had a tibial component that was based on the femoral component in hip replacements and had a long stem while the talar component replaced most of the body of the talus. A two-component design had either a fixed polyethylene inlay or none at all. At first, these TAA were implanted with cement but developers quickly realized the shortcomings of this type of fixation when they yielded poor results (Lord & Marotte, 1973). Overall, short-term results of the first generation TAA were quite good and encouraging. After six months, a study reported 83% of 63 ankles had excellent results (Stauffer, 1977). After 23 months, another study showed that 43% of TAA yielded excellent results, 29% with good results and an overall satisfactory rate of 73% (Stauffer, 1979; Stauffer & Segal, 1981). Even with follow-up at 36 months, 24 of 34 patients reported to be “extremely happy” with the procedure (Newton, 1982).

After a number of years, long-term studies reported high failure rates and complications with the first generation TAA. A study described failure rates of 21%, 35%, and 39% at five, ten, and 15 years respectively (Kitaoka et al., 1994). Other trials studying specific TAA showed similar results with 60% and 90% loosening after five and ten years respectively for the CONAXIAL Beck-Steffee prosthesis (Wynn & Wilde, 1992) and a 100% complication rate after 5.5 years for the Imperial College of London Hospital prosthesis (Bolton-Maggs et al., 1985). Overall, the first generation of TAA was met with a plethora of complications such as poorly designed surgical tools leading to inaccurate positioning and sizing of the prosthesis. This along with a two component prosthesis that did not have enough surface area to distribute weight appropriately resulted in rapid deterioration of the prosthesis and an increased risk of malleolar fractures. Developers spent years understanding cementing techniques and excessive
bone removal led to loosening of the prosthesis and poor joint stability (Bolton-Maggs et al., 1985). A study comparing ankle arthrodesis and TAA showed that 88% of TAA had progressive radiolucent lines after 15 months. In addition, only 4 out of 21 patients (19%) were pain free whereas 9 out of 12 patients in the ankle arthrodesis group were pain free for up to 15 years (Demottaz et al., 1979). The poor long-term results were just as disappointing if not worse than the outcomes from ankle arthrodesis and any enthusiasm that developers had for TAA was extinguished. For the next few years, many focused their attention back on ankle arthrodesis.

When interest in TAA was revived, the second generation of TAA came back with an un cemented fixation design. The results were excellent as 67% of the uncemented TAA as opposed to 27% of the cemented cases were satisfactory. Similarly, loosening was only observed in 23% of uncemented TAA as opposed to 85% of cemented cases (Takakura et al., 1990). The design philosophy was to create congruent and anatomically shaped prosthesis with minimal resistance. Therefore, many TAA were designed with articular surfaces that had similar curvatures to the bones to encourage full articular contact. To reduce resistance, the three component prosthesis was introduced where a moving polyethylene bearing was situated in between the tibial and talar component of the prosthesis. These changes to the TAA led to lower wear rates by reducing the load transfer and contact stress in the artificial joint and the moderately satisfactory results were encouraging for many developers (Hintermann, 2005). A study for the Buechel-Pappas™ prosthesis showed that five of the 24 patients had no pain, 11 with slight pain and eight with moderate pain (Buechel & Pappas, 1992) at follow-up while the survival rate for TAA reached 72.7% after ten years for the Scandinavian Total
Ankle Replacement (S.T.A.R.) prosthesis (Kofoed & Sorensen, 1998). As well at 3.5 years, none of the 35 patients had evidence of loosening and only one needed revision for malalignment (Kofoed & Danborg, 1995).

1.3 – Current Total Ankle Arthroplasty Designs

As of 2008, there are 20 known ankle implants worldwide with five of them having a two component design (Figure 1.18). Current TAA designs all utilize cementless fixation methods by bony ingrowth and are available in various sizes. Although many have adopted a three component design, popular prostheses such as AGILITY™ and the Takakura Nara Kyocera (TNK) have both kept a two component design. Yet concerns continue to be raised regarding the unwanted transfer of excessive shear and torque forces in these designs (Hintermann, 2005).

Most TAA only have prosthetic parts for the tibia and talus bones with the exception of AGILITY™ which uses screws to fuse the fibula and tibia together to change the ankle joint from a three bone to a simple two bone joint. The philosophy behind this design is because many of the TAA did not have enough surface area through which load could be appropriately distributed. Thus, AGILITY™ constructed a prosthesis that bridged the tibia and fibula so that the fibula could help bear some of the weight (Alvine, 1991).

The majority of talar prosthetic components are shaped to imitate the talus’ natural shape. Designs such as the AGILITY™ have even made attempts to make them anatomically correct by developing a talar component that is wider anteriorly than
Figure 1.18 - Current Total Ankle Arthroplasty Designs

Common TAA prostheses for the right ankle. White areas indicate the polyethylene inlay (fixed or mobile).
posteriorly. The HINTEGRA® on the other hand opted to completely reshape the joint by using a flat talar component. Tibial prosthetic components are typically made with flat surfaces with the exception of AGILITY™ where the tibial platform is concave. In addition, most utilize one or more stems on the superior surface to insert into the tibial shaft for fixation. Unfortunately, the flat tibial component is more prone to unwanted translational and rotational forces. To overcome this, TAA such as HINTEGRA® and TNK used screws to keep them in place but new concerns arose regarding the use of screws and their association with stress forces (Hintermann, 2005). In fact after 4.1 years, 20% of the 30 ankles replaced with the TNK prosthesis had broken screws (Takakura et al., 1990).

To prevent medial and lateral translation of the mobile polyethylene inlay in the three component design, most TAA included a raised medial and lateral ridge on both edges of the talar component or a ridge traveling down the median of the talar component which corresponds to a groove on the polyethylene inlay’s inferior surface. Other methods to prevent medial and lateral translation include a medial and lateral ridge protruding inferiorly from the tibial component of the TAA. These ridges function similarly to the medial and lateral malleoli in the ankle joint (Hintermann, 2005).

Although current TAA designs vary from each other, all have produced somewhat moderately satisfactory results when compared with first generation TAA (Buechel & Pappas, 1992; Kofoed & Danborg, 1995; Kofoed & Sorensen, 1998). Note that results from three component designs were also more favourable than those from two-component designs. Nevertheless, TAA is still not the first choice for orthopaedic
surgeons because the outcomes of TAA from longer follow-up studies still remain unclear and many complications continue to arise.

1.4 – Complications of Total Ankle Arthroplasty

Unlike its hip and knee counterparts, ankle arthroplasty had a much slower progression in development partly due to the many difficulties that it faced and still faces. These include a higher resultant moment of the bones and an increased compressive force encountered at the ankle joint, especially for obese patients. This is because of the inadequate amount of surface area for articulation in the ankle joint. Normally, the surface area at the ankle joint is 12 cm², an area much larger than at the hip or knee (Stauffer, 1977). However, in order to fit the prosthesis in place, the talus had to be resected, thus decreasing the surface area. This can result in compressive forces of up to 5.5 times the body weight due to the smaller surface area. Furthermore, it is extremely challenging to salvage or replace a TAA due to the amount of bone stock that is lost from the first implant (Conti & Wong, 2001).

Age is also an important factor since many patients that need TAA are younger and tend to place more stress on their prosthesis by participating in high impact activities. This leads to early deterioration of the implant and exacerbates other complications such as post-operative arthritis. Even if the TAA was successful, patients encountered complications with loss of motion due to soft tissue scarring and contracture as well as periarticular ossifications in up to 30% of TAA (Anderson et al., 2003; Valderrabano et al., 2004; Wood & Deakin, 2003).
There are also many complications related to the implant itself and the implantation procedure. One of the most common complications is malpositioning of the prosthetic components. Especially since the ankle joint size is tight and small, it is challenging to accurately resect parts of the bones with the cutting jigs and tools available. Proximal or distal displacement of the prosthesis results in implanting the components in softer and weaker bone such as areas closer to the shaft of the tibia or deeper into the body of the talus. This leads to a greater risk for subsidence and weakness in plantarflexion (for proximal displacements) or dorsiflexion (for distal displacements). Varus or valgus malpositioning leads to a varus or valgus positioning of the foot and ankle respectively which results in excessive discomfort and pain. They also put abnormal stresses on the polyethylene inlay which accelerates their deterioration. Medial or lateral malpositioning of the prosthesis adds stress to the medial or lateral malleoli and increases their chance of fracture. Finally, anterior or posterior malpositioning changes the center of rotation of the joint and affects the movements at the ankle (Hintermann, 2005). Overall, any kind of malpositioning causes prosthesis loosening, ankle instability and damages to the ligaments around the joint. In addition, patients with more than just 4° of malalignment experienced more pain with the TAA than without (Pyevich et al., 1998). Malpositioning is extremely common since 48% of patients in a study had more than 4° of deformity (Myerson & Mroczeck, 2003) while another study reported more than 5° of deformity in 35% of the patients (Wood, 2002).

Another related complication is the improper sizing of prosthetic components. Once again, the small joint size makes it difficult for orthopaedic surgeons to correctly estimate the best size for the prosthetic components. Proper sizing is crucial to maintain
the anatomy and biomechanics of the ankle and foot since a deviation from the center of rotation for the joint leads to unnatural movements and the presence of unwanted stresses. Other problems that can occur include impingement, damage to neighbouring soft tissues and migration of prosthetic components. Studies have also consistently reported that intraoperative and postoperative malleoli fractures can occur in up to 22% of TAA cases with a consistent trend of more medial fractures than lateral (Wood, 2002; Myerson & Mroczeck, 2003; Saltzman et al., 2003).

Another major complication occurs as a result of a disregard for physiological ankle biomechanics. Up until now, a common process of TAA design is revision of the prosthesis after observing results from long-term studies rather than designing based on what is known about their anatomy and kinematics. Many studies that were conducted to understand ankle movements measured motion included methods using surface tracers with detection cameras (Scott & Winter, 1991; Parks et al., 1994; Woodburn et al., 2002; Nester et al., 2007; Drewes et al., 2009), video fluoroscopy (Komistek et al., 2000) and roentgen stereophotogrammetric (Tuijthof et al., 2009a) analysis to name a few. Unfortunately, there are many downfalls to these methods as two-dimensional (2D) radiographs and the use of external markers that can overlap does not yield the most accurate results. In addition, many studies did not measure kinematics while the ankle was loaded with body weight. Since TAA are intended to be used during normal daily activities such as walking, it is important to measure the kinematics in a realistic loaded state. Another shortcoming is that most studies only examined motions at the ankle joint. However, since the bones in the foot interplay with each other and are also crucial in load transfer and foot movements, it is important to understand how all the joints articulate in
the foot to know how to best design a TAA that mimics the foot’s biomechanics. This is why there is a wide variation in prosthesis design as outlined in section 1.3 with each design emphasizing different kinds of movements at the ankle joint because there is currently no clear grasp of the movements at the ankle and foot joints. Many of these complications could be alleviated if designers understood the kinematics of the ankle and foot joint and had improved surgical techniques or equipment to properly size and position the prosthesis.

1.5 – Purpose of Thesis

The aim of this thesis is two-fold. Part one of this cadaveric study is to quantitatively examine the accuracy of producing a three-dimensional (3D) rapid-prototyped plastic ankle and foot model from rendering computed tomography (CT) scans. A three-way analysis will be performed to quantify the degree of error between the cadaveric bones, their CT segmentations, and their printed plastic models. In particular, the talus, calcaneus, navicular, cuboid, tibia and fibula bones will be tested.

Part two of this study is to analyze the kinematics of the joints in the foot and ankle while they move through the motions of dorsiflexion, neutral to plantarflexion in a loaded state. This pilot study will examine the articulations between the ankle, subtalar, and talonavicular (of the talocalcaneonavicular) joints since they all interact with the talus, a tarsal bone that directly receives weight transfer from the leg. Knowledge in this area can lead to improved development of total ankle prostheses that can better imitate the movements in the foot, thus avoiding inappropriate pressures on the joints which can contribute to pain, improper healing and arthritis.
Understanding of the kinematics of the foot and ankle coupled with a successful method to create structurally accurate 3D plastic models of the joint can potentially be used to improve surgical preparations, planning and techniques as well as outcomes for ankle surgeries.

1.6 – Hypotheses of Thesis

The hypotheses of the thesis are as follows:

Part 1

1. The printed 3D plastic models of the tibia, fibula, talus, calcaneus, navicular and cuboid bones are accurate representations of their corresponding cadaveric bones.

Part 2

1. Accurate analysis of the kinematics of the ankle and foot provides a better understanding allowing more accurate fitting and positioning of the TAA prosthesis.
2. The ankle, subtalar and talonavicular (of the talocalcaneonavicular) joints are able to translate and rotate more than what current TAA implant designs allow.
3. Loading of the foot with body weight causes considerable translation and rotation of the bones.
PART 1

Analyzing the Accuracy of Producing 3D Printed Models from CT Segmentation Renderings of Cadaveric Ankle and Foot Bones

2.1 – Experimental Design

In the past few years, there has been accelerated interest and advances in medical imaging due to their increased effectiveness and use in diagnostics, prevention and treatment. Unfortunately, there are still several limitations to conventional medical imaging. Imaging methods such as CT, magnetic resonance imaging (MRI) and radiography are available digitally in 3D but are still confined to a 2D virtual monitor. Recently, newer technologies such as rapid-prototype printing where 3D digital models could be printed into a physical 3D model have helped to overcome these barriers.

This method has been found to be accurate for the hip joint by novel studies that rendered and printed 3D models from CT scans of normal cadaveric hips for quantitative accuracy (Anstey et al., 2010; Lee, 2010; Smith et al., 2010). Furthermore, this process was applied into the surgical field by producing plastic preoperative hip models for each patient so that surgeons could then utilize them in the surgical planning process. This included the creation of personalized drilling templates for each patient based on their 3D renderings and printed hip models. Investigations reported this method to be as reliable and accurate as conventional computer-assisted hip resurfacing (Kunz et al., 2010).
Following the favourable results of this process in hip resurfacing surgeries, much interest was garnered as to whether the concept could be extended to other joints of the body such as the ankle and foot joints where surgical accuracy is needed for the success of treatments such as TAA. Therefore the methodology of this current study will be based on the aforementioned studies (Anstey et al., 2010; Lee, 2010; Smith et al., 2010).

### 2.2 – Materials and Methods

After approval from Queen’s University’s Research Ethics Board, four human cadaveric lower limbs were obtained from the Department of Biomedical and Molecular Sciences at Queen’s University, Kingston, Ontario, Canada. Two of these lower limbs, a left (#1) and a right (#2), were from the same male cadaver who was 83 years of age at time of death. The other two lower limbs, a left (#3) and a right (#4), were from the same female cadaver who was 61 years of age at time of death. All cadaveric lower limbs were dissected just above the knee joint.

Lower limbs #1, #2, #3 and #4 were imaged after they were used in Part 2 of the thesis (as described in section 3.2). CT scans of each lower limb were performed at Kingston General Hospital, Kingston, Ontario, Canada. The 2D CT image data were then imported into Mimics, an advanced medical image processing and editing software that is capable of segmenting 2D image data and rendering them into virtual 3D models. With this program, the tibia, fibula, talus, calcaneus, navicular and cuboid bones were segmented, constructed into digital models and then printed as 3D plastic models using a rapid-prototype printer located at the Human Mobility Research Centre, Kingston, Ontario, Canada.
Next, the cadaveric lower limbs were dissected until all soft tissues were removed from the bones. The 3D plastic models and the clean, dissected cadaveric bones were then laser scanned to obtain a digitization of their surface topography.

A three-way analysis was done to determine the goodness-of-fit between the following sets of data: i) the laser scanned cadaveric bones and the CT segmentation of cadaveric bones, ii) the CT segmentation of cadaveric bones and the laser scanned 3D plastic models of the cadaveric bones, and iii) the laser scanned 3D plastic models of the cadaveric bones and the laser scanned cadaveric bones.

A more detailed, step-wise protocol regarding the acquisition of CT images, 3D model rendering process, printing of plastic models, dissection, digitization of the model and cadaveric bones’ surface topography as well as the comparison analysis between the three data sets will be described in the following sections.

2.2.1 – Materials

CT Image Data Acquisition

A) GE Healthcare: Lightspeed+ XCR 16-slice CT Scanner with moving gantry

(Chalfont St. Giles, UK)

B) Re-writable R- compact discs for media transfer

Cadaveric Dissection

A) Four formalin-fixed cadaveric lower limbs (two left: #1, #3 and two right: #2, #4) with soft tissues partially intact. (These limbs were initially used in Part 2 of the thesis in section 3.2).

B) Dissection kit of scalpels, blades, forceps, bone saw, scissors
C) Fisher Scientific: Hydrogen Peroxide, 30%

D) Fume hood

E) Personal protection equipment such as gloves, safety goggle and lab coat

Computer Hardware

A) Dell™: OptiPlex 755 Intel® Core™ 2 Duo Processor with Windows XP Professional operating system (Round Rock, TX, USA)

Computer Software

A) Materialise: Mimics® 14.0 (Leuven, Belgium)

B) ShapeGrabber: SGCentral™ (Ottawa, Canada)

C) InnovMetric: PolyWorks® - IMAlign, IMMerge (Quebec, Canada)

D) MathWorks®: MATLAB® 7.10.0.499 (R2010a) (Natick, MA, USA)

Rapid-Prototype Printing

A) Stratasys®: Dimension® SST 1200es Rapid Prototype Printer, support software and printing platforms (Eden Prairie, USA)

B) Stratasys®: Acrylonitrile Butadiene Styrene (ABS) plus™ thermoplastic material (Eden Prairie, USA)

Laser Scanner

A) ShapeGrabber: LM600 3D laser scanner, calibration components and support software (Ottawa, Canada)
2.2.2 – CT Scan Acquisition

2.2.2.1 – CT Scan Parameters

The 2D CT data for the cadaveric lower limbs were imaged at a slice width of 0.625mm for an average of 720 slices per leg. The scanning was completed at an average technique of 120 peak kilovoltage and 98 milliampereseconds.

2.2.2.2 – Leg Positioning

A set of lower limbs (a left and right lower limb from the same cadaver) were imaged together in the same CT image. The lower limbs were positioned length-wise on the gantry on their posterior side and the gantry tilt was at 0°.

2.2.2.3 – Export CT Image Data

The CT image data were exported as the Digital Imaging and Communications in Medicine (DICOM) file format extension type and burned onto re-writable R- compact disc media for data transfer.

2.2.3 – Protocol for the 3D Model Rendering Process (CT Segmentation)

2.2.3.1 – Import CT Image Data

The DICOM data of the lower limbs’ CT images were imported into Mimics which then converted and saved them as the map cycle set (*.mes) file extension type, the file format which Mimics operates on. During the conversion process, a preview of the CT images in three views (frontal, sagittal and
transverse) was displayed in a new window and the user was asked to define the spatial orientation of the CT images by manually identifying and assigning the anterior/posterior, left/right, and top/bottom planes for the images.

2.2.3.2 – Thresholding

After the images had been imported, Mimics displayed the workspace as four windows: frontal view (top left window), transverse view (top right), sagittal view (bottom left), and 3D view of the completed segmentation (bottom right) (Figure 2.1). The first step of CT segmentation was ‘Thresholding’, a process to direct the program in specifically highlighting bony material in the CT images by applying a translucent, coloured overlay or ‘mask’ on pixels that were defined as bony material based on their density in Hounsfield Units (HU). Mimics’ pre-defined density for bony material (226-1851 HU) was used in this thresholding process (Figure 2.2). This process was performed only once to create the initial mask for all bones.

2.2.3.3 – Editing Masks

Once the initial mask was created, it was manually edited to give a proper representation of the talus, calcaneus, navicular, cuboid, tibia and fibula bones. This step was crucial because although the ‘Thresholding’ step highlighted all bony areas, there were situations in which Mimics was not able to clearly define the borders of each bone. This may have arisen because of the following: 1) in areas where the bones were in close contact with each other, Mimics might
Figure 2.1 - Mimics Workspace with Imported CT Images

*CT images of lower limbs #1 and #2.* Top left window: frontal view; top right window: transverse view; bottom left window: sagittal view; bottom right window: 3D view of the completed segmentation.

Figure 2.2 - Thresholding for Bony Material

*Frontal view of lower limbs #1 and #2.* Thresholding highlighted bony material with a green coloured mask.
have considered them as one continuous bone (Figure 2.3a), 2) some soft tissue such as cartilaginous areas may have been considered as bone if their density was within the pre-defined threshold for bone, and 3) Mimics may not have recognized bones with poor quality if they had a low density that fell below the pre-defined threshold for bone (Figure 2.3a). Thus, the user was able to utilize two functions from the ‘Edit Mask’ toolbar – ‘Draw’ and ‘Erase’ - in order to edit the masks.

The ‘Draw’ function came in various shapes and sizes and was used to fill in pixels of the mask where bony material was supposed to be highlighted (Figure 2.3b). The ‘Erase’ function also came in various shapes and sizes and was used to remove highlighted pixels from the mask where the bony anatomy had been over-represented (Figure 2.3b).

Other than editing the masks so that the bony anatomy was accurate, the user also had to ensure that there was always at least one pixel of space or gap between the masks of each bone (Figure 2.3b). This was crucial in order for Mimics to be able to recognize them as separate bones, a process that will be described in section 2.2.3.4. on ‘Region Growing’. This process of editing was completed for every slice of CT image data in all three views: sagittal, frontal and transverse.

### 2.2.3.4 – Region Growing

When the user was satisfied with the edited masks, the next step was to use the ‘Region Growing’ function to create independent masks for the talus,
Figure 2.3 - Edit Masks

Sagittal view of lower limb #2. (A) Arrowhead shows a region of the talus that the thresholding mask considered to be continuous with the navicular bone due to their close proximity. Arrow shows a region of the talus with poor bone quality (low density) and thus was not recognized as bone. (B) Arrowhead shows that the oversegmented region was erased. Notice that there is at least one pixel of space between the bones. Arrow indicates that the undersegmented areas were drawn in.
calcaneus, navicular, cuboid, tibia and fibula (Figure 2.4). In order for Mimics to recognize each bone as being separate from one another, the program required at least one pixel of space or gap between the masks of each bone to indicate that they were not connected. Step 2.2.3.3 could be re-visited to further edit the mask if needed.

2.2.3.5 – Calculate Polylines and Cavity Fill from Polylines

The ‘Calculate Polylines’ function created a continuous outline of the most exterior pixels of the mask (Figure 2.5a). Note that the polylines were only visible in the transverse plane window. The contours of these polylines were then examined in every slice to ensure good continuity of the bone’s exterior surface. If there were any discrepancies in the contours, the mask could be further edited by using the ‘Edit Mask’ functions as outlined in section 2.2.3.3 and the polylines would then be re-calculated.

When the polylines were deemed acceptable, the ‘Cavity Fill from Polylines’ function was used to fill all the pixels within the polyline outline (Figure 2.5b). This step was useful because it automatically filled in pixels of bony material that might have missed during the editing process. As well, even though it was normal to have empty spaces within the bone (eg. areas with trabecular bone), this function filled in those areas so that Mimics would consider the bone as a completely solid structure. This was beneficial for the printing of the CT segmentations into plastic 3D models so that the models would be printed solid.
**Figure 2.4 - Region Growing**

*Sagittal view of lower limb #2.* Region growing allowed the user to create an independent mask for each bone (shown here for the talus bone in blue).

**Figure 2.5 - Calculate Polylines and Cavity Fill from Polylines**

*Transverse view of lower limb #2.* (A) The polyline outline (shown in magenta) is continuous around the contours of the talus (blue); (B) The cavities of the talus outlined by the polylines were filled (shown in purple).
2.2.3.6 – Calculate 3D from Mask

The segmentation mask of each bone was then carefully re-analyzed slice-by-slice in all three planes of view to ensure that the bony anatomy was accurately represented with the highlighted pixels in the mask. When the masks were satisfactory, the function ‘Calculate 3D’ was used to take the 2D segmented data from the mask to calculate a 3D virtual model of the bone (Figure 2.6). The surface topography of the 3D rendering of the highlighted bone in the mask was analyzed to ensure that no extraneous pixels were present to alter the true anatomy of the bone. If these pixels were present, step 2.2.3.3 was re-visited to examine the mask for those extraneous pixels and to correct them. The 3D rendering of the bone was then re-calculated after any changes were made to the segmentation.

2.2.3.7 – Exporting Files and Printing of the Plastic Models

When the final 3D rendering of the segmented data was satisfactory, the masks for each bone of interest were exported to a new file extension type known as the American Standard Code for Information Interchange (ASCII) stereolithography (*.stl) file type. This file extension type was then sent to the rapid-prototype printer where the 3D rendering of each bone was printed in the ABSplus™ material as a 3D plastic model (Figure 2.7).
**Figure 2.6 - 3D Virtual Model**

*Antero-lateral view of lower limb #2.*

3D virtual models of the tibia (green), fibula (yellow), talus (purple), calcaneus (red), navicular (beige), and cuboid (violet) bones.

---

**Figure 2.7 - Printed 3D Plastic Models**

*Right lower limb #2.* 3D plastic models of the tibia, fibula, cuboid, navicular, talus and calcaneus.
2.2.4 – Cadaveric Dissection

2.2.4.1 – Dissection of the Bones

After the lower limbs were used in Part 2 of this thesis (as described in section 3.2), the lower limbs were further dissected to isolate the ankle and foot bones of interest: talus, calcaneus, navicular, cuboid, tibia and fibula. Dissection was done by carefully removing as much of the soft tissue as possible down to the bone and articular surfaces of the bones. This included all the skin, fascial layers, surrounding muscles, ligaments and tendons. Since a lot of the soft tissues such as the periosteum were difficult to remove with simple dissection tools, the bones were then soaked in a solution of one part 30% hydrogen peroxide solution with one part water under a fume hood for at least three days. The reaction of hydrogen peroxide with the soft tissue caused protein bonds to be broken and consequently softened the tissue and released them from the bones. The bones were then removed from the solution and further dissected until all of the soft tissues were removed. Note that hydrogen peroxide also acted as a bleaching agent although it was not used for that purpose (Figures 1.4, 1.5, 1.7, 1.11, 1.13, 1.14).

2.2.4.2 – Preservation of Cadaveric Material

The cleaned and dissected bones were preserved by keeping the tissues hydrated with moistening solution. The bones were wrapped in moistened cloths and kept at room temperature in a sealed plastic bag.
2.2.5 – Laser Scanning Methodology

2.2.5.1 – Calibration of the Laser Scanner

An initial calibration of the laser scanner was completed before performing any scans. This step required the user to follow the laser scanning software’s protocol in orienting a calibration platform through a range of positions to test the camera’s ability to detect and measure the reflected laser beam off of the calibration platform. This process ensured the accuracy of the camera in scanning the surface topography of the scanned materials.

2.2.5.2 – Configuration of the Laser Scanner

At the beginning of each laser scan for each bone, the laser scanner was configured to set the most appropriate parameters to optimally scan the bone of interest. The first parameter was the laser scan field size which controlled the area that the laser scanner would scan from. This was adjusted according to the size of each bone. The second parameter was the intensity of the laser power which was chosen based on the ability of the camera to detect the reflected laser from the scanned surfaces of the bone. In general, a higher laser power was required for bones that were darker, smaller and/or further away from the camera. Conversely, a lower laser power was required for bones that were brighter, larger and/or closer to the camera. In this thesis, the power settings were either set at levels 3 or 4 with the highest setting available at level 8. The third parameter was the resolution of the laser which was set at 0.500mm and the fourth parameter regarding the laser’s depth of field was kept at default settings.
2.2.5.3 – Laser Scans and Exporting Laser Scan Patches

Laser scanning of the bones was performed by taking several laser scan patches or snapshots (Figure 2.9). Each patch showed the bone oriented in different positions in space to ensure that the entire surface of the bone was scanned and represented by at least one laser scan patch. It was also crucial that there were common overlapping regions of bony surface between patches as this was necessary for accurate stitching of the patches, a process described in section 2.2.5.5. When the entire surface topography of the bone was laser scanned and represented by at least one laser scan patch, the patches were then exported as a prefetch (*.pf) file extension type.

2.2.5.4 – Importing Laser Scan Patches into IMAlign and Editing

The laser scan patches in the *.pf file type were imported one by one into IMAlign. Upon import, extraneous parts of the laser scan patches that did not represent the bone’s surface topography were manually selected and deleted (Figure 2.8). This was done by using the ‘Volume Selection’ function in the ‘Selection’ toolbar, highlighting the area with the unwanted data and deleting them.

2.2.5.5 – Stitching Laser Scan Patches and Best Fit Alignment

At this point, the surface topography of the bone was represented by several laser scan patches of different regions of the bone. In order to create a complete 3D representation of the laser scanned bone, each individual laser scan
Figure 2.8 - Removing Extraneous Data from a Laser Scan Patch

Distal tibia from lower limb #4. The extraneous data is highlighted (yellow outline) and then deleted.

Figure 2.9 - Stitching Laser Scan Patches

Right talus, lower limb #2. (A) Two different laser scan patches were imported into IMAlign. Three distinct yet overlapping points (red circles) were selected on both patches to stitch the patches together. (B) The first laser scan patch (grey) and the second laser scan patch (pink) from Figure 2.9a were stitched together.
patches must be stitched together. This was accomplished by using the ‘N-Point Pairs Alignment’ function which required the selection of at least three distinct but overlapping points or features between two patches (Figure 2.9a). Thus, it was necessary for the laser scan patches to share some overlapping regions with each other so that there were a sufficient number of points to properly position each laser scan patch with one another. Every time a new patch was imported, it was displayed side-by-side with the previously imported patch and the images were re-oriented so that common points could be easily chosen. Once the points were selected, IMAlign superimposed one patch over the other by way of matching the points between the two laser scan patches together (Figure 2.9b).

The ‘Best Fit Alignment and Comparison’ function was then used to better align the patches together. This function applied a pre-defined algorithm to integrate the two patches into one based on how accurately the selected points matched up. Iterations of the algorithm were done for this matching process until best fit alignment was achieved. If the required iterations were greater than 100, the three overlapping points were re-selected and the ‘Best Fit Alignment and Comparison’ function was performed again. Once the aforementioned criteria were met and the laser scan patches were stitched together, they were locked using a ‘Lock’ function. These steps were repeated for every laser scan patch that was imported.

When all laser scan patches were imported and stitched together, all of the patches were unlocked except for one and a final ‘Best Fit Alignment and Comparison’ was performed on all of the patches. If the required iterations to find
the best fit exceeded 1000, the patches that visually did not fit best with the other patches were removed and the final ‘Best Fit Alignment and Comparison’ was attempted again. If the required number of iterations were still not met, the entire process was re-started by importing the patches once again and performing the matching process described above.

2.2.5.6 – Reduce Overlap and Exporting Laser Scan Patches

After the patches were all aligned with one another, the ‘Reduce Overlap’ function was performed which removed any overlapping segments between individual laser scan patches. As a result, all areas of the surface topography would only be represented by a portion of a single laser scan patch (Figure 2.10). In order to undergo a three-way analysis, the laser scan patches were exported as an *.stl file extension type.

2.2.6 – Quantitative Assessment (Three-Way Analysis)

A three-way analysis was done to determine the goodness-of-fit between the following sets of data: i) the laser scanned cadaveric bones and the CT segmentation of cadaveric bones, ii) the CT segmentation of cadaveric bones and the laser scanned 3D plastic models of the cadaveric bones, and iii) the laser scanned 3D plastic models of the cadaveric bones and the laser scanned cadaveric bones.

2.2.6.1 – Importing Laser Scan Patches into Mimics

The aligned laser scan patches of the cadaveric bones and 3D plastic
**Figure 2.10 - Completed Laser Scan Models**

*Right lower limb #2.* (A) Talus, antero-medial view; (B) Calcaneus, antero-medial view; (C) Navicular, posterior view; (D) Cuboid, plantar view; (E) Tibia, Postero-lateral view; (F) Fibula, medial view.
models in *.stl file type from section 2.2.5.6 were imported into the *.mcs file type of their respective CT segmented bones from section 2.2.3.6. Thereafter, the laser scan renderings of the cadaveric bones and 3D plastic models as well as the CT segmentation for the same bone all appeared in the same coordinate system in Mimics.

2.2.6.2 – Point and Global Registration

At this point, the three renderings were displayed in the same coordinate system but may be located and oriented differently from each other in space because they were all created in different files and software (Figure 2.11a). Thus, the user had to align both the laser scanned rendering of the cadaveric bone and the 3D plastic model to the CT segmentation. This was done by selecting all of the laser scan patches of the cadaveric bone and using the ‘Point Registration’ function where at least three distinct but overlapping landmarks or features between the two renderings were selected. Mimics then found the best fit between the points and moved the laser scan patches of the cadaveric bone onto the fixed CT segmentation rendering (Figure 2.11b). This process was also performed for the laser scan patches of the 3D plastic model.

After the two laser scan renderings were re-located and re-oriented to a position closer to the CT segmentation rendering, the ‘Global Registration’ function was used to further minimize the distance between each laser scan patch with the CT segmentation. To accomplish this step, a laser scan patch was selected as the movable part and the CT segmentation as assigned the fixed
Figure 2.11 - Aligning Laser Scan Patches with the CT Segmentation

Right talus, lower limb #2.
(A) The laser scan patches of the cadaveric bone (yellow) and the 3D plastic model (red) were imported into Mimics which already had the corresponding CT segmentation (purple). (B) After ‘Point Registration’, the laser scan patches of the talus (red) were aligned with the corresponding CT segmentation.
part. ‘Global Registration’ was then performed using automatic settings as pre-defined by Mimics. The user then used ‘Global Registration’ a second time with the same laser scan patch but with manual settings instead where the parameters were set as ‘Distance Threshold’ at 0.5mm, ‘Number of Iterations’ at 10000 and ‘Subsample Percentage’ at 100%. The ‘Distance Threshold’ defined the acceptable distance between the movable laser scan patch and the fixed CT segmentation rendering in order for the points to be usable while the ‘Number of Iterations’ limited the number of times that the algorithm for ‘Global Registration’ could be applied. The ‘Subsample Percentage’ defined how many points Mimics was allowed to use during registration with a higher percentage yielding more accuracy. This two-step ‘Global Registration’ was completed for all laser scan patches on the CT segmented rendering.

2.2.6.3 – Exporting CT Segmentation and the Aligned Laser Scan Patches

Once the laser scan patches of both the cadaveric bones and 3D plastic models were spatially aligned with the CT segmentation rendering, the CT segmentation rendering and all of the laser scan patches were exported as *.stl file types.

2.2.6.4 – Three-Way Analysis

All of the *.stl files from section 2.2.6.3 were imported into MATLAB for the three-way analysis. It is important to note that this *.stl file type is a format that describes the surface geometry of 3D objects with a triangulated surface
which was computed using the Delaunay triangulation (Barber et al., 1996). The triangulated data set consists of triangle vertices (points), edges (vertex connections) and normal vectors to each triangular face.

After import, the laser scan patch was aligned with the CT segmentation rendering for manual editing. Before registration, the user was allowed to use a series of edit functions such as ‘Select’, ‘Deselect’ and ‘Delete’ to remove any extraneous data in the laser scan patch; for example, image data of the edge of the table surface from which the bone was laser scanned. This extraneous data would not have “corresponding points” on the segmentation and hence would skew the registration and the results. An iterative closest point (ICP) algorithm (Besl & McKay, 1992) was performed in MATLAB to register (align) the laser scan patch with the CT segmentation rendering. Following registration, points having a corresponding point greater than 1.96 standard deviations from the mean (i.e., representing the 5% extreme outliers) were temporarily removed from the laser scan and the ICP registration was performed again to improve alignment. Following the second registration, five outcome measures were calculated for the closest-point match: the mean squared error (MSE), root-mean-square error (RMSE), average distance (AVE), average distance with directional signs (AVE_SIGN) and the maximum deviation (MAX_D) of the laser scan from the CT segmented rendering. This process was repeated for every laser scan patch of the cadaveric bones and the 3D plastic models. When they were all matched, the results were combined to give an overall matching result for that bone.
To calculate the matching between the laser scan patches of the cadaveric bones with the 3D plastic model, MATLAB imposed each laser scan patch of the cadaveric bones onto a 3D rendering of the plastic models which was made from a combination of its laser scan patches. The overall matching result for that bone was calculated and described in the same five outcome measures.

2.3 – Results

A three-way comparison was performed to determine the goodness-of-fit between the laser scanned cadaveric bones, CT segmentation of cadaveric bones and the laser scanned 3D plastic models of the cadaveric bones. Analysis was done for the talus, calcaneus, navicular, cuboid, tibia and fibula bones of two left (#1 and #3) and two right (# 2 and #4) lower limbs.

2.3.1 – Quantitative Results

High accuracy was reported as having low RMSE values or a small distance between the matches. Overall, sub-millimetre shape accuracy was found for all three comparisons: i) the laser scanned cadaveric bones with the CT segmentation of cadaveric bones, ii) the CT segmentation of cadaveric bones with the laser scanned 3D plastic models of the cadaveric bones, and iii) the laser scanned 3D plastic models of the cadaveric bones with the laser scanned cadaveric bones (Table 2.1, Table 2.2, and Table 2.3). Accuracy ranged from the highest at an RMSE of 0.077mm for the comparison between the CT segmentation and the 3D plastic model of the navicular to the lowest at an RMSE of 0.431mm for the comparison between the CT segmentation to the
Table 2.1 - CT Segmentation to 3D Plastic Model Match (in mm)

<table>
<thead>
<tr>
<th></th>
<th>MSE</th>
<th>RMSE</th>
<th>AVE</th>
<th>AVE_SIGN</th>
<th>MAX_D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Talus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.009</td>
<td>0.096</td>
<td>0.076</td>
<td>-0.025</td>
<td>0.384</td>
</tr>
<tr>
<td>2</td>
<td>0.008</td>
<td>0.088</td>
<td>0.069</td>
<td>-0.023</td>
<td>0.379</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>0.078</td>
<td>0.060</td>
<td>-0.031</td>
<td>0.319</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
<td>0.088</td>
<td>0.068</td>
<td>-0.036</td>
<td>0.565</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.008</td>
<td>0.087</td>
<td>0.068</td>
<td>-0.029</td>
<td>0.411</td>
</tr>
<tr>
<td><strong>Calcaneus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.013</td>
<td>0.116</td>
<td>0.088</td>
<td>-0.022</td>
<td>0.566</td>
</tr>
<tr>
<td>2</td>
<td>0.012</td>
<td>0.108</td>
<td>0.083</td>
<td>-0.024</td>
<td>0.505</td>
</tr>
<tr>
<td>3</td>
<td>0.007</td>
<td>0.081</td>
<td>0.064</td>
<td>-0.025</td>
<td>0.365</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
<td>0.088</td>
<td>0.068</td>
<td>-0.030</td>
<td>0.375</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.010</td>
<td>0.098</td>
<td>0.076</td>
<td>-0.025</td>
<td>0.453</td>
</tr>
<tr>
<td><strong>Navicular</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.004</td>
<td>0.066</td>
<td>0.053</td>
<td>-0.021</td>
<td>0.237</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>0.071</td>
<td>0.056</td>
<td>-0.019</td>
<td>0.306</td>
</tr>
<tr>
<td>3</td>
<td>0.007</td>
<td>0.083</td>
<td>0.065</td>
<td>-0.040</td>
<td>0.776</td>
</tr>
<tr>
<td>4</td>
<td>0.007</td>
<td>0.086</td>
<td>0.068</td>
<td>-0.050</td>
<td>0.369</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.006</td>
<td>0.077</td>
<td>0.061</td>
<td>-0.032</td>
<td>0.422</td>
</tr>
<tr>
<td><strong>Cuboid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.005</td>
<td>0.071</td>
<td>0.055</td>
<td>-0.025</td>
<td>0.295</td>
</tr>
<tr>
<td>2</td>
<td>0.007</td>
<td>0.084</td>
<td>0.067</td>
<td>-0.024</td>
<td>0.305</td>
</tr>
<tr>
<td>3</td>
<td>0.007</td>
<td>0.082</td>
<td>0.065</td>
<td>-0.045</td>
<td>0.276</td>
</tr>
<tr>
<td>4</td>
<td>0.007</td>
<td>0.086</td>
<td>0.068</td>
<td>-0.035</td>
<td>0.374</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.007</td>
<td>0.081</td>
<td>0.064</td>
<td>-0.032</td>
<td>0.313</td>
</tr>
<tr>
<td><strong>Tibia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.020</td>
<td>0.140</td>
<td>0.101</td>
<td>-0.023</td>
<td>0.846</td>
</tr>
<tr>
<td>2</td>
<td>0.011</td>
<td>0.105</td>
<td>0.078</td>
<td>-0.026</td>
<td>0.530</td>
</tr>
<tr>
<td>3</td>
<td>0.007</td>
<td>0.084</td>
<td>0.067</td>
<td>-0.039</td>
<td>0.355</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
<td>0.089</td>
<td>0.070</td>
<td>-0.044</td>
<td>0.390</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.011</td>
<td>0.105</td>
<td>0.079</td>
<td>-0.033</td>
<td>0.530</td>
</tr>
<tr>
<td><strong>Fibula</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.008</td>
<td>0.090</td>
<td>0.070</td>
<td>-0.047</td>
<td>0.409</td>
</tr>
<tr>
<td>2</td>
<td>0.009</td>
<td>0.096</td>
<td>0.076</td>
<td>-0.042</td>
<td>0.413</td>
</tr>
<tr>
<td>3</td>
<td>0.010</td>
<td>0.102</td>
<td>0.082</td>
<td>-0.053</td>
<td>0.364</td>
</tr>
<tr>
<td>4</td>
<td>0.009</td>
<td>0.094</td>
<td>0.077</td>
<td>-0.057</td>
<td>0.328</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.009</td>
<td>0.096</td>
<td>0.076</td>
<td>-0.050</td>
<td>0.378</td>
</tr>
<tr>
<td></td>
<td>MSE</td>
<td>RMSE</td>
<td>AVE</td>
<td>AVE_SIGN</td>
<td>MAX_D</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td><strong>Talus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.166</td>
<td>0.408</td>
<td>0.304</td>
<td>-0.029</td>
<td>2.208</td>
</tr>
<tr>
<td>2</td>
<td>0.200</td>
<td>0.447</td>
<td>0.343</td>
<td>-0.040</td>
<td>1.970</td>
</tr>
<tr>
<td>3</td>
<td>0.180</td>
<td>0.425</td>
<td>0.321</td>
<td>-0.072</td>
<td>1.973</td>
</tr>
<tr>
<td>4</td>
<td>0.198</td>
<td>0.445</td>
<td>0.348</td>
<td>-0.048</td>
<td>1.908</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.186</strong></td>
<td><strong>0.431</strong></td>
<td><strong>0.329</strong></td>
<td><strong>-0.047</strong></td>
<td><strong>2.015</strong></td>
</tr>
<tr>
<td><strong>Calcaneus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.268</td>
<td>0.517</td>
<td>0.412</td>
<td>-0.027</td>
<td>1.951</td>
</tr>
<tr>
<td>2</td>
<td>0.201</td>
<td>0.449</td>
<td>0.346</td>
<td>-0.023</td>
<td>2.230</td>
</tr>
<tr>
<td>3</td>
<td>0.111</td>
<td>0.334</td>
<td>0.258</td>
<td>-0.030</td>
<td>1.726</td>
</tr>
<tr>
<td>4</td>
<td>0.163</td>
<td>0.403</td>
<td>0.293</td>
<td>-0.019</td>
<td>2.861</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.186</strong></td>
<td><strong>0.426</strong></td>
<td><strong>0.327</strong></td>
<td><strong>-0.025</strong></td>
<td><strong>2.192</strong></td>
</tr>
<tr>
<td><strong>Navicular</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.132</td>
<td>0.363</td>
<td>0.285</td>
<td>-0.016</td>
<td>1.451</td>
</tr>
<tr>
<td>2</td>
<td>0.087</td>
<td>0.295</td>
<td>0.230</td>
<td>-0.035</td>
<td>1.227</td>
</tr>
<tr>
<td>3</td>
<td>0.066</td>
<td>0.256</td>
<td>0.201</td>
<td>-0.052</td>
<td>0.964</td>
</tr>
<tr>
<td>4</td>
<td>0.096</td>
<td>0.309</td>
<td>0.238</td>
<td>0.018</td>
<td>1.175</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.095</strong></td>
<td><strong>0.306</strong></td>
<td><strong>0.239</strong></td>
<td><strong>-0.021</strong></td>
<td><strong>1.204</strong></td>
</tr>
<tr>
<td><strong>Cuboid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.210</td>
<td>0.459</td>
<td>0.351</td>
<td>-0.041</td>
<td>2.809</td>
</tr>
<tr>
<td>2</td>
<td>0.193</td>
<td>0.439</td>
<td>0.330</td>
<td>-0.051</td>
<td>1.505</td>
</tr>
<tr>
<td>3</td>
<td>0.106</td>
<td>0.325</td>
<td>0.253</td>
<td>-0.048</td>
<td>1.287</td>
</tr>
<tr>
<td>4</td>
<td>0.155</td>
<td>0.394</td>
<td>0.307</td>
<td>-0.058</td>
<td>1.485</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.166</strong></td>
<td><strong>0.404</strong></td>
<td><strong>0.310</strong></td>
<td><strong>-0.050</strong></td>
<td><strong>1.771</strong></td>
</tr>
<tr>
<td><strong>Tibia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.191</td>
<td>0.437</td>
<td>0.336</td>
<td>-0.026</td>
<td>1.899</td>
</tr>
<tr>
<td>2</td>
<td>0.162</td>
<td>0.402</td>
<td>0.319</td>
<td>-0.031</td>
<td>1.493</td>
</tr>
<tr>
<td>3</td>
<td>0.076</td>
<td>0.275</td>
<td>0.192</td>
<td>-0.042</td>
<td>1.625</td>
</tr>
<tr>
<td>4</td>
<td>0.084</td>
<td>0.290</td>
<td>0.216</td>
<td>-0.031</td>
<td>1.597</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.128</strong></td>
<td><strong>0.351</strong></td>
<td><strong>0.265</strong></td>
<td><strong>-0.033</strong></td>
<td><strong>1.654</strong></td>
</tr>
<tr>
<td><strong>Fibula</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.263</td>
<td>0.513</td>
<td>0.386</td>
<td>-0.054</td>
<td>2.015</td>
</tr>
<tr>
<td>2</td>
<td>0.173</td>
<td>0.416</td>
<td>0.315</td>
<td>-0.038</td>
<td>1.942</td>
</tr>
<tr>
<td>3</td>
<td>0.098</td>
<td>0.313</td>
<td>0.238</td>
<td>-0.050</td>
<td>1.593</td>
</tr>
<tr>
<td>4</td>
<td>0.063</td>
<td>0.252</td>
<td>0.198</td>
<td>-0.070</td>
<td>0.982</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.149</strong></td>
<td><strong>0.373</strong></td>
<td><strong>0.284</strong></td>
<td><strong>-0.053</strong></td>
<td><strong>1.633</strong></td>
</tr>
</tbody>
</table>
Table 2.3 - 3D Plastic Model to Cadaveric Bone Match (in mm)

<table>
<thead>
<tr>
<th></th>
<th>MSE</th>
<th>RMSE</th>
<th>AVE</th>
<th>AVE_SIGN</th>
<th>MAX_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.152</td>
<td>0.390</td>
<td>0.284</td>
<td>-0.009</td>
<td>2.296</td>
</tr>
<tr>
<td>2</td>
<td>0.188</td>
<td>0.434</td>
<td>0.326</td>
<td>-0.036</td>
<td>2.042</td>
</tr>
<tr>
<td>3</td>
<td>0.186</td>
<td>0.431</td>
<td>0.321</td>
<td>-0.056</td>
<td>2.157</td>
</tr>
<tr>
<td>4</td>
<td>0.204</td>
<td>0.451</td>
<td>0.348</td>
<td>-0.015</td>
<td>1.930</td>
</tr>
<tr>
<td>Average</td>
<td>0.182</td>
<td>0.426</td>
<td>0.320</td>
<td>-0.029</td>
<td>2.106</td>
</tr>
<tr>
<td>Calcaneus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.255</td>
<td>0.505</td>
<td>0.391</td>
<td>-0.049</td>
<td>1.932</td>
</tr>
<tr>
<td>2</td>
<td>0.203</td>
<td>0.451</td>
<td>0.343</td>
<td>-0.019</td>
<td>2.499</td>
</tr>
<tr>
<td>3</td>
<td>0.117</td>
<td>0.342</td>
<td>0.261</td>
<td>0.025</td>
<td>1.805</td>
</tr>
<tr>
<td>4</td>
<td>0.162</td>
<td>0.402</td>
<td>0.288</td>
<td>0.023</td>
<td>2.901</td>
</tr>
<tr>
<td>Average</td>
<td>0.184</td>
<td>0.425</td>
<td>0.321</td>
<td>-0.005</td>
<td>2.284</td>
</tr>
<tr>
<td>Navicular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.134</td>
<td>0.366</td>
<td>0.281</td>
<td>-0.014</td>
<td>1.603</td>
</tr>
<tr>
<td>2</td>
<td>0.078</td>
<td>0.279</td>
<td>0.216</td>
<td>-0.015</td>
<td>1.158</td>
</tr>
<tr>
<td>3</td>
<td>0.066</td>
<td>0.257</td>
<td>0.201</td>
<td>-0.015</td>
<td>1.312</td>
</tr>
<tr>
<td>4</td>
<td>0.096</td>
<td>0.310</td>
<td>0.235</td>
<td>0.026</td>
<td>1.405</td>
</tr>
<tr>
<td>Average</td>
<td>0.093</td>
<td>0.303</td>
<td>0.233</td>
<td>-0.005</td>
<td>1.369</td>
</tr>
<tr>
<td>Cuboid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.199</td>
<td>0.446</td>
<td>0.340</td>
<td>-0.019</td>
<td>2.464</td>
</tr>
<tr>
<td>2</td>
<td>0.171</td>
<td>0.414</td>
<td>0.310</td>
<td>-0.026</td>
<td>1.714</td>
</tr>
<tr>
<td>3</td>
<td>0.107</td>
<td>0.326</td>
<td>0.248</td>
<td>0.034</td>
<td>1.239</td>
</tr>
<tr>
<td>4</td>
<td>0.150</td>
<td>0.387</td>
<td>0.293</td>
<td>-0.004</td>
<td>1.833</td>
</tr>
<tr>
<td>Average</td>
<td>0.157</td>
<td>0.393</td>
<td>0.298</td>
<td>-0.004</td>
<td>1.812</td>
</tr>
<tr>
<td>Tibia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.170</td>
<td>0.412</td>
<td>0.308</td>
<td>0.017</td>
<td>1.912</td>
</tr>
<tr>
<td>2</td>
<td>0.155</td>
<td>0.394</td>
<td>0.302</td>
<td>-0.027</td>
<td>1.530</td>
</tr>
<tr>
<td>3</td>
<td>0.076</td>
<td>0.276</td>
<td>0.183</td>
<td>0.011</td>
<td>1.823</td>
</tr>
<tr>
<td>4</td>
<td>0.081</td>
<td>0.285</td>
<td>0.198</td>
<td>0.032</td>
<td>1.469</td>
</tr>
<tr>
<td>Average</td>
<td>0.120</td>
<td>0.342</td>
<td>0.248</td>
<td>0.008</td>
<td>1.684</td>
</tr>
<tr>
<td>Fibula</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.269</td>
<td>0.519</td>
<td>0.390</td>
<td>-0.006</td>
<td>2.245</td>
</tr>
<tr>
<td>2</td>
<td>0.184</td>
<td>0.429</td>
<td>0.325</td>
<td>-0.020</td>
<td>2.797</td>
</tr>
<tr>
<td>3</td>
<td>0.114</td>
<td>0.338</td>
<td>0.248</td>
<td>0.004</td>
<td>1.512</td>
</tr>
<tr>
<td>4</td>
<td>0.057</td>
<td>0.239</td>
<td>0.180</td>
<td>-0.012</td>
<td>1.191</td>
</tr>
<tr>
<td>Average</td>
<td>0.156</td>
<td>0.381</td>
<td>0.286</td>
<td>-0.009</td>
<td>1.936</td>
</tr>
</tbody>
</table>
cadaveric talus bone. In general, except for the navicular bone in #4, the CT segmentations of the six bones in the four lower limbs were always larger than their corresponding 3D models and cadaveric bones as shown by the negative values for the AVE_SIGN outcome measure.

The 3D plastic model to CT segmentation matches revealed the highest combined accuracy with results from the six bones ranging from 0.077mm to 0.105mm. On the other hand, with the exception of the fibula, the CT segmentation to cadaveric bone matches had the lowest combined accuracy with results from the six bones ranging from 0.306mm to 0.431mm. Values from the 3D model to cadaveric bone matches were very similar to those from the CT segmentation to cadaveric bone matches with a combined accuracy from the six bones ranging from 0.303mm to 0.426mm.

In the 3D plastic model to CT segmentation matches, the navicular had the highest accuracy (0.077mm) followed by cuboid (0.081mm), talus (0.087mm), fibula (0.096mm), calcaneus (0.098mm), and finally the tibia with the lowest accuracy (0.101mm). The CT segmentation to cadaveric bones matches yielded a different trend with the navicular once again with the highest accuracy (0.306mm) but subsequently followed by the tibia (0.351mm), fibula (0.373mm), cuboid (0.404mm), calcaneus (0.426mm), and finally the talus with the lowest accuracy (0.431mm). The 3D model to cadaveric bone matches had the same trend as that found in the CT segmentation to cadaveric bone matches as shown in Table 2.2 and Table 2.3.

2.3.2 – Topographical Colourmaps

The residual distances between the matches were plotted onto a topographical
colourmap for each of the six bones from the four lower limbs. These colourmaps visually demonstrated the areas where there was mismatch with positive values indicating that the object being matched (cadaveric bone) is further away or larger than the object it is being matched to (either the CT segmentation or 3D plastic model). On the colourmaps for the talus bone in the CT segmentation to cadaveric bone and 3D plastic model to cadaveric bone matches, the trochlea, head of the talus as well as the anterior, middle and posterior calcaneal surfaces had high positive values with the edges of those surfaces having the highest values (Figure 2.12). On the other hand, large negative values were found for surfaces on the body of the talus just inferior to the trochlea as well as the sulcus tali. Overall, the trend is that areas with articular surfaces tend to have positive residual distances whereas non-articular areas had negative residual distances.

The same trend was observed for the other five bones. For the calcaneus, the anterior, middle and posterior talar surfaces as well as the edges of the articular surface with the cuboid bone had large positive values whereas the calcaneal sulcus and notch between the medial and lateral processes had the highest negative values (Figure 2.13). The posterior end of the calcaneus which acts as an insertion site for the Achilles tendon varies from having high positive values or high negative values.

The navicular bone had positive residual distances for the two ridges on its anterior surface and for the edges of the posterior concave articulating surface (Figure 2.14). The tuberosity on the medial aspect of the navicular also had some small positive values. On the other hand, the inferior surface of the navicular showed areas with negative residual distances.
Figure 2.12 - Topographical Colourmap of the Talus

*Right talus, lower limb #2, inferior (left) and superior (right) views.* Positive residual distances found at the trochlea, head of the talus and anterior, middle and posterior calcaneal surfaces. Negative residual distances found just inferior to trochlea and in the sulcus tali.

Figure 2.13 - Topographical Colourmap of the Calcaneus

*Right calcaneus, lower limb #2, superior (left) and inferior (right) views.* Positive residual distances found at the anterior, middle and posterior talar surfaces and the articular surface with the cuboid bone. Negative residual values were found at the calcaneal sulcus and notch between the medial and lateral processes.
Figure 2.14 - Topographical Colourmap of the Navicular

Right navicular, lower limb #2, anterior (left) and posterior (right) views. Positive residual distances found at the edges of posterior concave articulating surface and medial aspect of tuberosity. Negative residual values found at the inferior surface.

Figure 2.15 - Topographical Colourmap of the Cuboid

Right cuboid, lower limb #2, lateral (left) and plantar (right) views. Positive residual distances found at the edges of the cuboid’s anterior and posterior articular surfaces with the calcaneus and metatarsals respectively. Negative residual distances found on either side of the ridge, especially the peroneal sulcus.
Positive residual distances were most prominent on the edges of the cuboid’s posterior and anterior articular surfaces with the calcaneus and metatarsals respectively (Figure 2.15). The negative residual distances were apparent on either sides of the ridge on the plantar surface, especially in the peroneal sulcus.

The inferior edge of the most distal end of the tibia was reported to have positive residual distances (Figure 2.16). This was most common on the inferior end of the tibia near the medial malleolus. In addition, the distal and lateral surfaces (fibular notch) of the tibia where the bone articulates with the fibula had some positive residual differences whereas the fibular notch itself and the anterior and posterior aspects of the distal tibia had negative values.

The edges of the fibula’s most distal end as well as the articular surface on its medial side that articulates with the tibia showed positive residual distances (Figure 2.17). Conversely, the malleolar fossa had high negative values.

2.3.3 – Qualitative Analysis by Visual Examination

Finally, it is important to note that visual qualitative examination with the naked eye revealed that the cadaveric bones had a much more defined surface topography with sharper and bolder edges and bumps on the bone as compared with the CT segmentation and 3D plastic model which have very smooth contours (Figure 2.18).

2.4 – Discussion

Researchers have recently begun to ponder the effectiveness of computer-assisted
Figure 2.16 - Topographical Colourmap of the Tibia

*Right tibia, lower limb #2, postero-lateral (left) and infero-anterior (right) views.* Positive residual distances found at the edges of the fibular notch and inferior ridge of the tibia, especially of the medial malleolus. Negative residual distances found at the fibular notch and some on the anterior and posterior parts of the distal tibia.

Figure 2.17 - Topographical Colourmap of the Fibula

*Right fibula, lower limb #2, lateral (left) and medial (right) views.* Positive residual distances found at the edges of the fibula’s distal end and at the medial side where it articulates with the tibia. Negative residual values found at the malleolar fossa.
Figure 2.18 - Qualitative Comparisons Between the Cadaveric Bones with their CT Segmentations and 3D Plastic Models

*Right talus, lower limb #2, medial view.* (A) Cadaveric bone; (B) CT segmentation; (C) Plastic model. Arrows pointing to distinct features on the cadaveric bone that were absent on the CT segmentation and plastic model.
surgeries in improving total ankle arthroplasties and reducing complications. This idea follows studies which have quantitatively been able to produce an accurate 3D plastic hip model from CT scans (Anstey et al., 2010; Lee, 2010; Smith et al., 2010). These models have, in turn, been successfully used by orthopaedic surgeons to make personalized drilling templates for each patient as a guide during hip resurfacing surgeries (Kunz et al., 2010). It is the aim of this thesis to apply this same kind of theory to TAA. With the computer’s precision positioning and sizing as well as 3D imaging and physical representations of the patient’s ankle, orthopaedic surgeons will be able to better plan and execute the surgery. It was hypothesized that this rendering and printing process would be effective in producing accurate 3D models of bones in ankle and foot joints.

Overall, the CT rendering and 3D model printing process was found to be accurate for the bones in the ankle and foot as evidenced by the sub-millimetre accuracy found between the cadaveric bones, their CT segmentations and 3D printed plastic models. The most accurate match had an RMSE of 0.077mm while the most inaccurate match had a value of only 0.431mm. Therefore these plastic models are helpful in the proper sizing of the prosthesis and the creation of personalized drilling templates for better malpositioning during surgery.

As reported in the results, the overall CT segmentations of all six bones were always larger (with one exception) than both their corresponding 3D printed models and cadaveric bones although the differences were still sub-millimetre. It is suggested that the ABSplus™ thermoplastic material from the 3D printed models could have possibly endured some shrinkage during the hardening process. Another reason could be due to
the limitations of the rapid-prototype printer’s printing resolution. In addition, CT segmentations may be larger than their corresponding cadaveric bones due to the over-segmentation of the bones in Mimics as a result of misinterpreting calcified soft tissues as bony material because the pixels in that region had an HU value that was considered to be bone tissue (226-1851 HU).

Misinterpretation of tissue by during segmentation could also explain the residual distances found on the topographical colourmaps. In all six bones, positive residual distances were found at the articular surfaces of the bones with larger positive values at the edges of the articular surfaces. On the other hand, negative residual distances were found at non-articulating surfaces with larger negative values at deep grooves of the bones such as the sulcus tali and calcaneal sulcus. Articular surfaces were generally under-segmented because the operator was apprehensive about accidentally including the neighbouring bone that was interacting with the articular surface of interest. For example, the operator might have had difficulty determining the outline of the posterior calcaneal surface on the talus and thus opted to under-segment the posterior talar surface on the calcaneus as a precaution. On the other hand, the non-articulating surfaces were over-segmented possibly because the operator knew that there weren’t any nearby bony material from neighbouring bones and thus was more liberal in the segmentations.

As reported in the results, the CT segmentation to cadaveric bone matches had the greatest inaccuracy while the 3D plastic model to cadaveric bone matches yielded very similar results. The cause for this inaccuracy can be mainly attributed to the CT segmentation (as described in the previous paragraphs) and the soft tissue removal process. Even with visual examination, the dissected cadaveric bones had sharper and
more distinct features whereas the CT segmentations yielded digital 3D models of the
bones with smooth surface topography. This was likely due to the operator’s
predisposition to think that the bones should be smoother than they are in reality, thus
ultimately affecting the editing process. This suggests that operators in the future should
be aware of potential biases during the editing process where they are more likely to
smooth out the surfaces of the bones as well as under-segment articular surfaces and
over-segment non-articular surfaces. With regards to the cadaveric dissections, it was still
difficult to remove all soft tissues even after soaking the bones in hydrogen peroxide.
This resulted in residual soft tissue being present in the laser scan patches of the
cadaveric bones which consequently contributed to positive values of residual distance in
the topography colormaps.

It was noted that in all three sets of comparisons, the navicular bone was always
the most accurately rendered, laser scanned and printed bone. It could be argued that the
accuracy is due to the navicular bone’s small size and surface area. However, the cuboid
bone is similarly as small in size. A potential reason for this can be explained by the
navicular bone’s smoother bone contour which has fewer protuberances, grooves, sulci or
other distinct features. Therefore, this entire process of producing a printed model of
cadaveric bones is suggested to be most accurate for bones that have a smoother surface
topography.

Finally, aside from human errors in the CT segmentation, other causes of
inaccuracies include the resolution of the CT scanner and laser scanner as well as the
potential change in resolutions during file type conversions. As well, there is potentially a
small source of error in the stitching of laser scan patches together through ‘Best fit
alignment and comparison’ by IMAlign (as described in section 2.2.5.5) and in the registration matching process by Mimics and MATLAB (as described in 2.2.6.2 and 2.2.6.4 respectively).

2.4.1 – Limitations

This study is not without some limitations. First, as described in the discussion, there were several areas where minor errors could potentially surface such as human error in the CT segmentation, software errors in the matching process as well as equipment error from the CT scanner, laser scanner or rapid-prototype printer.

Second, this pilot study only examined the accuracy of rendering and printing four lower limbs (one set of left and right lower limbs from a male and one set from a female). To acquire a better indication of the average accuracy of the studied process, it would be better to have a larger sample size.

Other limitations include the lengthy process it took to segment and print the bones and models. On average, it took about 24-36 hours to segment CT data of all six bones from a lower limb into a digital 3D rendering while it took approximately 10 to 12 hours to print the plastic models. In a clinical situation, although this process can increase the accuracy of the surgery, the inefficiency in producing a plastic model of the patients’ ankle and foot bones can prolong the surgical planning process and delay the surgery date for a patient. In addition, it can increase the number of personnel involved in the surgery because of the need for an operator to render and print the models. Thus, this method is most likely not suitable to be incorporated in emergency or rushed surgeries (Rengier et al., 2010).
Finally, the CT image data in this study were obtained at a slice width of 0.625mm for increased detail. However, in normal clinical practice, the smallest slice width used for CT scans is 1.250mm in order to protect the patient from intense exposure to radiation. This limitation could produce less detailed CT image data which increases the chance of error in CT segmentation. Thus, it would be important to determine the optimal slice width of the CT scans so that there is a good balance between detail and patient health. In addition, it is beneficial to examine the accuracy of this rendering and printing process for CT data taken at 1.250mm slice widths or other more optimal slice widths to determine the effectiveness of incorporating this process in clinical applications.

2.4.2 – Future Directions

The results from the study can be utilized to direct and guide future research in the improvement of technology-based diagnostics and surgeries. As suggested in section 2.4.1, this study could be improved by testing out the process with more bones to obtain a greater sample size. In addition, other studies could be done to determine ways to improve aspects of this study where error could arise such as a method to decrease human error in rendering CT segmentations or improve equipment resolutions.

Since the rendering and printing process has been performed and tested to be successful for the hip joint and with successful results from this study for the joints in the ankle and foot, the process can be repeated to determine its accuracy for other joints in the body. A potential investigation could be to test the accuracy of the process on the
bones of the wrist which are smaller in size and equally or more complex than the joints in the ankle and foot.

To make this process more applicable in clinical situations, future studies could investigate ways to improve the efficiency of the rendering and printing process so that the method could be applied to a wider variety of surgery types. Testing should also examine optimal slice widths for CT scans so that CT image data could be acquired with great detail yet still be safe for the patient’s health. Finally, since this method has been found to be accurate for bones in the ankle and foot, the process should be incorporated in trial studies for ankle and foot surgeries to determine its effectiveness in surgical planning and in improving the surgical process through the creation and use of individualized drilling templates.
Chapter 3

PART 2

Analyzing the Kinematics of Loaded Joints in the Ankle and Foot

3.1 – Experimental Design

An important factor in the poor outcome of TAA is the current lack of knowledge on the kinematics of the bones in the ankle and foot. Previous studies have mainly used external markers (Scott & Winter, 1991; Parks et al., 1994; Woodburn et al., 2002; Nester et al., 2007; Drewes et al., 2009) or 2D radiographs to track the motions of the foot (Komistek et al., 2000; Tuijthof et al., 2009a). However, because of the methods used, these studies have been limited in describing a true representation of the kinematics in the foot (Sauser et al., 1983, Tuijthof et al., 2009a).

More recently, some studies have begun to measure kinematics of the ankle joint (and some the subtalar joint as well) by utilizing CT or MRI scans and segmenting the bones to create a virtual 3D model (Hirsch et al., 1996; Udupa et al., 1998; Mattingly et al., 2006). By using principal component analysis (PCA) and its results to acquire the centroid and principal axes for a particular joint, they have been able to accurately measure the translation and rotation of bones within the ankle joint. Thus, with the discovery that CT segmentation of cadaveric bones is reliable within sub-millimeter accuracy (Part 1 of the thesis, chapter 2) and with the success of PCA based on CT segmentations, the methodology for this study will be based on the aforementioned studies.
However, an important component that these studies were lacking was loading of the ankles. Loading of the ankles with body weight would make the kinematic results more applicable to the design of TAA implants since patients are required to place weight on their feet for normal daily activities. Therefore, this study loaded each lower limb with the estimated body weight of the donor from which they came from. In addition, only the plantarflexed, neutral and dorsiflexed positions were studied because this pilot study had an intention to start with studying a simple yet important movement for day-to-day activities.

An extension made to this study includes the kinematic examination of the talocalcaneonavicular joint in addition to the ankle and subtalar joints. Although current ankle prostheses only focuses on the ankle joint and the construction of tibial and talar components, it would be beneficial to the design of TAA implants to understand how the closely related bones of the ankle and foot articulate with each other and facilitate the transfer of load. Finally, another change made to this study was the use of cadaveric limbs due to the high intensity of radiation used by the 3D fluoroscopic scanner for increased detail to the image data. As well, a cadaveric option allowed for musculature dissection so that the muscles could be artificially contracted to actively induce plantarflexion and dorsiflexion of the foot.

3.2 – Materials and Methods

As described in section 2.2, intact cadaveric lower limbs (#1, #2, #3 and #4) were attained from the Department of Biomedical and Molecular Sciences at Queen’s University, Kingston, Ontario, Canada. They were dissected until only the muscles,
ligaments, tendons, major retinacula and joint capsule remained on the bones of the foot. The extensor and flexor muscles of the leg were released from their origin attachments to the bones but their insertion sites remained intact.

Each dissected lower limb was then secured in a custom wooden jig with an optional loading mechanism. By pulling on the group of extensor or flexor muscles, the lower limbs were actively situated into three positions - neutral, dorsiflexion, and plantarflexion - and a 3D fluoroscopic image was taken at each position. All imaged positions were loaded with the donor’s weight to simulate the force received by the joints in the ankle and foot. In addition, the lower limbs were imaged in an unloaded neutral position to allow for comparison with the loaded state. All images were performed at Kingston General Hospital, Kingston, Ontario, Canada.

The 3D fluoroscopic image data were then imported into Mimics and the talus, calcaneus, navicular, tibia and fibula bones for each lower limb for all four positions were segmented and constructed into sets of digital models.

An analysis of the kinematics of the ankle and foot joints was then performed to describe the translation and rotation between the neutral unloaded, dorsiflexion loaded and plantarflexion loaded positions with the neutral loaded position in the following sets of articulations: i) ankle joint, ii) subtalar joint, and iii) talonavicular joint of the talocalcaneonavicular joint.

A more detailed, step-wise protocol regarding the dissection, design and construction of the jig, acquisition of 3D fluoroscopic images, 3D model rendering process and kinematics analysis will be described in the following sections.
3.2.1 – Materials

Cadaveric Dissection

A) Four formalin-fixed cadaveric lower limbs (two left: #1, #3 and two right: #2, #4) with soft tissues intact

B) Dissection kit of scalpels, blades, forceps, bone saw, scissors

Custom Jig for Leg Positioning

A) 1/2" Plywood

B) 9/16" Cup hooks

C) Two pulleys, each with a safe work load of 110 lbs

D) Braided Nylon Rope, 3/16", safe work load of 90 lbs

E) Fishing line, 30 lbs/183 m

F) Fishing hooks, size 6

G) 3/4" Dowels

H) Screws

M) Straps to fasten jig to gantry and cadaveric leg to jig

N) Load of 160 lbs and 185 lbs

Drill and Surgical Pin

A) Shanz Pin, 5mm diameter x 200mm length

B) CONMED™ Linvatec: PRO2000 PowerPro® Console, PRO6100 PowerPro® Electric II System and PRO2250 1/4" (6.5mm) Stainless Steel Keyless Chuck with 4.1 Cannulation (Utica, NY, USA)

C) 3/16" Drill bit
3D Fluoroscopic Image Data Acquisition

A) General Electric (GE) Healthcare: Innova 4100IQ for interventional radiology with moving gantry (Chalfont St. Giles, UK)

B) Re-writable R- compact discs for media transfer

Computer Hardware

A) Dell™: OptiPlex 755 Intel® Core™ 2 Duo Processor with Windows XP Professional operating system (Round Rock, TX, USA)

Computer Software

A) Materialise Mimics® 14.0 (Leuven, Belgium)

B) MathWorks®: MATLAB® 7.10.0.499 (R2010a) (Natick, MA, USA)

3.2.2 – Cadaveric Dissection

3.2.2.1 – Dissection

Dissection of the lower limbs was performed by first removing the skin, subcutaneous tissue, fascial layers and synovial sheaths from the leg and foot up until the base of the proximal phalanges (Figure 3.1). None of the blood vessels or nerves were preserved while special care was taken to ensure that the ankle joint capsule, superior and inferior extensor retinaculum, superior and inferior peroneal retinaculum, flexor retinaculum, and interosseous membrane were intact to make the active simulation of dorsiflexion and plantarflexion more realistic by pulling on the extensor and flexor muscles. All muscles of the leg were preserved and delicately released from their origin attachment sites while they remained attached to the lower limb by their insertion sites (Figure 3.2).
Figure 3.1 - Dissected Lower Limbs

Right lower limb #2. (A) Anterior view; (B) Lateral view.
Figure 3.2 - Dissected Lower Limbs with Muscles Partially Detached

*Right lower limb #2.* (A) Antero-lateral view showing muscles of the anterior compartment of the leg.
Figure 3.2 continued - Dissected Lower Limbs with Muscles Partially Detached

Right lower limb #2. (B) Postero-medial view showing the deep group of muscles in the posterior compartment of the leg. The posterior tibial artery has been removed.
Figure 3.2 continued - Dissected Lower Limbs with Muscles Partially Detached

Right lower limb #2. (C) Medial view showing the superficial group of muscles in the posterior compartment of the leg.
Figure 3.2 continued - Dissected Lower Limbs with Muscles Partially Detached

Right lower limb #2. (D) Lateral view showing the muscles in the lateral compartment of leg.
3.2.2.2 – Drilling for Surgical Pin Placement

A hole was drilled transversely into the proximal end of the tibia from a medial to lateral direction. The hole was positioned posterior to the tibial tuberosity but slightly anterior to the plane of the fibula. When the drilling was complete, a Shanz pin was inserted into the hole and positioned so that an equal length of the surgical pin was protruding out from either end of the holes.

3.2.2.3 – Preservation of Cadaveric Material

To prevent drying of the soft tissue, the lower limbs were preserved through immersion in a moistening solution bath at room temperature.

3.2.3 – Jig Design and Construction

A custom jig was constructed to hold the lower limb in place while it was actively positioned into neutral, dorsiflexion or plantarflexion. In addition, the jig was designed with an optional loading device to simulate the weight of a person on the joints in the ankle and foot (Figure 3.3).

The jig plank was measured to be 84cm in length and 20.3cm in width so that an entire leg and foot could fit in it. It was designed with a plate 37cm in height (30cm above the plank of the jig) on one end of the jig where two rows of cup hooks located near the inferior end of the plate were screwed into place. The bottom row had eight cup hooks and was 1cm above the plank of the jig whereas the top row had 10 cup hooks and was 10cm above the jig plank. These cup hooks were used to tie and secure fishing lines and hooks that were pulling the extensor or flexor muscles to create active dorsiflexion or
Figure 3.3 - Custom Jig

(A) Side of the jig. The footplate (right) is where the bottom of the foot rests. (B) Shows the footplate with dowels to keep the calcaneus in place and holes where the ropes travel through to enter the pulley system. (C) The pulleys attach to heavy loads.
plantarflexion (as described in 3.2.4.2). On the other end of the jig was another plate (known as the footplate) of the same height where the foot would rest. Two holes were drilled into the footplate 5.2cm up from the plank of the jig and each 5.5cm away from the sides of the footplate. During the experiment, ropes attached to the Shanz pins in the tibia would traverse through these holes to enter a pulley system with a load attached at the end of the rope as described in 3.2.4.3. In addition, two holes, each 6.8cm away from the sides of the plank, were drilled near the edge against the footplate so that dowels 4.5cm high could be inserted to secure the foot in place during the loaded experiment. On the other side of the footplate, a block of wood with two pulleys fastened to the superior surface was screwed to the footplate just inferior to the drilled holes for the ropes. Parallel cut-outs of 5 cm in width were also removed from either side of the jig’s plank where straps to secure the leg onto the plank could be tied in.

3.2.4 – 3D Fluoroscopic Image Acquisition

3.2.4.1 – Jig Set-Up

The jig was set-up so that it was positioned length-wise on the gantry with the footplate at the edge of the gantry. This was necessary so that during a loaded experiment, the rope secured to the Shanz pin in the tibia would enter the pulley system and hang a load without being interrupted by the gantry. Straps and ropes were used to fasten the jig to the gantry so that it would remain in place during the loaded experiments. The gantry tilt was at 0°.
3.2.4.2 – Leg Positioning

3.2.4.2.1 – Neutral Position

The lower limb was positioned on the jig with the foot flat on the footplate and the posterior portion of the calcaneus situated in between the two dowels. Straps were also used to secure the leg onto the jig (Figure 3.4).

3.2.4.2.2 – Dorsiflexion Position

The extensor muscles in the anterior compartment of the leg - tibialis anterior, extensor hallucis longus, extensor digitorum longus and peroneus tertius - were manually pulled to actively bring the foot into a dorsiflexed position. To keep these extensor muscles in a state of constant tension so that the dorsiflexed position would be maintained, fishing hooks were inserted into the belly of each muscle or tendon and fishing line attached to the hooks were tightly wound and tied to the cup hooks on the plate opposite of the footplate. Straps were also used to secure the leg onto the jig (Figure 3.5).

3.2.4.2.3 – Plantarflexion Position

The flexor muscles in the posterior compartment of the leg - gastrocnemius, soleus, flexor hallucis longus, flexor digitorum longus, and tibialis posterior - were manually pulled to actively bring the foot into a plantarflexed position. The muscles in the lateral compartment of the leg -
Figure 3.4 - Leg Positioning and Load Set-Up - Neutral Position

Left lower limb #1 set up in the neutral position in the jig on the gantry. The 3D fluoroscopic imager is seen in the back. A rope tied to either end of the shanz pin in the tibia is set in a pulley system with a load.
Figure 3.5 - Leg Positioning and Load Set-Up - Dorsiflexion Position

Left lower limb #1 set up in the dorsiflexion position with the extensor muscles pulled and held in place by fishing hooks and fishing lines.
peroneus longus and peroneus brevis - were also manually pulled since they had some weak participation in plantarflexion as well. To keep these flexor muscles in a state of constant tension so that the plantarflexed position could be maintained, fishing hooks and fishing lines were utilized in the same manner as that described in section 3.2.4.2.2. A thick wooden block was placed under the posterior side of the proximal leg on the plank of the jig while a thin block was placed inferior to the calcaneus. These blocks were put into place to assist in maintaining the plantarflexed position, especially during a loaded experiment. Straps were also used to secure the leg onto the jig (Figure 3.6).

3.2.4.3 – Load Set-Up

A rope with a high working load was tightly secured on either end of the protruding portion of the Shanz pin (Figures 3.4, 3.5, 3.6). The rope ran along the plank of the jig and each fed through the pre-drilled holes in the footplate. Each rope then entered a pulley system and both were tightly attached to the same load so to hang the load off the ground.

For lower limbs #1 and #2 which were from the same cadaver, a load of 185 lbs was used. Lower limbs #3 and #4 which were from the same cadaver used a load of 160 lbs. The load weight was chosen based on an approximate estimation of the cadaver’s body weight before death by using the cadaver’s height and visual physique. In order to see the effect of loading with body weight on the joints of the ankle and foot, an over-estimation rather than an under-
Figure 3.6 - Leg Positioning and Load Set-Up - Plantarflexion Position

Left lower limb #1 set up in the plantarflexion position with the flexor muscles pulled and held in place by fishing hooks and fishing lines.
estimation was preferred since it was realistic for individuals to be carrying extra weight (and thus exert extra weight on those joints) in their normal day-to-day activities.

The load was only used during imaging and was released from the rope in order to switch between the neutral, dorsiflexed and plantarflexed position.

3.2.4.4 – 3D Fluoroscopic Image Parameters

The 3D fluoroscopic data were imaged at a slice distance of 0.232mm for an average of 512 slices per leg. The pixel size was 0.232mm and the image size was at 512 by 512 pixels.

3.2.4.5 – Export 3D Fluoroscopic Image Data

The 3D fluoroscopic images were exported as the DICOM file format extension type and burned onto re-writable R-compact disc media for data transfer.

3.2.5 – Protocol for 3D Model Rendering Process (CT Segmentation)

3.2.5.1 – Import 3D Fluoroscopic Image Data

The DICOM data were manually imported into Mimics which converted and saved the files as *.mcs. A detailed outline of the steps is described in section 2.2.3.1.
3.2.5.2 – Thresholding

A detailed outline of these steps is described in section 2.2.3.2.

3.2.5.3 – Editing Masks

A detailed outline of these steps is described in section 2.2.3.3.

3.2.5.4 – Region Growing

A detailed outline of these steps is described in section 2.2.3.4.

3.2.5.5 – Calculate Polylines and Cavity Fill from Polylines

A detailed outline of these steps is described in section 2.2.3.5.

3.2.5.6 – Calculate 3D from Mask

A detailed outline of these steps is described in section 2.2.3.6.

3.2.5.7 – Exporting Files

When the final 3D rendering of the segmented data was satisfactory, the masks for each bone of interest were exported to a (*.stl) file extension type.

3.2.6 – Quantitative Analysis of the Kinematics

The kinematics of the joints of the ankle and foot were quantitatively analyzed and described by the parameters of translation and rotation. The motions between the
neutral unloaded, dorsiflexion loaded and plantarflexion loaded positions (referred to as the study conditions) with respect to the neutral loaded position were described in the following sets of articulations: i) tibia and fibula with talus, ii) talus with calcaneus, and iii) talus with navicular. In order to describe 3D motion, it is imperative to define the position and orientation of each bone. This is achieved through the calculation of a common coordinate system. Note that all calculations were conducted using MATLAB.

3.2.6.1 – Kinematics of Tibia and Fibula with Talus

The 3D kinematics of both the tibia and fibula articulating together with the talus was analyzed. The standard for reporting ankle joint motion was set by the Standardization and Terminology Committee (STC) of the International Society of Biomechanics (ISB) (Wu et al., 2002) based on the Joint Coordinate System (JCS) which was originally proposed by Grood and Suntay in 1983 for the knee joint (Grood & Suntay, 1983). This recommendation used bony landmarks from the entire intact tibia and fibula to calculate the coordinate frame. However, due to the limitations of the 3D fluoroscopic image scanner, only the distal portion of the tibia and fibula could be imaged. Therefore, the coordinate frame was calculated from a different methodology that was proposed in 2005 by a co-author of the aforementioned paper (Siegler et al., 2005). The recommendation was to situate the origin of the coordinate frame at the inter-malleolar point which was located midway between the medial (MM) and lateral (LM) malleolus of the tibia and fibula respectively (Figure 3.7). The z-axis was then defined as the line connecting the MM and LM with the lateral as the positive direction. The x-axis
was calculated as the line perpendicular and pointing anterior to a plane that connected MM, LM and the centroid of the most proximal cross-section of the tibia. Finally, the y-axis was defined as the common line perpendicular to the x- and z-axis.

The extent of the tibia and fibula segmentations was not consistent between study conditions. In order to define a consistent coordinate frame for comparison, all four tibia segmentations corresponding to each study condition were registered to each other and the largest segmentation model was used as the basis for selecting anatomical landmarks and the centroid at the proximal cross-section. After determining the coordinate frame, the inverse registration was applied to permit an identical coordinate frame to exist in each study condition.

In this analysis, the motion of the tibiofibular complex was described relative to the talus. To accomplish this, the talus in each study condition was registered to the neutral loaded talus. The same registration was also applied to the tibiofibular complex and the tibiofibular coordinate system of the corresponding study condition. The motion of the bones was explained by comparing the rotation and translation of the study condition tibiofibular coordinate system with respect to the neutral loaded condition (Figure 3.8).

For each study condition, rotation about the z-axis represented anterior/posterior (where anterior rotation of tibiofibular complex dorsiflexed the foot), and was calculated by projecting the study condition x-axis onto the x-z plane in the neutral loaded state and computing the angle between the projection and the study condition x-axis (Figure 3.7). Rotation about the x-axis represented
Figure 3.7 - Coordinate Frame for Tibia and Fibula with Talus

Right lower limb #2, anterior view. Origin is between LM and MM (both purple stars) where the three axes meet. The z-axis (green) points laterally, x-axis (red) is perpendicular to the plane with LM, MM and the centroid of the tibia’s most proximal cross-section (green star) and y-axis (orange) is perpendicular to both the x- and z-axis.

Figure 3.8 - Calculating Kinematics for Ankle Joint (Neutral Loaded to Neutral Unloaded Position)

Right lower limb #2, anterior view. The ankle joint in neutral unloaded position (blue) was imposed on the neutral loaded position (black). Kinematics was calculated by measuring the angle between the axes in the coordinate system for the tibiofibular complex in the neutral loaded position (filled lines) and the axes in the coordinate system for the tibiofibular complex in the neutral unloaded position (dashed lines). The same is done for the dorsiflexion and plantarflexion study conditions.
medial/lateral rotation (where lateral rotation of the tibia everted the foot) and was calculated by projecting the study condition y-axis onto the x-y plane in the neutral loaded state and computing the angle between the projection and the study condition y-axis. Rotation about the y-axis described internal/external rotation of the tibia and fibula (where external rotation of the tibia was coupled with adduction of the foot) and was calculated by projecting the study condition z-axis onto the y-z plane in the neutral loaded state and computing the angle between the projection and the study condition z-axis.

3.2.6.2 – Kinematics of Talus with Calcaneus

The 3D kinematics of the talus articulating with the calcaneus was analyzed. Although the STC also recommended a coordinate frame based on JCS, this method was abandoned due to the numerous amount of recent and past papers (Udupa et al., 1998; Stindel et al., 1999; Mattingly et al., 2006) using a coordinate frame based on the geometric centroid and the principal axes (Udupa et al., 1998). This method recommended the origin of the coordinate frame to be at the geometric centroid, or center of mass (assuming homogenous mass distribution), of the fixed bone. The three principal axes, or moments of inertia which intersect to meet at the centroid of this bone, was then calculated using PCA and its results. The x-, y-, and z- axes were chosen as the principal axes having the most anterior, dorsal and lateral orientations, respectively (Figure 3.9).

In order to define a consistent coordinate frame across all loading conditions (and avoid any errors due to discrepancies in segmentation) the talus
Figure 3.9 - Coordinate Frame and Calculating Kinematics for Talus with Calcaneus (Neutral Loaded to Neutral Unloaded Position)

*Right lower limb #2, antero-lateral view.* The coordinate frame (filled lines) was calculated for the talus in the neutral loaded position (black). The origin was located at the centroid of the talus where the z-axis (green), x-axis (red), and y-axis (orange) intersect. The subtalar joint in the neutral unloaded position (blue) with its coordinate system (dashed line) was imposed on the subtalar joint in the neutral loaded position. The same is done for the dorsiflexion and plantarflexion study conditions.
frame was defined from PCA of the neutral loaded state only. The other study conditions were registered to the neutral loaded state and the inverse registration was applied to define the coordinate frame for each condition.

In this analysis, the calcaneus was the fixed bone and the motion of the talus was described. The calcaneus in each study condition was registered to the calcaneus in the neutral loaded state; the registration was applied to the talus and the talus coordinate system of the corresponding study condition to assess motion. The motion of the bones was explained by comparing the rotation and translation of the study condition talus coordinate system with respect to the neutral loaded condition (Figure 3.9).

For each study condition, rotation about the z-axis represented anterior/posterior rotation (where anterior rotation of the talus plantarflexed the foot), and was calculated by projecting the study condition x-axis onto the x-z plane in the neutral loaded state and computing the angle between the projection and the study condition x-axis. Rotation about the x-axis represented medial/lateral rotation (where medial rotation of the foot everted the foot), and was calculated by projecting the study condition y-axis onto the x-y plane in the neutral loaded state and computing the angle between the projection and the study condition y-axis. Rotation about the y-axis described internal/external rotation of the talus (where external rotation of the talus abducted the foot) and was calculated by projecting the study condition z-axis onto the y-z plane in the neutral loaded state and computing the angle between the projection and the study condition z-axis.
3.2.6.3 – Kinematics of Talus with Navicular

Detailed methods for quantitatively analyzing and describing the kinematics between the talus and navicular were previously outlined in section 3.2.6.2. The same talus coordinate frame determined using PCA was used as the basis for this analysis (Figure 3.10).

In this analysis, the navicular was the fixed bone and the motion of the talus was described. The navicular in each study condition was registered to the navicular in the neutral loaded state; the registration was applied to the talus and the talus coordinate system of the corresponding study condition to assess motion. The motion of the bones was explained by comparing the rotation and translation of the study condition talus coordinate system with respect to the neutral loaded condition (Figure 3.11).

For each study condition, rotation about the z-axis represented anterior/posterior rotation (where anterior rotation of the talus plantarflexed the foot), and was calculated by projecting the study condition x axis onto the x-z plane in the neutral loaded state and computing the angle between the projection and the study condition x-axis (Figure 3.10). Rotation about the x-axis represented medial/lateral rotation (where medial rotation of the talus everted the foot), and was calculated by projecting the study condition y axis onto the x-y plane in the neutral loaded state and computing the angle between the projection and the study condition y-axis. Rotation about the y-axis described internal/external rotation of the talus (where external rotation of the talus abducted the foot) and was calculated by projecting the study condition z-axis
Figure 3.10 - Coordinate Frame for Talus with Navicular

Right lower limb #2, antero-lateral view. Origin is placed at the centroid of the talus where the z-axis (green), x-axis (red), and y-axis (orange) meet.

Figure 3.11 - Calculating Kinematics for Talonavicular Joint (Neutral Loaded to Neutral Unloaded Position)

Right lower limb #2, antero-lateral view. The talonavicular joint in the neutral unloaded position (blue) was imposed on the neutral loaded position (black). Kinematics is calculated by measuring the angle between the axes in the coordinate system for the talus in the neutral loaded position (filled lines) and the axes in the coordinate system for the tibiofibular complex in the neutral unloaded position (dashed lines). The same is done for the dorsiflexion and plantarflexion study conditions.
onto the y-z plane in the neutral loaded state and computing the angle between the projection and the study condition z-axis.

3.3 – Results

The kinematics for the ankle, subtalar and talonavicular (of the talocalcaneonavicular) joints as they went through loaded motions of dorsiflexion to plantarflexion were described using the outcome measures of translation (in mm) and rotation (in degrees). For the ankle joint, the movements of tibia and fibula together with respect to a fixed talus were reported (Table 3.1). The kinematics at the subtalar joint was described by reporting the translation and rotation of the talus with relation to a fixed calcaneus (Table 3.2) whereas the talonavicular (of the talocalcaneonavicular) joint was described by the talus’ movements with relation to a fixed navicular bone (Table 3.3).

3.3.1 – Movement from Neutral Unloaded to Neutral Loaded Position (Figure 3.12)

3.3.1.1 – Ankle Joint

When moving from the neutral unloaded to the neutral loaded position (Figure 3.12), the tibia and fibula translated an average absolute value of 1.5mm with values ranging from 0.4mm to 2.5mm between the four lower limbs. In addition, the tibiofibular complex posteriorly rotated an average of 13.6°, externally rotated an average of 9.1° and medially rotated an average of 7.6° in relation to the talus. There was one exception with the description of medial rotation where lower limb #3 had lateral tibiofibular rotation instead. Also notable was lower limb #4 which showed a much higher degree of rotation at 31.9° than
Table 3.1 - Kinematics of the Tibia and Fibula with Talus

<table>
<thead>
<tr>
<th>Translation of Tibiofibular Complex (Absolute value in mm)</th>
<th>Rotation of Tibiofibular Complex (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anterior</td>
</tr>
<tr>
<td>Lower Limb #1</td>
<td></td>
</tr>
<tr>
<td>NL to NU</td>
<td>0.4</td>
</tr>
<tr>
<td>NL to DL</td>
<td>0.9</td>
</tr>
<tr>
<td>NL to PL</td>
<td>2.0</td>
</tr>
<tr>
<td>Lower Limb #2</td>
<td></td>
</tr>
<tr>
<td>NL to NU</td>
<td>1.1</td>
</tr>
<tr>
<td>NL to DL</td>
<td>1.3</td>
</tr>
<tr>
<td>NL to PL</td>
<td>1.5</td>
</tr>
<tr>
<td>Lower Limb #3</td>
<td></td>
</tr>
<tr>
<td>NL to NU</td>
<td>1.9</td>
</tr>
<tr>
<td>NL to DL</td>
<td>1.3</td>
</tr>
<tr>
<td>NL to PL</td>
<td>1.5</td>
</tr>
<tr>
<td>Lower Limb #4</td>
<td></td>
</tr>
<tr>
<td>NL to NU</td>
<td>2.5</td>
</tr>
<tr>
<td>NL to DL</td>
<td>2.0</td>
</tr>
<tr>
<td>NL to PL</td>
<td>2.2</td>
</tr>
</tbody>
</table>

NL = Neutral Loaded, NU = Neutral Unloaded, DL = Dorsiflex Loaded, PL = Plantarflex Loaded

Table 3.2 - Kinematics of the Talus with Calcaneus

<table>
<thead>
<tr>
<th>Translation of Talus (Absolute value in mm)</th>
<th>Rotation of Talus (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Posterior</td>
</tr>
<tr>
<td>Lower Limb #1</td>
<td></td>
</tr>
<tr>
<td>NL to NU</td>
<td>2.1</td>
</tr>
<tr>
<td>NL to DL</td>
<td>4.8</td>
</tr>
<tr>
<td>NL to PL</td>
<td>1.1</td>
</tr>
<tr>
<td>Lower Limb #2</td>
<td></td>
</tr>
<tr>
<td>NL to NU</td>
<td>1.9</td>
</tr>
<tr>
<td>NL to DL</td>
<td>1.1</td>
</tr>
<tr>
<td>NL to PL</td>
<td>1.6</td>
</tr>
<tr>
<td>Lower Limb #3</td>
<td></td>
</tr>
<tr>
<td>NL to NU</td>
<td>3.0</td>
</tr>
<tr>
<td>NL to DL</td>
<td>0.3</td>
</tr>
<tr>
<td>NL to PL</td>
<td>0.8</td>
</tr>
<tr>
<td>Lower Limb #4</td>
<td></td>
</tr>
<tr>
<td>NL to NU</td>
<td>2.7</td>
</tr>
<tr>
<td>NL to DL</td>
<td>0.1</td>
</tr>
<tr>
<td>NL to PL</td>
<td>2.8</td>
</tr>
</tbody>
</table>

NL = Neutral Loaded, NU = Neutral Unloaded, DL = Dorsiflex Loaded, PL = Plantarflex Loaded
Table 3.3 - Kinematics of the Talus with Navicular

<table>
<thead>
<tr>
<th>Lower Limb #1</th>
<th>Translation of Talus (Absolute value in mm)</th>
<th>Rotation of Talus (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL to NU</td>
<td>2.6</td>
<td>-10.7</td>
</tr>
<tr>
<td>NL to DL</td>
<td>3.8</td>
<td>-13.3</td>
</tr>
<tr>
<td>NL to PL</td>
<td>1.1</td>
<td>-7.4</td>
</tr>
<tr>
<td>NL to NU</td>
<td>1.6</td>
<td>-9.5</td>
</tr>
<tr>
<td>NL to DL</td>
<td>2.8</td>
<td>-6.6</td>
</tr>
<tr>
<td>NL to PL</td>
<td>7.4</td>
<td>5.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower Limb #2</th>
<th>Translator of Talus (Absolute value in mm)</th>
<th>Rotation of Talus (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL to NU</td>
<td>5.4</td>
<td>-16.3</td>
</tr>
<tr>
<td>NL to DL</td>
<td>0.6</td>
<td>-1.3</td>
</tr>
<tr>
<td>NL to PL</td>
<td>7.4</td>
<td>5.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower Limb #3</th>
<th>Translator of Talus (Absolute value in mm)</th>
<th>Rotation of Talus (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL to NU</td>
<td>2.3</td>
<td>-7.6</td>
</tr>
<tr>
<td>NL to DL</td>
<td>0.6</td>
<td>1.3</td>
</tr>
<tr>
<td>NL to PL</td>
<td>0.2</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower Limb #4</th>
<th>Translator of Talus (Absolute value in mm)</th>
<th>Rotation of Talus (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL to NU</td>
<td>4.6</td>
<td>-0.9</td>
</tr>
<tr>
<td>NL to DL</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>NL to PL</td>
<td>2.1</td>
<td>-2.6</td>
</tr>
</tbody>
</table>

NL = Neutral Loaded, NU = Neutral Unloaded, DL = Dorsiflex Loaded, PL = Plantarflex Loaded
Figure 3.12 - Kinematics from Neutral Unloaded to Neutral Loaded

*Right lower limb #2.* Shows the ankle and foot in neutral unloaded (blue) and neutral loaded (red) positions. (A) Anterior view; (B) Superior view; (C) Lateral view; (D) Medial view.
the other lower limbs (Table 3.1).

3.3.1.2 – Subtalar Joint

More translation was reported at the subtalar joint when a load imitating body weight was applied. The talus translated an average absolute value of 2.4mm in relation to a fixed calcaneus bone with values ranging from 1.9mm to 3.0mm. The talus also rotated posteriorly an average of 7°, rotated internally 6.5° and rotated laterally 9.8°. Note that there was an exception with lower limb #4 that rotated posteriorly 0.8° instead of anteriorly like the rest of the lower limbs (Table 3.2).

3.3.1.3 – Talonavicular (of Talocalcaneonavicular) Joint

The most translation occurred at the talonavicular joint where the talus translated an average absolute value of 3.6mm in relation to a fixed navicular bone with values ranging from 1.6mm to 5.4mm. The greatest degree of rotation also occurred at this joint with the talus rotating posteriorly an average of 9.4°, rotating internally an average of 12.7° and rotating laterally 20.9°. It is important to note that although the talus rotated posteriorly at a range of 9.5° to 16.3° in lower limbs #1 to #3, lower limb #4 only rotated 0.9° (Table 3.3).
3.3.2 – Neutral Loaded to Dorsiflex Loaded Position (Figure 3.13)

3.3.2.1 – Ankle Joint

When moving from the loaded neutral state to a loaded dorsiflexed state, the tibia and fibula together translated an average absolute value of 1.3mm with values ranging from 0.8mm to 2.0mm. In addition, the tibiofibular complex anteriorly rotated an average of 25.5°, internally rotated an average of 6.4° (with one exception where there was external rotation in lower limb #4 as well as a much lower degree of rotation in lower limb #3 at 2.1°) (Table 3.1) and laterally rotated an average of 6.9° in relation to the talus.

3.3.2.2 – Subtalar Joint

The talus translated an average absolute value of 1.6mm with values ranging from 0.1mm to 4.8mm. The talus also rotated anteriorly at an average degree of 3.8°, rotated externally 2.4° and rotated medially at 3.7°. Note that for lower limb #4, the talus rotated slightly in the opposite direction for the three rotation parameters that was previously described (Table 3.2).

3.3.2.3 – Talonavicular (of Talocalcaneonavicular) Joint

When the foot was dorsiflexed, the talus translated an average absolute value of 1.9mm with values ranging from 0.2mm to 3.8mm. The talus also rotated anteriorly an average of 5.3°, rotated externally 4.0° and rotated medially 8.2°. There was one exception for lower limb #4 where the talus slightly rotated
Figure 3.13 - Kinematics from Neutral Loaded to Dorsiflex Loaded

Right lower limb #2. Shows the ankle and foot in neutral loaded (red) and dorsiflex loaded (green) positions. (A) Anterior view; (B) Superior view; (C) Lateral view; (D) Medial view.
posteriorly instead of anteriorly. In addition, lower limb #4 consistently produced smaller degrees of rotation as compared with the other three lower limbs (Table 3.3).

3.3.3 – Neutral Loaded to Plantarflexed Loaded Position (Figure 3.14)

3.3.3.1 – Ankle Joint

When the foot was plantarflexed, the tibia and fibula together translated an average absolute value of 1.9mm with values ranging from 1.5mm to 2.2mm. The tibiofibular complex rotated the most in the plantarflexed position with posterior rotation at an average of 45.5°, internal rotation at 16.8° and medial rotation at 14.8° when compared with a fixed talus (Table 3.1).

3.3.3.2 – Subtalar Joint

Similar to when the foot was in dorsiflexion, the talus only translated an absolute value of 1.6mm with values ranging from 0.8mm to 2.8mm. The results suggested that the talus rotated anteriorly at an average of 1.6°. However, two (lower limbs #2 and #4) had values indicating that the talus rotated posteriorly at 0.3° and 2.4° instead. For the other rotation parameters, the talus rotated externally at an average of 1.7° and rotated medially at 0.6° with the exception of lower limb #2 that rotated laterally at 2.2° (Table 3.2).
Figure 3.14 - Kinematics from Neutral Loaded to Plantarflex Loaded

Right lower limb #2. Shows the ankle and foot in neutral loaded (red) and plantarflex loaded (purple) positions. (A) Anterior view; (B) Superior view; (C) Lateral view; (D) Medial view.
3.3.3.3 – Talocalcaneonavicular Joint

Altogether, the talus translated an average absolute value of 3.2mm with relation to the fixed navicular bone with values ranging from 1.1mm to 7.4mm. The talus also rotated anteriorly an average of 2.9° (with an exception of lower limb #2 that rotated posteriorly at 5.9°), rotated externally 6.1° and rotated medially 8.2° (Table 3.3).

3.4 – Discussion

Much of the TAA prosthesis designs have been revisions based on observations from short and a few long-term studies on TAA surgeries. Designers do incorporate some results from anatomical and kinematic studies such as ensuring that the prosthesis allows for a certain range of motion but many of those studies have been conducted using outdated methods such as utilizing external surface markers (Scott & Winter, 1991; Parks et al., 1994; Woodburn et al., 2002; Nester et al., 2007; Drewes et al., 2009) or 2D images to measure movement at the ankle joint (Komistek et al., 2000; Tuijthof et al., 2009a). In addition, many of the studies did not include loading of the ankle joint with body weight which makes the results less applicable for TAA patients who carry daily activities on their feet. Finally, only the ankle joint has been examined when it comes to designing TAA prosthesis because all TAA only have prostheses for the tibial and talar bone components. However, since the complex system of bones in the ankle and foot are interrelated in transfer of weight and movement, it is important that the kinematics of other joints in the foot be taken into consideration when designing TAA prostheses.
3.4.1 – Ankle Joint

Some results for the ankle joint were consistent with the anatomy of the ankle joint. As reported in the results, the ankle joint had less translation but more rotational movements. In the three loaded positions of dorsiflexion, neutral and plantarflexion, the tibia and fibula complex had little translation (0.4mm to 2.5mm) and more anterior/posterior rotation (7.2° to 51.9°), internal/external rotation (2.1° to 24.8°) and medial/lateral rotation (2.2° to 31.9°). These findings are appropriate because the tibiofibular mortise and its medial and lateral malleoli offer a tight grip on the trochlea of the talus, thus limiting the amount of translation available.

Aside from the expected rotation of the tibiofibular mortise into dorsiflexion, translation and the other two rotation parameters of the ankle joint were least when the foot went into dorsiflexion. This is expected since the dorsiflexed position is anatomically the most stable position for the ankle joint due to the talus’ broader body anteriorly than posteriorly. Plantarflexion on the other hand had the most translation and rotation which again can be accounted for by the talus’ narrower body on the posterior aspect.

This study showed that there was some translation and a considerable amount of rotation to the ankle joint when a load was applied to a foot in the neutral position. After it was loaded, the ankle joint behaved similarly to the foot in a plantarflexed position in that the tibiofibular complex rotated posteriorly and medially. The only difference was that the tibia and fibula rotated externally at an average of 9.1° in the neutral position while they rotated 16.8° internally during plantarflexion.
As expected, the range of rotation in the anterior/posterior direction was the greatest since this study examined kinematics during movement from dorsiflexion to plantarflexion. This was followed by internal/external rotation and then medial/lateral rotation indicating that the ankle joint is least able to support medial/lateral rotation possibly due to the limitations of the medial and lateral malleoli.

Overall, these results are of particular interest to the design of TAA prosthesis because most current designs are mainly constructed to allow for plantarflexion and dorsiflexion as well as some internal and external rotation. Total ankle prosthesis such as the AGILITY™ allows for a total 60° of motion including internal/external rotation and some slight translation (Hintermann, 2005). Buechel-Pappas™ allows for at most 9.2° of dorsiflexion and 25° of plantarflexion (Rippstein, 2003) whereas the HINTEGRA® provides at most 39° range of motion (Hintermann et al., 2004). Postoperation, it was found that SALTO® allowed 15.2° to 38.3° of motion (Bonnin et al., 2004) while S.T.A.R. provided 10° of dorsiflexion, 30° of plantarflexion and 15° of internal/external rotation (Hintermann, 2005). In comparison with the results revealed from this study, the current prostheses do not provide enough range of motion for dorsiflexion and plantarflexion as well as internal/external rotation in the loaded state. In addition, most TAA implants do not allow for much inversion/eversion due to the constraints that the designs provide such as the medial and lateral wings of the tibial or talar components that are used to prevent medial and lateral translation of the polyethylene inlay or talus bone (Figure 1.18). Designs without these wings but with a sulcus in the median of the talar component and a corresponding ridge on the polyethylene inlay are the only prostheses that allows for inversion/eversion, however, the degree of this motion is very small. Since
eversion and inversion occurs to some degree simply from loading an ankle in the neutral position (7.6°) and can reach up to 14.8° in plantarflexion, it is highly suggested that future TAA implant designs focus on allowing for more eversion/inversion.

3.4.2 – Subtalar Joint

In general, the subtalar joint did not have too much translation at an absolute range of 0.1mm to 4.8mm when compared to a fixed calcaneus. However, there was still on average more translation in the subtalar joint than the ankle joint. As well, anterior/posterior rotation (range, 0.3° to 11.7°), internal/external rotation of the talus (range, 0.1° to 7.9°) and medial/lateral rotation (range, 0.1° to 12.2°) were at a minimal at the subtalar joint. This is consistent with the anatomy of the subtalar joint which is believed to be mainly responsible for inversion and eversion of the foot. The reason why this study did not reveal more medial/lateral rotation was because only dorsiflexion/plantarflexion positions were tested. Thus, it was appropriate to see a limited amount of medial/lateral rotation of the talus.

Surprisingly, the subtalar joint translated and rotated the most when a load was placed on the neutral position as compared to when the loaded neutral foot was dorsiflexed or plantarflexed. This indicated that translation and rotation didn’t occur much at the subtalar joint when the foot was dorsiflexed or plantarflexed. Instead, only the action of loading the foot caused noteworthy change to the joint. The talus rotated posteriorly, laterally and internally when loaded with body weight but perhaps more rotation could have been observed if the foot underwent eversion and inversion as well.
In terms of translation, the subtalar joint translated an absolute average of 1.6mm in both the dorsiflexed and plantarflexed position. With regards to rotation, the subtalar joint consistently rotated a bit more in all three parameters in the dorsiflexed position than when it was plantarflexed. The subtalar joint also consistently supported rotation in the anterior/posterior direction more than it supported rotation in the other two directions. This could be due to the reason that only dorsiflexion and plantarflexion was studied or it could suggest that the subtalar joint is capable of more rotation in the anterior/posterior direction. In addition, there was a trend of greater internal/external rotation of the talus (with an exception at the dorsiflexed position) in the subtalar joint than medial/lateral rotation. This could be explained by the bony anatomy of the subtalar and the fact that the talus articulates inferiorly with the calcaneus which limits the amount of medial and lateral rotation that can occur.

Finally, the subtalar joint seemingly moved in similar ways when the foot was dorsiflexed or plantarflexed. In both positions, the subtalar joint externally rotated and also rotated medially. Although the joint also rotated anteriorly in the dorsiflexed position, the same could not be said with certainty for the plantarflexed position since two lower limbs rotated posteriorly instead in the plantarflexed position.

3.4.3 – Talonavicular (of Talocalcaneonavicular) Joint

Overall out of the three joints studied, the talonavicular joint displayed the most translation at an absolute range of 0.2mm to 7.4mm. The joint also allowed a lot of rotation at a range of 0.1° to 16.3° for anterior/posterior rotation, 0.6° to 18.3° for internal/external rotation and 0.6° to 27.6° for medial/lateral rotation. This is consistent
with the anatomy of the talonavicular joint in that the navicular only articulates with the rounded head of the talus and that it is a modified ball-and-socket joint with more range of motion than the other two joints. Although the ankle joint still had an overall greater degree of rotation, the talonavicular joint was able to exceed the ankle joint’s degree of rotation for certain rotational parameters in specific positions. Out of the three rotational directions, the talus rotated to the highest degree in the medial/lateral direction. Again, this can be explained by the anatomy of the ball-and-socket joint in which the round head of the talus could easily pivot in the corresponding concave side of the navicular bone.

Similar to the subtalar joint, the talonavicular joint unexpectedly translated and rotated the most when a load was applied in the neutral position as compared to when the loaded foot was dorsiflexed or plantarflexed. As opposed to the ankle joint, this indicated that the joints of the foot were more affected by the action of loading body weight on the foot than by dorsiflexion or plantarflexion.

The talonavicular joint was also analogous to the subtalar joint in that the joint moved in a similar fashion when the foot was dorsiflexed or plantarflexed. In both positions, the talonavicular joint rotated anteriorly, medially, and externally.

3.4.4 – Limitations

This study is quite novel in terms that there are hardly any other studies that examine the subtalar and talonavicular joint while the foot is loaded with the weight of a body. Thus, there are still many areas for improvement to confirm the kinematics found at these joints. First, the jig used to hold the leg in place during imaging for 3D fluoroscopic data was built with metal screws. Unfortunately, this interfered with the
imaging process and some images looked slightly skewed (Figure 3.15). As a result, the image data could have potentially been subject to over or under-segmentation, thus misleading the calculation of the centroid of the bones and subsequent coordinate frame. Similarly, due to the limits of the 3D fluoroscopic scanner, parts of the tibia, fibula, and calcaneus especially in the neutral and dorsiflexed position were cut-off from the image data. As described in section 3.2.6.1, the coordinate frame for the ankle joint might have been different if calculations were made based on the standardized JCS recommended by the ISB where intact tibia and fibula image data were required. Since some of the calcaneus was cut-off, the same areas from intact calcaneus bones of other lower limbs and positions were also manually cut-off so that all the bones would be relatively equal in shape and size for centroid calculation. This manual editing could have allowed for some human error that could potentially alter the outcome measures. As a result, even though translation in the posterior/anterior, superior/inferior and medial/lateral directions were calculated, only the absolute value of translation was reported in the results since it was unknown whether translation in specific directions were true values due to the possible variation in coordinate frame calculation. In addition, this could have been the cause for the occasional non-uniform trends in the results. For example in the subtalar joint when the foot was plantarflexed, two lower limbs reported anterior rotation of the talus while the other two lower limbs reported relatively similar absolute values of rotation but in the posterior direction. Thus it was difficult to determine whether the talus actually rotated anteriorly or posteriorly in relation to the calcaneus in that position.
Figure 3.15 - Distortion in the 3D Fluoroscopic Images

Right lower limb #2. (A) Undistorted CT images of calcaneus bone; (B) Arrows show the distortions in the 3D fluoroscopic images due to the jig’s metal screws.
The previous problem could have been improved if the study had a higher sample size since the study was conducted with only four lower limbs, one set of left and right lower limbs from a male and one set from a female. With more lower limbs, it could have been easier to determine the values that were outliers since the range of values for each outcome measure is currently quite large.

Another limitation was with regards to the set-up of the leg in the jig during image scanning. To actively induce dorsiflexion or plantarflexion, the extensor or flexor muscles were pulled and then held in place by fishing hooks and fishing lines. However, it was very challenging to tie the fishing lines tight enough to the cup hooks on the jig’s plate and thus full imitation of muscle contractions could not be achieved. This was the reason why wooden blocks had to be inserted under the foot or leg to help keep them in place while the load was applied. As a result, this could have potentially made the plantarflexion position less realistic.

3.4.5 – Future Directions

As a pilot study, the ideas and results from this study opens a road to many potential studies on the kinematics of the foot and ankle joints. First, it would be exciting to see the kinematics of the ankle joint with the fibula treated as a separate bone since most kinematic studies either only study the tibia or group them together as the tibiofibular mortise (Siegler et al., 2005; Mattingly et al., 2006; Tuijthof et al., 2009a; Tuijthof et al., 2009b; Beimers et al., 2008). However, insight into the way the talus bone moves with relation to the fibula could provide some understanding in TAA implant designs and prevention of malleolar fractures. In order to better draw conclusions on the
kinematics of the joints, it is also recommended that comparisons between bones be done with a single fixed bone across all comparisons, such as the talus bone.

This study examined three joints: ankle, subtalar and talonavicular joint. However, since the bones of the foot are all inter-related and partake in load transfer and movements of the foot, future studies should also investigate the kinematics of other joints in the foot such as the calcaneocuboid joint. In addition, studies should consider the kinematics of these joints through other motions such as adduction and abduction of the foot as well as eversion and inversion which are all important in walking, other daily activities and ultimately in TAA designs.

In order for the results to be even more applicable to TAA, studies could take more images of the motion from dorsiflexion to plantarflexion by scanning the bones at every few degrees of extension or flexion. Another possibility could be the use of a dynamic walking cadaveric lower limb model as attempted by Nester et al. (2007).

Finally, to make kinematic calculations easier to compute and more accurate, studies could employ the use of the centroid of a bone and its helical axis instead of principal axes. The helical axis method has recently become more popular (Tuijthof et al., 2009a; Tuijthof et al., 2009b; Beimers et al., 2008) because it is able to describe translation and rotation with just one axis (Woltring et al., 1985; Woltring, 1994) as compared with the three principal axes required for describing motion. Unfortunately, the downfall of calculating the helical axis is that the results are extremely difficult to understand by a layperson which is why it was not the method of choice in this study.
Chapter 4

Conclusion

In conclusion, Part 1 of this study showed that the process of rendering CT segmentations of ankle and foot bones into 3D plastic models was successful with sub-millimetre accuracy, thus confirming the hypothesis. It is therefore suggested that this process be implemented into pre-operative planning for ankle surgeries such as TAA where the use of models to visualize the ankle and foot joints as well as to create individualized drilling templates would be beneficial to reduce complications of TAA and alleviate problems with malpositioning and improper sizing. Overall Part 2 of this study showed that the ankle, subtalar, and talonavicular (of the talocalcaneonavicular) joints translated and rotated more than the allowed range of motion designed in current TAA implants. In addition, all three joints had a considerable amount of inversion/eversion and medial/lateral rotation of the tibiofibular mortise or adduction/abduction of the foot. This is important because most TAA prostheses do not provide an adequate amount of inversion and eversion motions. Loading of the foot with normal body weight caused a remarkable amount of translation and rotation to the joints. In fact in two of the joints (subtalar and talonavicular), the action of loading the joints induced a greater change in movement than did the actions of plantarflexion or dorsiflexion. These results confirmed the hypotheses of the study and it is suggested that these results be taken into consideration when designing new TAA implants.
References


