Tibiotalar arthrodesis: development of a novel jig and alignment guide

Adam Mathew Ropchan
The University of Western Ontario

Supervisor
Lawendy, Abdel-Rahman
The University of Western Ontario

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The first part of this thesis focuses on determining the rate of reoperation to the ipsilateral lower limb and if any patient/surgical factors are associated with reoperation for nonunion and infection. The second part of this thesis turns attention to developing a jig and alignment guide to improve outcomes, and to standardize this procedure. The rationale for developing the jig and alignment guide is based on the success of such devices in improving the outcomes in total hip and knee arthroplasty.

**Keywords:** tibiotalar arthrodesis, ankle arthrosis, rate of reoperation, non-union/malunion, infection, tibiotalar jig and alignment guide.
THE CO-AUTHORSHIP

While each of the co-authors listed below made important contributions to this work, I am the principal author who designed all the projects and performed all of the experimental data acquisition, collection, and analysis. All manuscripts presented in this thesis were prepared by me, with the consultation and critical review by the co-authors.

Abdel-Rahman Lawendy, MD, PhD, FRCSC, in his role as my supervisor, orthopaedic surgeon, and the principal investigator of the lab, provided strong leadership on the project, offering direction and guidance on all surgical techniques and assessment of outcomes, as well as a critical evaluation of all work.

Mark MacLeod, MD, FRCSC, in his role as an orthopaedic surgeon and co-investigator, provided initial sketches for the jig, as well as guidance on surgical techniques.

David Sanders, MD, FRCSC, in his role as a project advisor and orthopaedic surgeon, provided guidance on surgical techniques and a much-appreciated critical review of all the manuscripts.

Aaron Gee, MSc, in his role of a research associate, provided assistance with physical jig development and testing.

Moaz Chohan, MD, in his role as a research assistant, provided help with all chart reviews and patient data compilation.
DEDICATION

This thesis is dedicated to my father who unfortunately passed away before seeing me graduate medical school. It was his journey through six joint replacements and a number of other medical issues that helped inspire me to become a physician and specifically an orthopaedic surgeon. While his suffering may have been what inspired me, what has sustained me on my own journey have been the qualities he has instilled in me: his love of science and discovering new things, his steadfastness in the face of unbearable suffering, and belief that when you start something, you finish it, just to name a few. Perhaps, fittingly for this thesis, one of his favourite quotes was “Let the tool work for you” – I hope through the groundwork laid in this thesis that I can add one more tool to the orthopaedic surgeon’s toolbelt.
ACKNOWLEDGEMENTS

This thesis would not be possible without the assistance of a number of very important people.

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Appendix II.2 Lawson Health Research Institute Approval

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LIST OF ABBREVIATIONS

3D, three-dimensional
AITL, anterior inferior tibiofibular ligament
AO, Arbeitsgemeinschaft für Osteosynthesefragen
AP, anteroposterior
ATFL, anterior talofibular ligament
CAD, computer-aided design
CFL, calcaneofibular ligament
CSTAR, Canadian Surgical Technologies and Advanced Robotics
COM, centre of mass
COP, centre of pressure
CT, computed tomography
EDL, extensor digitorum longus
EHL, extensor hallucis longus
FDL, flexor digitorum longus
FHL, flexor hallucis longus
GFR, ground reaction force
ITFL, interosseous tibiofibular ligament
MRI, magnetic resonance imaging
MT, metatarsal
MTPJ, metatarsophalangeal joint
PT, peroneus tertius
PTFL, posterior talofibular ligament
PITL, posterior inferior tibiofibular ligament
REB, research ethics board
ROM, range of motion
SACH, solid ankle cushion heels
SD, standard deviation
SEM, standard error of mean
TA, tibialis anterior
TP, tibialis posterior
TTFL, transverse tibiofibular ligament
WS, webspace
CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW.
CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

Tibiotalar arthrodesis is the standard surgical procedure for treating end-stage ankle arthrosis (Canale and Beaty 2008). Arthrodesis is the artificial induction of joint ossification between two bones (ankylosis) by surgery, usually performed in order to relieve intractable joint pain that cannot be managed by pain medication, splints, or other normally indicated treatments (Canale and Beaty 2008).

1.1 ANATOMY OF THE ANKLE

The ankle (Figure 1.1) is a synovial diarthrodial joint that is actually a complex of three joints: the tibiotalar joint (talocrural joint), the tibiofibular joint, and the talofibular joint (Robinson and Keith 2016). Together, these articulations allow for the hallmark dorsi- and plantarflexion of the ankle, while providing significant stability to the joint at rest (DiGiovanni and Greisberg 2007). Important stabilizers of the ankle include the medial, lateral, and tibiofibular ligaments (i.e. syndesmotic ligaments) and the musculotendinous structures about the ankle (Gray, Standring et al. 2005, DiGiovanni and Greisberg 2007). Comprehension of the anatomy of the musculotendinous structures and the neurovascular bundles surrounding the ankle joint is important where surgical approaches to the ankle are concerned.
Figure 1.1. **Anatomy of ankle joint.** The ankle joint is composed of tibia, fibula and talus, forming tibiotalar (talocrural), tibiofibular, and talofibular joints.

*Adapted from Earth’s Lab – Ankle Joint.*

[https://www.earthslab.com/anatomy/ankle-joint-talocrural-joint/](https://www.earthslab.com/anatomy/ankle-joint-talocrural-joint/)
1.1.1 Osteology and Chondrology

The ankle joint is comprised of three bones: tibia, talus, and fibula. The distal aspects of the fibula and tibia form the ankle mortise in which the dome of the talus resides. The tibial aspect of the mortise includes the medial malleolus and tibial plafond, while the fibular aspect of the mortise includes the lateral malleolus (Thordarson 2013). Where bony surfaces are in contact with each other, their surfaces are covered in hyaline cartilage, including the tibiofibular joint (Hermans, Beumer et al. 2010, Thordarson 2013).

1.1.1.1 Distal Tibia

The tibia is the second longest and strongest bone in the human body (Marieb, Mallatt et al. 2010). The distal aspect of the tibia is characterized by its triangle-shaped diaphysis that gives way to a more rectangular-shaped metaphysis/epiphysis, with a medial projection (the medial malleolus) extending both distally and medially (Marieb, Mallatt et al. 2010, Netter 2011). It articulates with the dome of the talus.

The tibial plafond (inferior articular surface) may be found in up to 3° of valgus, and is externally rotated 20°-30° compared to the knee (DiGiovanni and Greisberg 2007). The plafond is covered in hyaline cartilage with a mean depth of 1.16 mm (Millington, Grabner et al. 2006, Millington, Li et al. 2007). The cartilage is typically thickest centrally and anteriorly, as well as in the transitional area from the plafond to the medial malleolus (Millington, Grabner et al. 2006, Millington, Li et al. 2007).
The medial malleolus is split anterior to posterior by a longitudinal groove, forming a smaller anterior colliculus and larger posterior colliculus (Thordarson 2013). The lateral aspect of the medial malleolus, known as the articular facet, is covered in hyaline cartilage that is approximately 0.85 mm thick (Millington, Grabner et al. 2006, Millington, Li et al. 2007). It articulates with the medial aspect of the talus.

Another aspect of the distal tibia is what is classically known as the fibular notch (though it goes by several other names), with its official name being *incisura fibularis tibiae* (Hermans, Beumer et al. 2010). It lies posterolaterally in the epiphysis of the distal tibia (DiGiovanni and Greisberg 2007). In most people, the fibular notch is concave, increasing in depth from proximal to distal; however, in a sizeable minority, the fibular notch is actually quite shallow (Hermans, Beumer et al. 2010). The cartilage on the tibial facet in direct contact with the fibula is hyaline in nature and is less than 0.5 mm thick (Ebraheim, Taser et al. 2006). It is a continuation of the articular cartilage from the plafond (Hermans, Beumer et al. 2010).

1.1.1.2 Talus

The talus is the second largest of the tarsal bones (after the calcaneus) (White, Black et al. 2011). It consists of three parts: the head, neck, and body (White, Black et al. 2011). It is a unique bone for two reasons: the majority of its surface is covered in articular cartilage, and it has no muscular attachments
(DiGiovanni and Greisberg 2007). The talar body is the portion that sits within the mortise and will be the focus of this section.

The talar body contains four key anatomical structures: the posterior process, the lateral process, the posterior facet, and the talar dome (DiGiovanni and Greisberg 2007, Netter 2011). The posterior process is made up of the lateral and medial tubercles, with the groove for the flexor hallucis longus tendon between them (Netter 2011). The tubercles also act as attachment sites for the lateral and medial ligaments that stabilize the ankle (Netter 2011). The lateral process partially articulates with the distal fibula and, like the tubercles of the posterior process, acts as a site for ligamentous attachment (Netter 2011). The posterior facet is concave; it is covered in hyaline cartilage and articulates with the posterior facet of the calcaneus, forming one aspect of the subtalar joint (Netter 2011, Brockett and Chapman 2016).

The talar dome is of particular importance. It is wedge-shaped, wider anteriorly compared to posteriorly by about 4.2 mm (Kelikian, Sarrafian et al. 2011), and convex in the sagittal plane, with an average radius of convexity of about 20 mm (Kelikian, Sarrafian et al. 2011). It also contains medial and lateral shoulders, with a *trochlea* between them (Kelikian, Sarrafian et al. 2011). Further medially and laterally are the medial and lateral facets; these are more vertically oriented to articulate with the medial and lateral malleoli (Kelikian, Sarrafian et al. 2011). The average cartilage depth of the talus is 2.38 mm; the thickest articular cartilage is found over the shoulders of the talus, anterolaterally and posteromedially (Millington, Grabner et al. 2006, Millington, Li et al. 2007).
1.1.1.3 *Distal Fibula*

The shaft of the fibula appears to make a quarter turn externally as it flares into the metaphysis/epiphysis (Marieb, Mallatt et al. 2010). The non-articulating aspect of the lateral malleolus makes up the lateral aspect of the distal fibula, and the triangle-shaped articular facet of the lateral malleolus makes up the medial aspect of the distal fibula (Netter 2011), articulating with the lateral aspect of the talus (Netter 2011). It is covered in hyaline cartilage that is approximately 0.85 mm thick (Millington, Grabner et al. 2006, Millington, Li et al. 2007).

Just proximal to the lateral malleolus is the *crista interossea fibularis*, a ridge along the fibula that becomes a convex triangle that fits within the concave fibular notch of the tibia (Hermans, Beumer et al. 2010). Its articular surface is covered in cartilage where anteriorly it is less than 0.5 mm, but posteriorly can range anywhere from 1-5 mm thick (Ebraheim, Taser et al. 2006).

1.1.2 *Ligaments of the Ankle*

There are essentially three groups of ligaments that provide passive stability to the ankle: the lateral ligament complex, medial ligament complex, and syndesmotic ligament complex (Gray, Standring et al. 2005, Thordarson 2013). The lateral ligaments all originate on the lateral malleolus, while the medial ligaments all originate on the medial malleolus (Netter 2011). The tibiofibular ligaments (Figure 1.2) include anterior and posterior ligaments, as well as the distal interosseous membrane (Thordarson 2013).
Figure 1.2. Ligaments of the ankle joint. The joint is comprised of lateral ligament complex, medial ligament complex, and syndesmotic ligament complex.

Adapted from OpenStax College, via Wikimedia Commons.
1.1.2.1 *Lateral Ligament Complex*

The lateral ligament complex includes the anterior talofibular ligament (ATFL), the calcaneofibular ligament (CFL), and the posterior talofibular ligament (PTFL) (Kelikian, Sarrafian et al. 2011, Thordarson 2013). These structures are responsible for the prevention of excessive inversion of the ankle and sagittal translation of the talus (DiGiovanni and Greisberg 2007).

The ATFL is generally formed by two bands (though single and triple variants exist), with the upper band being larger than the lower (Kelikian, Sarrafian et al. 2011). Its origin is the inferior oblique segment of the anterior border of the lateral malleolus – it then courses anteromedially and inserts on the talar body, just anterior to the lateral malleolar articular surface (Kelikian, Sarrafian et al. 2011, Thordarson 2013). The ATFL ranges from 15-20 mm long, 6-8 mm wide, and 2mm across (Thordarson 2013). It is the weakest, hence the most commonly injured, ligament of the lateral ligament complex (Thordarson 2013). The ATFL provides resistance to inversion while the ankle is plantarflexed (DiGiovanni and Greisberg 2007).

The CFL is a cordlike or flat oval ligament that originates from the lower segment of the anterior border of the lateral malleolus, just below the origin of the ATFL (Kelikian, Sarrafian et al. 2011). It generally courses inferiorly, posteriorly, and medially around the tip of the lateral malleolus, but does not attach to it in any way, though there are a number of variations (Kelikian, Sarrafian et al. 2011). It also courses underneath the peroneal tendons (Kelikian, Sarrafian et al. 2011, Thordarson 2013). The ligament then inserts on a small tubercle on the upper
lateral aspect of the calcaneus, called the *tuberculum ligamenti calcaneo fibularis* (Hermans, Beumer et al. 2010, Thordarson 2013). The ligament measures anywhere from 20-40 mm long, 4-5 mm wide, and 3-8 mm across (Kelikian, Sarrafian et al. 2011, Thordarson 2013). It provides resistance to inversion while the ankle is in dorsiflexion (DiGiovanni and Greisberg 2007).

The PTFL is trapezoidal in shape and originates on the posteromedial aspect of the lateral malleolus. The ligament travels medially in a horizontal fashion, with short and intermediate fibres inserting along the posteroinferior border of the lateral malleolar articular surface of the talus, while the long fibres insert on the trigonal process of the talus (Kelikian, Sarrafian et al. 2011). The PTFL is the strongest of the three lateral ligaments, and is rarely injured (Thordarson 2013). The ligament measures 30 mm in length, 5 mm in width, and 5-8 mm across (Kelikian, Sarrafian et al. 2011, Thordarson 2013).

1.1.2.2 Medial Ligament Complex

The medial ligament complex, or deltoid ligament, is split into two distinct layers: superficial and deep (Thordarson 2013). Although there have been a number of descriptions of the complex that vary in their interpretation of the distinctness of its various parts, for the most part they agree on the basic tenet of the presence of two layers (Kelikian, Sarrafian et al. 2011). The deltoid ligament prevents excessive eversion, and like the lateral ligaments, it provides sagittal plane restraint, with the deep fibres playing a larger role than the superficial fibres (DiGiovanni and Greisberg 2007).
The superficial component originates at the anterior colliculus of the medial malleolus, and fans out into three components (Kelikian, Sarrafian et al. 2011, Thordarson 2013): the talonavicular component running anteriorly and inserting on the medial aspect of the navicular; the tibiocalcaneal component, running inferiorly and inserting on the sustentaculum tali of the calcaneus; and the posterior tibiotalar component, that runs posterolaterally and inserts on the medial tubercle of the talus (Thordarson 2013).

The deep component is separated into two distinct ligaments: the anterior and posterior deep tibiotalar ligaments (Thordarson 2013). The deep anterior tibiotalar ligament originates at the tip of the anterior colliculus and anterior aspect of the intercollicular groove of the medial malleolus, and inserts just below the articular surface of the medial talus (Kelikian, Sarrafian et al. 2011, Thordarson 2013). Interestingly, this ligament may be completely absent in some individuals, while it is of variable size and caliber in others (Kelikian, Sarrafian et al. 2011).

The deep posterior tibiotalar ligament, the strongest segment of the medial ligament complex, is described as conical, and may be divided into two distinct bands or be multifascicular in nature (Kelikian, Sarrafian et al. 2011). It originates at the intermolecular fosse, the anterior surface of the posterior colliculus, and the upper aspect of the anterior colliculus; it makes its way posteriorly, inferiorly, and laterally to insert on the medial talus below the articular surface (Kelikian, Sarrafian et al. 2011, Thordarson 2013). The ligament measures 15 mm at its base (origin) and 10 mm at its tip (insertion), is approximately 15 mm long, and
measures 15-20 mm in width and 5-15 mm in diameter (Kelikian, Sarrafian et al. 2011).

1.1.2.3 Syndesmotic Ligament Complex

The syndesmotic ligament complex includes four ligaments: anterior inferior tibiofibular ligament (AITFL), posterior inferior tibiofibular ligament (PITFL), transverse tibiofibular ligament (TTFL) or inferior transverse ligament, and interosseous tibiofibular ligament (ITFL) (Thordarson 2013). The distal tibiofibular joint is also stabilized by the distal aspect of the interosseous membrane (Kelikian, Sarrafian et al. 2011).

The AITFL is a flat, trapezoidal, fibrous ligament originating at the longitudinal tubercle over the anterior distal fibular shaft and lateral malleolus (Ebraheim, Taser et al. 2006, Kelikian, Sarrafian et al. 2011), coursing proximally and medially, to insert on the anterolateral tubercle of the tibia (Kelikian, Sarrafian et al. 2011). The upper aspect of the ligament measures about 8.9 mm in length, while inferiorly it measures about 21 mm in length. The width decreases from proximal to distal (4.9 mm to 3.8 mm) while the diameter increases (1.8 mm to 2.2 mm). The AITFL may be divided into two or three bands, or it may be multifascicular in nature (Kelikian, Sarrafian et al. 2011).

The PITFL is a strong ligament originating from a tubercle above the digital fossa of the lateral malleolus (Kelikian, Sarrafian et al. 2011). It courses proximally and medially, and inserts on the posterolateral tibial tubercle, with some fibres extending to the lateral border of the groove for the posterior tibialis
The upper portion of the ligament is 9.7 mm long while the lower portion is 22 mm, while the width remains similar throughout (17 mm) (Ebraheim, Taser et al. 2006). Its diameter decreases from the ligament origin to its insertion (11 mm to 8.3 mm) (Ebraheim, Taser et al. 2006).

TTFL is the deep portion of the posterior tibiofibular ligament, although some consider it a distinct ligament (Ebraheim, Taser et al. 2006, DiGiovanni and Greisberg 2007, Kelikian, Sarrafian et al. 2011, Thordarson 2013). The ligament is thick, strong, conoid, and has a twist to its fibres (Kelikian, Sarrafian et al. 2011). It originates from a round posterior tubercle above the digital fossa of the fibula, coursing proximally, medially, and posteriorly before changing direction at the posterior border of the tibial articular surface to a more horizontal track (Kelikian, Sarrafian et al. 2011). The TTFL inserts on the posterior border of the tibial articular surface, and may even reach the medial border of the medial malleolus (Ebraheim, Taser et al. 2006, Kelikian, Sarrafian et al. 2011). The ligament is 37 mm long, 4.2 mm wide, and has a diameter of 2.1 mm (Ebraheim, Taser et al. 2006).

The ITFL is a strong ligament that prevents proximal migration of the talus between the tibia and fibula, and acts as a restraint to transverse motion between tibia and fibula (Thordarson 2013). It originates at the anteroinferior triangular segment on the medial aspect of the distal fibular shaft, inserting on the distal lateral shaft of the tibia, above the talofibular articulation (Kelikian, Sarrafian et al. 2011, Thordarson 2013).
Acting together, the syndesmotic ligaments allow the fibula to rotate, translate, and migrate proximally when the wider anterior aspect of the talus sits within the mortise during dorsiflexion (Thordarson 2013). They also allow force transmission through the fibula, allowing it to take on approximately 16% of the axial load placed on the leg (Thordarson 2013).

1.1.3 Musculotendinous and Neurovascular Structures of the Ankle

A significant number of musculotendinous and neurovascular structures traverse the ankle joint. These are best described using the same anatomical terminology as those within the leg, i.e. four separate compartments (Figure 1.3): anterior, lateral, deep posterior, and superficial posterior (Kelikian, Sarrafian et al. 2011). Given that the anatomy, especially the neurovascular one, is variable, only the most common or general anatomy is discussed in the following section.

1.1.3.1 Anterior Compartment

The anterior compartment consists of four muscles (from medial to lateral): tibialis anterior (TA), extensor hallucis longus (EHL), extensor digitorum longus (EDL) and peroneus tertius (PT) (Gray, Standring et al. 2005). All four muscles originate proximal to the ankle joint on the anterior surface of the tibia, fibula and interosseous membrane, and pass underneath two bands of fibrous tissue – superior and inferior extensor retinacula – that prevent bowstringing of the tendons as they make their way to their insertions on the dorsum of the foot (Gray, Standring et al. 2005, Marieb, Mallatt et al. 2010, Netter 2011). The TA is
Figure 1.3. **Compartments of the leg.** There are four compartments in the leg that contain the muscles, nerves, arteries, and veins that cross the ankle.

*Adapted from Atlas of Human Anatomy. (Netter, 2011)*
the prime mover of dorsiflexion, also acting as an inverter and supporter of the medial arch of the foot (Marieb, Mallatt et al. 2010). The EHL extends the great toe at the interphalangeal joint and metatarsophalangeal joint (MTPJ), and aids in dorsiflexion (Marieb, Mallatt et al. 2010). The EDL extends the remaining toes, mainly at their MTPJs, while the PT dorsiflexes and everts the foot (Marieb, Mallatt et al. 2010). The deep peroneal nerve innervates all of these muscles, well proximal to the ankle joint (Marieb, Mallatt et al. 2010) (Figure 1.4).

In between (and slightly deep to the TA and EHL) runs the anterior tibial artery (medial) as well as the deep peroneal nerve (lateral) (Gray, Standring et al. 2005, Kelikian, Sarrafian et al. 2011). They both follow the TA and EHL tendons through the extensor retinacula. Just below the ankle, the EHL passes over top of the structures so that the anterior tibial artery and deep peroneal nerve run laterally to the EHL (Gray, Standring et al. 2005, Kelikian, Sarrafian et al. 2011).

The medial and intermediate dorsal cutaneous nerves, the terminal branches of the superficial peroneal nerve, lie superficial to the retinacula (Gray, Standring et al. 2005, Kelikian, Sarrafian et al. 2011). These pass between the peroneus longus and EDL, and come out superficial to the extensor retinacula over the EDL, where they provide sensory innervation to the dorsum of the foot (Gray, Standring et al. 2005, Hoppenfeld, De Boer et al. 2009). The perforating peroneal artery courses just above the tibiofibular syndesmosis and comes out anteriorly to anastomose with the anterior lateral malleolar artery (Gray, Standring et al. 2005, Marieb, Mallatt et al. 2010). Superficial but further medial,
Figure 1.4  Anterior structures crossing the ankle.

Adapted from Atlas of Human Anatomy. (Netter, 2011)
both the long saphenous vein and nerve course over the anterior aspect of the medial malleolus (Gray, Standring et al. 2005, Kelikian, Sarrafian et al. 2011).

1.1.3.2 Lateral Compartment

The lateral compartment consists of the peroneus longus, peroneus brevis and the superficial peroneal nerve (Figure 1.5) (Gray, Standring et al. 2005). Both peronei are innervated by the superficial peroneal nerve, originate on the shaft of the fibula, course posterior to the lateral malleolus, and carry out plantarflexion and eversion of the foot (Marieb, Mallatt et al. 2010).

The peroneus longus inserts on the medial cuneiform and base of the first metatarsal, while the peroneus brevis inserts at the base of the fifth metatarsal (Marieb, Mallatt et al. 2010). While the superficial peroneal nerve lies within the lateral compartment in the leg, by the time it reaches the ankle, it has divided into its terminal branches and coursed anteriorly, thus no longer remaining within the lateral compartment (Gray, Standring et al. 2005, Netter 2011).

1.1.3.3 Deep Posterior Compartment

An abundance of structures passes through the deep posterior compartment: three tendons, two arteries, and a nerve are bounded by the tibia, fibula and interosseous membrane anteriorly and transverse intermuscular septum posteriorly (Figure 1.6) (Netter 2011). The three tendons (from medial to lateral) are tibialis posterior (TP), flexor digitorum longus (FDL) and flexor hallucis
Figure 1.5  Lateral structures crossing the ankle.

Adapted from Atlas of Human Anatomy. (Netter, 2011)
Figure 1.6  Medial structures crossing the ankle.

Adapted from Atlas of Human Anatomy. (Netter, 2011)
longus (FHL) (Gray, Standring et al. 2005, Marieb, Mallatt et al. 2010, Netter 2011). The tendons originate proximally on the tibia, fibula and interosseous membrane, and receive their innervation from the tibial nerve (Marieb, Mallatt et al. 2010). They each pass through individual fibrous tunnels as they make their way posterior to the medial malleolus (Kelikian, Sarrafian et al. 2011).

The TP is the most anterior and closest to the medial malleolus; it inserts on the plantar surface of several tarsals and metatarsals, and is the prime muscle of inversion (Marieb, Mallatt et al. 2010). It also plantarflexes the foot and maintains the medial arch (Marieb, Mallatt et al. 2010). The FDL lies just posterior to the TP and inserts on the plantar aspect of the distal phalanges of the second through fifth toes (Marieb, Mallatt et al. 2010). It flexes and inverts the foot, and flexes the toes (Marieb, Mallatt et al. 2010).

The two arteries are the posterior tibial and peroneal arteries (Marieb, Mallatt et al. 2010). The posterior tibial artery lies just posterior to the FDL and superficial to the tibial nerve (Gray, Standring et al. 2005); the peroneal artery initially follows along the posterior aspect of the interosseous membrane just medial to the fibula (Gray, Standring et al. 2005). It then splits into two branches, posterior and anterior (Kelikian, Sarrafian et al. 2011). The anterior, or perforating branch, courses anteriorly, just above the tibiofibular syndesmosis (Kelikian, Sarrafian et al. 2011).

The tibial nerve lies just posterior and deep to the posterior tibial artery (Gray, Standring et al. 2005, Hoppenfeld, De Boer et al. 2009). The nerve makes
its way around the medial malleolus and terminates as the medial and lateral plantar nerves on the sole of the foot (Marieb, Mallatt et al. 2010).

1.1.3.4 Superficial Posterior Compartment

The superficial posterior compartment incorporates two muscles: the gastrocnemius (superficial) and soleus (deep), with the transverse intermuscular septum separating it from the deep posterior compartment (Figure 1.6) (Marieb, Mallatt et al. 2010, Netter 2011). The gastrocnemius originates from the medial and lateral femoral condyles, while the soleus originates from the posterior surface of the tibia, fibula, and interosseous membrane (Marieb, Mallatt et al. 2010). The two muscles combine together to form one insertional tendon distally – the Achilles tendon – which attaches to the posterior tuberosity of the calcaneus (Marieb, Mallatt et al. 2010).

Superficially and posteriorly, the sural nerve and small saphenous vein are generally central proximally, and course just posterior to the peroneal tendons at the ankle joint (Gray, Standring et al. 2005).

1.2 ANKLE BIOMECHANICS

Traditionally, the ankle has been thought of as a “hinge joint’ with motion (dorsi/plantar flexion) in a single (sagittal) plane. While this description is useful for its simplicity, motion at the ankle joint is much more complicated and will be discussed further in section 1.2.1. The clinical or practical range of motion will be
discussed in section 1.2.2, ankle stability in section 1.2.3, and the ankle joint through the gait cycle will also be explored in detail in section 1.2.4.

1.2.1 Ankle Motion

Motion at the ankle occurs at two joints: the talocrural joint and the distal tibiofibular joint. Controversy remains about the axis of motion of the talocrural joint; both views are presented below. Motion at the distal tibiofibular joint is subtle but plays an important role in the overall biomechanics of the ankle.

1.2.1.1 Talocrural Joint Motion

Motion of the talocrural joint occurs in three planes (also known as triplanar motion): the transverse, sagittal, and coronal (Harris, Smith et al. 2008). This is made possible by the unique shape of the talus, as well as the orientation of the plafond and malleoli (Stiehl and Inman 1991). Given the significant differences in thought about the axis of motion, what is common to both schools of thought is presented first, followed by an explanation of each theory.

In relation to the transverse plane, the malleoli are externally rotated (posterolaterally) approximately 20-30° (malleolar plane) (Inman 1976). The facets of the medial and lateral malleoli converge posteriorly in relation to this plane, accommodating the wedge shape of the talus (Stiehl and Inman 1991). The vertical planes of the medial and lateral facets of the talus are 83.9° (range 70-93°; SD 5.2°) and 89.2° (range 80-95°; SD 2.8°) in relation to the malleolar plane (Stiehl and Inman 1991). The medial and lateral malleoli and medial and
lateral facets of the talus remain in contact throughout the entire range of motion, as confirmed by computed tomography studies (Lindsjö, Hemmingsson et al. 1979). In the coronal plane, the midline of the tibia forms on average a $93^\circ$ angle with the plafond (angle measured medial to midline), with a range of $88^\circ$ to $100^\circ$ (Stiehl and Inman 1991).

There are two schools of thought with regards to the shape of the talus and the resultant axis of motion of the ankle joint (Kelikian, Sarrafian et al. 2011). In 1952, Close and Inman in proposed a uniaxial theory, later basing it on the premise that the talus is a frustum of a cone (Close and Inman 1952, Close 1956, Inman 1976). Singh (Singh, Starkweather et al. 1992) further corroborated this theory. Anatomical studies indicate a number of findings: first, the medial and lateral shoulders of the talus have differing arcs of curvature but subtend nearly the same angle. The angle medially is $103\pm14^\circ$ and laterally $106\pm13^\circ$ (Inman 1976). The medial shoulder corresponds to the medial facet and the lateral shoulder corresponds to the lateral facet. The lateral facet is nearly always circular in shape with its radius, on average, $2.1\pm1.1$ mm longer than the medial facet (Inman 1976). The medial facet is almost always circular, but it takes on a slightly deviated shape approximately 20% of the time (Inman 1976). The malleoli follow a similar pattern: the lateral malleolus is circular in shape in nearly all cases, while the medial facet may not quite be circular in up to 15% of cases (Inman 1976). The average angle subtended by the lateral facet is $69\pm8^\circ$ and that of the medial facet is $55\pm11^\circ$ (Inman 1976). The radius of curvature on the lateral malleolus in the majority of cases is quite similar (within 2 mm) to that of
the lateral facet of the talus, while medially the radius of the malleolus is, on average, $2.1 \pm 1.1$ mm longer than that of the medial facet of the talus (Inman 1976). As a result of these measurements, Inman described the axis of the ankle to be, on average, 5 mm distal to the tip of the medial malleolus, and 3 mm distal to and 8 mm anterior to the tip of the lateral malleolus (Inman 1976).

The multiaxial nature of motion in the ankle joint is defended by several investigators (Barnett and Napier 1952, Hicks 1953, Sammarco 1977, Siegler, Chen et al. 1988, Lundberg, Svensson et al. 1989, Siegler, Konow et al. 2018). Barnett and Napier’s construct agreed with Close and Inman’s construct on the lateral talar facet: its arc of curvature is that of a true circle (Barnett and Napier 1952, Close and Inman 1952). The two teams diverge with regards to the lateral talar facet: Barnett and Napier’s construct describes the arc of curvature of the medial facet as that of two circles with differing radii, with the smaller circle (radius less than the lateral talar facet) describing the anterior third of the medial talar facet, while the larger circle (radius larger than the lateral talar facet) describing the posterior two-thirds of the medial talar facet. Therefore, with the ankle dorsiflexed, the axis is pointing downward and laterally; in plantar flexion, the axis is pointing downward and medially (Barnett and Napier 1952). The transition occurs within a few degrees of the talus being in neutral position (Barnett and Napier 1952).

Hicks (Hicks 1953) further confirmed Barnett and Napier’s findings, classifying the joint axes by identifying when rods, placed at the hypothesized axes, no longer translated with movement of the joint, but simply rotated. The
dorsiflexion axis was found to be 1.5 cm anterior to the tip of the medial malleolus and 0.5 cm inferior to the tip of the lateral malleolus, while the plantar flexion axis was found to be 1.5 cm anterior and 1.0 cm inferior to the tip of the medial malleolus and 0.5 cm superior to the tip of the lateral malleolus (Hicks 1953).

Lundberg et al. (Lundberg, Svensson et al. 1989) improved our understanding of the multiaxial nature of ankle motion through roentgen stereophotogrammetry studies in humans that used 0.8 mm tantalum beads embedded into the bones of subjects’ feet and ankles. The ankles were taken through range of motion from 30° dorsiflexion to 30° plantar flexion while weight bearing. The axes of motion were determined at 10° intervals (Lundberg, Svensson et al. 1989). The authors found that, on average, the axis was downward and lateral in dorsiflexion, and downward and medial in plantar flexion. Although the change in axis seemed to occur abruptly at times, it also seemed to occur gradually in some subjects (Lundberg, Svensson et al. 1989). In the horizontal plane, the axes for each of the subjects were always close to the tips of the malleoli (Lundberg, Svensson et al. 1989). Moreover, the authors also determined the axes of the ankle joint with rotation of the leg and with pronation and supination of the foot, again while weight bearing (Lundberg, Svensson et al. 1989). Significant variability in the axes was found, but, interestingly, all axes (including those calculated for dorsiflexion and plantar flexion) appeared to pass through a single area of the talar trochlea (Lundberg, Svensson et al. 1989). This
point happened to be at the midpoint of a line drawn between the tips of the malleoli (Lundberg, Svensson et al. 1989).

Sammarco (Sammarco 1977) described the axes (instant centres of rotation) of motion of the ankle, along with surface velocities, as the ankle was taken through weight bearing and non-weight bearing dorsiflexion and plantar flexion; the axis of motion could be anywhere, from above the body of the talus to below the body of the talus (Sammarco 1977). An important contribution from Sammarco's work is a description of how the ankle moves: when motion is initiated, there is distraction of the plafond and talus, followed by sliding, and finally with jamming at the end of range of motion (Sammarco 1977).

In an award-winning paper from 2018, Siegler et al. (Siegler, Konow et al. 2018) performed computed-tomography scans of 26 ankles in healthy subjects between 18 and 35 years of age. The images were converted to 3D figures using computer software, while circles of best fit were determined for the lateral, medial, and central aspects of the trochlea (Siegler, Konow et al. 2018). In contradiction to Inman’s theory, the radius of curvature of the medial facet was found to have a significantly longer (25.7 mm, SD 4.8 mm) than the curvature of the lateral facet (21.7 mm, SD 2.9 mm) (Siegler, Konow et al. 2018). Interestingly, Siegler’s results did agree with Inman in showing an existence of a single curvature that describes the medial facet, in contradiction to Barnett and Napier (Barnett and Napier 1952, Inman 1976, Siegler, Konow et al. 2018). Overall, the authors believe the shape of the trochlea to be a skewed cone, with its apex lateral, as opposed to medial (Siegler, Konow et al. 2018); they assumed this discovery
explains why the ankle goes into inversion and internal rotation as it moves from dorsiflexion to plantar flexion (Siegler, Konow et al. 2018). Of interest was also the discovery that there was a decrease in the concavity in the coronal plane (from anterior to posterior), implying that there may be some allowance for independent inversion/eversion in neutral/dorsiflexion (Siegler, Konow et al. 2018).

1.2.1.2 Distal Tibiofibular Joint Motion

Motion at the distal tibiofibular joint was recognized as far back as 1899, by the famous French anatomists, Poirier and Charpy (Poirier 1895). Poirier and Charpy described the tibiofibular joint as being elastic, accommodating the talus throughout the range of motion while maintaining contact between all articular surfaces. The motion has since been quantified by a number of investigators (Close 1956, Weinert, McMaster et al. 1973, Scranton, McMaster et al. 1976, Kärrholm, Hansson et al. 1985, Ahl, Dalen et al. 1987): Close (Close 1956) described a 1.5 mm diastasis and a 2.5° external rotation of the fibula when the ankle was brought from plantar to dorsiflexion; Kärrholm et al. (Kärrholm, Hansson et al. 1985) used roentgen stereophotogrammetry to assess fibular motion in children, finding that in an unloaded state, the fibula moved from full plantar flexion to full dorsiflexion 1.4 mm laterally, 0.8 mm posteriorly and 0.5 mm distally; Ahl et al. (Ahl, Dalen et al. 1987) determined that the fibula translated laterally 1.0 mm and posteriorly 0.9 mm from full plantar flexion to dorsiflexion; the distal translation of the fibula during weight bearing was later confirmed and
quantified as 2.4 mm on average (Weinert, McMaster et al. 1973, Scranton, McMaster et al. 1976). Finally, it was determined that with weight bearing, neutral plantar/dorsiflexion, and external rotation (75 Nm), the fibula translates medially 0-2.5 mm, externally rotates 2-5°, and translates posteriorly 1.0-3.1 mm (Beumer, Valstar et al. 2003).

1.2.2 Ankle Range of Motion

A great deal of effort has gone into explaining the triplanar motion of the ankle, and how the fibula moves to accommodate the talus within the mortise. Clinically, however, it is more important to determine the normal range of motion of the ankle, and the parameters that make it abnormal.

The major components of ankle range of motion are dorsi- and plantar flexion (Kelikian, Sarrafian et al. 2011). In 1965, the American Academy of Orthopedic Surgeons published values for dorsi- and plantar flexion as 18° of dorsiflexion and 48° of plantar flexion, considering them the standards (American Academy of Orthopaedic Surgeons 1965). These values are often criticized given that their reference population was not defined, and values were not stratified by age or gender (Boone and Azen 1979, Roaas and Andersson 1982, Soucie, Wang et al. 2011).

Since then, there have been a number of studies attempting to quantify dorsi and plantar flexion of the ankle in defined populations (Boone and Azen 1979, Roaas and Andersson 1982, Walker, Sue et al. 1984, Alanen, Levola et al. 2001, Moseley, Crosbie et al. 2001, Soucie, Wang et al. 2011). All of these have
been heterogeneous with regards to their populations, measurement techniques, and whether passive and/or active range of motion was measured. The most in-depth clinical study was conducted by Soucie et al. (Soucie, Wang et al. 2011), in which 674 healthy subjects between ages of 2-69 years and near equal gender representation underwent measurement of passive dorsi/plantar flexion. The findings, summarized in Table 1.1, found statistically significant differences between the 2-8 age group and the three other age groups, as well as between the 9-19 and the 45-69 age groups (Soucie, Wang et al. 2011).

Active range of motion in men aged 1-54 years was measured by Boone and Azen (Boone and Azen 1979). In subjects less than 19 years of age, dorsiflexion was 13.0±4.7° and plantar flexion 58.2±6.18°; in those greater than 19 years of age, dorsiflexion was 12.2±4.1° and plantar flexion was 54.3±5.9° (Boone and Azen 1979). The difference in plantar flexion was noted to be significant (Boone and Azen 1979).

Given the axis (or axes) of motion of the ankle, motion must also occur in the transverse and coronal planes. These movements are not often quantified in clinical practice, but are important to understand when discussing gait (Kelikian, Sarrafian et al. 2011). Close and Inman described 5°-6° of external rotation as the ankle was brought into dorsiflexion, in relation to the tibia, while weight bearing (Kelikian, Sarrafian et al. 2011). Lundberg then described both rotation and pronation/supination: from neutral to 30° dorsiflexion, external rotation to 8.9° occurred; from 0-10° plantar flexion, 1.4° of internal rotation occurred; and from
Table 1.1. Summary of ankle dorsiflexion and plantar flexion values.

Numbers shown are in degrees, with 95% confidence interval in the bracket (Soucie, Wang et al. 2011).

<table>
<thead>
<tr>
<th>GENDER</th>
<th>Age 2-8</th>
<th>Age 9-19</th>
<th>Age 20-44</th>
<th>Age 45-69</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>Dorsiflexion 24.8 (22.5-27.1)</td>
<td>17.3 (15.6-19.0)</td>
<td>13.8 (12.9-14.7)</td>
<td>11.6 (10.6-12.6)</td>
</tr>
<tr>
<td></td>
<td>Plantar flexion 67.1 (64.8-69.4)</td>
<td>57.3 (54.8-59.8)</td>
<td>62.1 (60.6-63.6)</td>
<td>56.5 (55.0-58.0)</td>
</tr>
<tr>
<td>Male</td>
<td>Dorsiflexion 22.8 (21.3-24.3)</td>
<td>16.3 (14.9-17.7)</td>
<td>12.7 (11.6-13.8)</td>
<td>11.9 (10.9-12.9)</td>
</tr>
<tr>
<td></td>
<td>Plantar flexion 55.8 (54.4-57.2)</td>
<td>52.8 (50.8-54.8)</td>
<td>54.6 (53.2-56.0)</td>
<td>49.4 (47.7-51.1)</td>
</tr>
</tbody>
</table>
10°-30° plantar flexion, 0.6° of external rotation occurred (Kelikian, Sarrafian et al. 2011). Supination occurred as the ankle was taken from plantar to dorsiflexion (Kelikian, Sarrafian et al. 2011).

1.2.3 Ankle Stability

The stability of the ankle is dependent on both passive and dynamic components (McCullough and Burge 1980, Gray, Standring et al. 2005). Factors involved in passive stability include the contours of the articular surfaces, the ligamentous complexes (lateral, deltoid, distal tibiofibular), the crossing and attached tendon tunnels, and the capsular attachments (Stormont, Morrey et al. 1985, Donatelli 1996, Gray, Standring et al. 2005, Kelikian, Sarrafian et al. 2011). Active stability is imparted by gravity, muscle action, and ground reaction forces, and is best discussed as part of gait (Gray, Standring et al. 2005, Kelikian, Sarrafian et al. 2011).

The most in-depth study of the factors affecting passive stability of the ankle was conducted in a cadaveric experiment, where the specimens were tested in physiologically loaded and unloaded states in dorsiflexion, neutral, and plantar flexion, determining how much the ligaments and articular surfaces contributed to passive stability under a variety of stresses (Stormont, Morrey et al. 1985). A structure was considered to be a primary restraint if it contributed over 33% of the restraint to the joint, and a secondary restraint if it fell between 10-33% (Stormont, Morrey et al. 1985). The findings of rotation and inversion/eversion are summarized in Tables 1.2 and 1.3, respectively.
Table 1.2. Primary and secondary restraints in rotation of the ankle. $1^\circ$: primary; $2^\circ$: secondary.

Adapted from (Stormont, Morrey et al. 1985).

<table>
<thead>
<tr>
<th></th>
<th>Posterior talofibular ligament</th>
<th>Calcaneofibular ligament</th>
<th>Anterior talofibular ligament</th>
<th>Deltoid ligament</th>
<th>Articular surface</th>
</tr>
</thead>
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<td>Plantar flexion</td>
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</tbody>
</table>
Table 1.3.  Primary and secondary restraints in inversion/eversion of the ankle. $1^\circ$: primary; $2^\circ$: secondary.

*Adapted from (Stormont, Morrey et al. 1985).*

<table>
<thead>
<tr>
<th></th>
<th>Loaded inversion</th>
<th>Unloaded inversion</th>
<th>Loaded eversion</th>
<th>Unloaded eversion</th>
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<tbody>
<tr>
<td></td>
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<td>Neutral</td>
<td>Dorsiflexion</td>
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<tr>
<td>Posterior talofibular ligament</td>
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<td>$1^\circ$</td>
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<tr>
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<tr>
<td>Deltoid ligament</td>
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<tr>
<td>Articular surface</td>
<td>$1^\circ$</td>
<td>-</td>
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</tbody>
</table>
In a more recent cadaveric study, to anterior/posterior and medial/lateral stability was assessed (Watanabe, Kitaoka et al. 2011). Unlike before, a restraint was considered to be primary if it provided at least 50% restraint (Watanabe, Kitaoka et al. 2011). In the unloaded ankle, it was found that the lateral ligaments provided 71-81% of the restraint to anterior translation, and the deltoid provided 50-80% of the restraint to posterior translation, while the deltoid provided more restraint in plantar flexion than dorsiflexion (Watanabe, Kitaoka et al. 2011). The articular surfaces were found to be responsible for all of the stability in anterior/posterior translation when the joint was loaded physiologically, regardless of foot positioning (Watanabe, Kitaoka et al. 2011). In another study, Tochigi et al. (Tochigi, Rudert et al. 2006), who had previously determined the importance of the articular surface in anterior and posterior translation, found that neither the lateral ligaments nor the deltoid ligaments reached the 50% threshold in providing stability to the ankle with medial and lateral translation in the unloaded state; in fact, they both appeared to contribute relatively equally (Watanabe, Kitaoka et al. 2011). In the loaded state, again the articular surfaces provided all of the stability (Watanabe, Kitaoka et al. 2011). It is also important to recognize that the ankle was most stable in dorsiflexion, in comparison to the plantar flexed position, in all instances (Watanabe, Kitaoka et al. 2011).

1.2.4 Load Bearing

The ankle is a load bearing joint. The total weight-bearing area of the ankle joint is 11-13 cm²; the fibula bears one-sixth of this weight, transmitting it to
the talus (Lambert 1971, Kelikian, Sarrafian et al. 2011). A number of investigators have studied contact areas and pressures using a variety of methods and through-range of motion.

Using a carbon black transference technique, Ramsey and Hamilton (Ramsey and Hamilton 1976) determined the contact area to be $4.40 \pm 1.21 \text{ cm}^2$ in neutral, and $3.69 \text{ cm}^2$ in $20^\circ$ of plantar flexion. They also discovered that even a 1 mm shift in the talus decreased the contact area by an astonishing 42% (Ramsey and Hamilton 1976).

Using a casting method, Kimizuka et al. (Kimizuka, Kurosawa et al. 1980) kept the ankle in neutral while applying a number of different loads (up to 1500 N). At 1500 N, the contact areas was found to be 483 mm$^2$, and to significantly decrease (34%) with external rotation of the joint to $20^\circ$ (Kimizuka, Kurosawa et al. 1980). Using pressure-sensitive film to quantify the contact area of the ankle joint, Hartford et al. (Hartford, Gorczyca et al. 1995) found the contact area to be 3.37 cm$^2$ under a load of 2300 N in neutral.

Using a surface digitization technique, Kura et al. (Kura, Kitaoka et al. 1998) found the contact area to be 439 mm$^2$ under a load of 667 N in neutral; the technique also allowed them to assess the contact areas between the malleoli and talar facets, as well as to determine contact areas through a variety of motions (Kura, Kitaoka et al. 1998).

Using stereophotography, Millington et al. (Millington, Grabner et al. 2007) were able to determine the contact areas under a variety of conditions. The talotibial contact area was found to be greatest in dorsiflexion at $7.34 \pm 1.69 \text{ cm}^2$. 
and least in plantar flexion, at $4.39 \pm 1.41 \text{ cm}^2$ (Millington, Grabner et al. 2007). The talofibular contact area was also greatest in dorsiflexion at $2.02 \pm 0.78 \text{ cm}^2$ and least in pronation, at $0.77 \pm 0.49 \text{ cm}^2$ (Millington, Grabner et al. 2007).

Additionally, the pressure between the three articular surfaces of the ankle (medial malleolar-medial facet of talus, plafond-talar dome, lateral malleolar-lateral facet of talus) has also been described (Michelson, Checcone et al. 2001). The pressure was found to increase at both talar facet/malleolar interfaces as the ankle was brought into dorsiflexion. The lateral aspect of the talar dome and plafond showed increasing pressure from $30^\circ$ plantar flexion to $5^\circ$ of dorsiflexion, with a slight drop-off after this point, while medially remaining generally stable from $30^\circ$ plantar flexion to $5^\circ$ dorsiflexion, with a sharp drop-off after this point (Michelson, Checcone et al. 2001).

1.2.5 Gait

Walking is a rhythmic motor activity used by humans to propel themselves forward, with “gait” used as a description of the patterns of this movement (Kelikian, Sarrafian et al. 2011). The gait cycle is made up of two phases: the stance and the swing phases (Rose and Gamble 2006, Perry and Burnfield 2010). The stance phase takes up 62% of the gait cycle; it begins when one’s foot strikes the ground and ends when one’s foot leaves the ground (Rose and Gamble 2006, Perry and Burnfield 2010). The swing phase lasts for the entire period the foot is off the ground, making up the other 38% of the gait cycle (Rose and Gamble 2006, Perry and Burnfield 2010).
One gait cycle is essentially one stride: it is defined as the “interval between two sequential initial floor contacts by the same limb” (Perry and Burnfield 2010). A step is defined as the timing between the initial contact of one foot and the initial contact of the alternate foot (Perry and Burnfield 2010). Cadence is defined as the number of steps taken per minute (Perry and Burnfield 2010).

In a fundamental study, still quoted in textbooks today, Murray et al. (Murray, Drought et al. 1964) used interrupted light photography to assess a number of parameters of gait in normal men. The authors found the average stride length of 156.5±14 cm, with a mean stride width of 8.0±3.5 cm; the step length was found to be 78.4±5.9 cm with left to right stepping and 78.1±6.3 cm with right to left stepping (Murray, Drought et al. 1964). The foot progression angle, i.e. the angle between a line connecting the heel to the second metatarsal and the line of progression of gait, was found to be 6.8±5.6° (Murray, Drought et al. 1964). With regards to cadence, the average was considered to be 110 steps/minute, with normal being 100-120 steps/minute; women, on average, were found to have a cadence of 5 steps more per minute (Kelikian, Sarrafian et al. 2011). Jogging and running affect these values. The change in all of these factors over one’s lifetime in healthy subjects are summarized in the book Human Walking by Rose and Gamble (Kelikian, Sarrafian et al. 2011).

The stance and swing phases can be further divided into five phases for stance and three for swing (Perry and Burnfield 2010). The participation of the ankle joint throughout these is discussed as follows: initial contact of the foot
signals the beginning of the stance phase and lasts 0-2% of the gait cycle (Perry and Burnfield 2010). The goal of this phase is to initiate the heel rocker and decelerate the lower limb (Perry and Burnfield 2010). The heel rocker is one of four separate pivots used throughout stance phase to redirect the more vertical force of gravity on the centre of mass (COM) to a force that can provide propulsion, as well as stability (Perry and Burnfield 2010). At this point, the ankle is held in neutral by the muscles of the anterior compartment of the leg (pretibial muscles) as the heel makes forceful contact with the ground (Perry and Burnfield 2010). The tibia itself is tilted approximately 15° anteriorly going into heel strike (Perry and Burnfield 2010). The vertical component of the ground reaction force (GRF) acting on the posteromedial heel ranges from 50-125% of body weight (Simon, Paul et al. 1981). The reason for the significant amount of GRF is that before contact, there has been a 1 cm “free fall” of the body weight onto the lower limb (Perry and Burnfield 2010). In addition to the vertical GRF, there is a forward-directed GRF and a medially-directed GRF acting on the heel, the magnitude of these being less than 20% of body weight (Jahss 1991).

The loading response is the next component of stance phase, and lasts 2-12% of the gait cycle (Perry and Burnfield 2010). The loading response, along with initial contact, serves the function of weight acceptance of the lower limb; it is characterized by heel-only support (Perry and Burnfield 2010). The ankle plantar-flexes as the subtalar joint everts, leading to progression of the heel rocker and realignment of the ankle joint axis (Perry and Burnfield 2010). The body weight force is nearly vertical and acts posteriorly to the ankle through the
heel, creating a posterior lever arm driving the foot to the floor (Perry and Burnfield 2010). The pretibial muscles act eccentrically to slow the progression of the foot to the floor; the foot reaches 5° of plantar flexion by 6% of the gait cycle (Perry and Burnfield 2010). The two combined actions extend the heel support period and draw the tibia forward in a controlled manner over the heel rocker, assisting with forward progression of the lower limb and shock absorption (Perry and Burnfield 2010).

The body weight force does not remain stagnant. Instead, it continues to progress forward over the ankle as the COM progresses forward (Perry and Burnfield 2010). The ankle is brought from plantar flexion to neutral, kept in this state by the pretibial muscles (Perry and Burnfield 2010). This response maintains the heel rocker during the second half of the loading response (Perry and Burnfield 2010). The centre of pressure (COP) moves from the posteromedial heel (generally) in a straight line, just distal to the calcaneus. In addition to plantar and dorsiflexion, it is important to note that the tibia is internally rotated 7° during this phase and begins to externally rotate (Kelikian, Sarrafian et al. 2011). By this time, the compressive force on the ankle has reached three times body weight (Stauffer, Chao et al. 1977).

The next phase of gait is mid-stance, lasting 12-31% of the gait cycle (Perry and Burnfield 2010). The ankle moves into dorsiflexion and the ankle rocker is developed. This phase of gait is characterized by the first and fifth metatarsal heads impacting the ground, leading to foot-flat support (Perry and Burnfield 2010). The body weight force has now moved in front of the ankle axis
and the tibia has moved from 5° of plantar flexion to 5° of dorsiflexion. The posterior superficial muscles of the leg, primarily the soleus, control progression and stability at this time (Perry and Burnfield 2010). The tibia begins to externally rotate from its 7° internally rotated state; the ankle and subtalar joint absorb this rotation (Kelikian, Sarrafian et al. 2011). The GRF is almost totally vertical, just under 100% of body weight throughout this phase (Jahss 1991). The forward shear tapers during this time, while the medial shear gives way to lateral shear and the medial torque gradually gives way to lateral torque (Jahss 1991). At the end of mid-stance, the COP has reached the forefoot (Klenerman 1991). The compressive force on the ankle generally plateaus during this phase (Stauffer, Chao et al. 1977).

The terminal stance phase lasts 31-50% of the gait cycle. The heel begins to rise, the ankle continues to dorsiflex and the next rocker (the forefoot rocker) takes over, allowing the COM to continue forward, allowing continued forward progression (Perry and Burnfield 2010). The ankle continues to dorsiflex a further 5°, to a total of 10° of dorsiflexion; the further 5° is due to the stretch of the Achilles tendon, while the soleus and gastrocnemius act eccentrically to prevent further dorsiflexion (Perry and Burnfield 2010). Tibial momentum is slowed and the ankle is stabilized, allowing the forefoot rocker to form (Perry and Burnfield 2010). The importance of the forefoot rocker is that it reduces the amount of fall of the COM and enhances forward progression by increasing the relative length of the lower limb (Perry and Burnfield 2010). Halfway through this phase, the soleus and gastrocnemius contract less, as a result of sensory feedback,
indicating that the stance foot is no longer a safe weight-bearing base (Perry and Burnfield 2010). The foot rolls off the forefoot rocker and pre-swing begins once the second foot reaches initial contact (Perry and Burnfield 2010). By this time, the COP has reached the space between the first and second metatarsal heads. The vertical GRF reaches its peak (108-112% of body weight) at 45% of the gait cycle and rapidly declines, while posterior shear force and lateral torque develop (Jahss 1991). In addition to the sagittal plane motion, the tibia has now reached its maximal external rotation of 8° (Kelikian, Sarrafian et al. 2011). A second peak in compressive force at the ankle occurs, reaching up to 5.5 times body weight with a small (0.7% body weight) force acting posteriorly (Stauffer, Chao et al. 1977). Mid-stance and terminal stance fall under the category of single-limb stance (Perry and Burnfield 2010).

The next phase is pre-swing, lasting 50-62% of the gait cycle. The goal of this phase is continued forward progress; it is also the time when both feet are in contact with the ground (Perry and Burnfield 2010). The body weight is rapidly transferred to the heel-strike limb from the pre-swing limb (Perry and Burnfield 2010). With the body weight removed from the pre-swing limb, there is a loss of the GRF; the soleus and gastrocnemius are no longer required to contract (Perry and Burnfield 2010). Despite the loss of contraction of the plantar flexors, the ankle continues into plantar flexion from the elastic recoil of the Achilles tendon, reaching 15° of plantar flexion. This occurs as the foot pushes off the last rocker, i.e. the toe rocker, accelerating the tibia forward (Perry and Burnfield 2010). The pretibial muscles then contract at the end of pre-swing to prevent further plantar
flexion, and ready themselves for dorsiflexion during the initial swing phase (Perry and Burnfield 2010). There is a small, forward-acting force across the ankle, reaching 0.3% of body weight (Stauffer, Chao et al. 1977).

Initial swing lasts 62-75% of gait cycle; its purpose is limb advancement (Perry and Burnfield 2010). An important component of limb advancement is making sure the foot clears the ground, this is accomplished by contraction of the pretibial muscles. By the end of this phase, the foot is in 5° of plantar flexion, compared to the 15° at the start of the phase (Perry and Burnfield 2010).

The mid-swing phase brings the foot to neutral or slight dorsiflexion and lasts 75-87% of the gait cycle (Perry and Burnfield 2010). The extensor hallucis longus is now relatively more active than the tibialis anterior, possibly due to the medial aspect of the foot being heavier than the lateral one (Perry and Burnfield 2010). Neutral positioning also requires less effort than that required for the concentric action (Perry and Burnfield 2010).

The terminal swing phase comprises the final portion of the gait cycle. The pretibial muscles activate in anticipation of heel strike, ideally keeping the ankle in neutral. Often, however, there is slight plantarflexion of 3-5° at heel strike (Perry and Burnfield 2010). The pre-swing, mid-swing, and terminal swing phases all accomplish the task of swing limb advancement (Perry and Burnfield 2010).
1.3 TIBIOTALAR ARTHRODESIS

Tibiotalar arthrodesis is a surgical procedure in which the distal tibia is fused to the talar body. This is achieved by denuding the articular surfaces of their cartilage and subchondral bone, creating congruent tibial and talar surfaces, compressing the tibia and talus together, and rigidly joining these two structures either by internal or external fixation. The ideal foot position in relation to the tibia is neutral plantar/dorsiflexion, 5-10° of external rotation, 0-5° valgus, and slight posterior translation (Buck, Morrey et al. 1987). Fixing the foot within these parameters improves patient outcomes and helps maintain a more normal gait pattern (Buck, Morrey et al. 1987). A successful tibiotalar arthrodesis provides significant pain relief along with a shoeable, plantigrade foot that allows for normal or near normal gait.

1.3.1 Indications

There are a number of indications for tibiotalar arthrodesis; these include end-stage ankle arthrosis from primary, post-traumatic, or inflammatory arthritis; deformity affecting shoe wear and gait; instability secondary to recurrent sprains or neurologic illness; as well as failed total ankle replacement (Nihal, Gellman et al. 2008). A comprehensive list of conditions that can be treated by tibiotalar arthrodesis is summarized in Table 1.4.
Table 1.4. Indications for tibiotalar arthrodesis.

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<tr>
<th>Arthritis</th>
<th>Neurological</th>
<th>Miscellaneous</th>
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<tr>
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<td>Failed total ankle replacement</td>
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<tr>
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<td>Charcot-Marie-Tooth disease</td>
<td>Severe equinus</td>
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<td>Cerebral palsy</td>
<td>contracture secondary</td>
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<td>Talus fracture</td>
<td>Stroke</td>
<td>to compartment</td>
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<td>syndrome of the leg</td>
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<tr>
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<tr>
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<td>Gout/pseudogout</td>
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<tr>
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<tr>
<td>Post-septic</td>
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</tbody>
</table>
1.3.1.1 **Contraindications**

There are no absolute contraindications to tibiotalar arthrodesis. Tibiotalar arthrodesis can be performed in the setting of infection and even in children, though neither condition is ideal (Mazur, Cummings et al. 1991, Klouche, El-Masri et al. 2011). Prior to proceeding with a tibiotalar arthrodesis, it should be confirmed, with as much certainty as possible that the patient’s pain and disability are coming from the tibiotalar joint.

1.3.2 **Clinical Evaluation**

A history and physical examination of every patient is imperative to providing the proper treatment to a patient with ankle pain or instability. A detailed pain history, including its effect on function, along with specific questioning regarding past injuries/instability and systemic illnesses will aid in determining the best course of treatment.

1.3.2.1 **Physical Examination**

Physical examination should include a gait examination, examination of the affected ankle as well as the joints above and below, and the contralateral ankle. If the history and physical exam are equivocal, intra-articular injection of the tibiotalar joint with local anaesthetic with or without steroid can be both diagnostic and therapeutic (Thomas and Daniels 2003, Nihal, Gellman et al. 2008).
1.3.2.2 Radiographic Evaluation

Weight-bearing anteroposterior (AP), lateral, and mortise radiographs of the ankle are the standard imaging required for evaluation of tibiotalar arthritis. Computed tomography (CT) and magnetic resonance imaging (MRI) can provide further details about the articular surfaces, bony deformities, and soft tissue abnormalities, but are not often required unless radiographic findings are incongruent with the patient’s history and physical exam findings.

1.3.3 Management of Ankle Arthrosis

1.3.3.1 Non-Operative Management

There are a number of non-operative treatments for end-stage ankle arthrosis and instability. Non-steroidal anti-inflammatories, acetaminophen, opiates/opioids, glucosamine chondroitin, and grape seed extracts are medications that have been used in the treatment of osteoarthritis/rheumatoid arthritis (Thomas and Daniels 2003, Nihal, Gellman et al. 2008).

Orthotics, footwear modifications, and braces may also provide relief. Footwear modifications include the addition of rocker-bottom soles and solid ankle cushion heels (SACH) (Thomas and Daniels 2003). Lace-up leather or polypropylene ankle-foot orthoses may provide some stability, while solid ankle-foot orthoses may be required in cases of gross instability (Thomas and Daniels 2003). A walking plaster cast can be applied to mimic the effects of a tibiotalar arthrodesis (Thomas and Daniels 2003).
Intra-articular injection can be both diagnostic and therapeutic. Hyaluronic acid injection and platelet-rich plasma injections are more recent interventions that require further evaluation, with small studies indicating some potentially lasting benefits with minimal risk of harm (Witteveen, Hofstad et al. 2015, Fukawa, Yamaguchi et al. 2017).

Activity modification, along with weight loss, may help patients manage their symptoms; weight loss has been shown to improve outcomes in both non-operative and operative management of arthritic joints (Thomas and Daniels 2003).

1.3.3.2 Operative Management

Outside of tibiotalar arthrodesis, there are a number of other surgical interventions that can be attempted for management of end-stage ankle arthrosis. Debridement of the ankle joint, often performed arthroscopically, can be helpful, especially in the setting of impinging osteophytes, loose bodies, and synovitis (Cheng and Ferkel 1998). Articular distraction is another possibility, with small studies showing some promise (Xu, Zhu et al. 2017). Supramalleolar osteotomy is another procedure that can be useful for treatment of asymmetric tibotalar arthritis (Hintermann, Knupp et al. 2016). Chondral/osteochondral (autologous/donor) procedures are other possibilities, though these are more useful in the setting of contained defects (Hangody, Vásárhelyi et al. 2008). Total ankle arthroplasty has been around over 40 years, and while outcomes and implant survival rates have improved substantially over time, total ankle
arthroplasty is generally limited to older, low-demand patients (Cody, Scott et al. 2018).

1.3.4 History of Tibiotalar Arthrodesis

The first tibiotalar arthrodesis was performed by Eduard Albert, a Bohemian surgeon trained in Vienna, to stabilize a paralyzed foot (Soren and Waugh 1980). He described this procedure in a paper dating to 1879; the articular surfaces of the tibia and talus were excised, and the leg placed in a plaster cast until fusion was achieved (Soren and Waugh 1980). Albert subsequently went on to fuse a number of other joints in the foot (Soren and Waugh 1980). He is also known for performing the first successful shoulder arthrodesis and publishing the first textbook espousing the benefits of using antiseptic to prevent post-operative infections (Buckwalter 2003). Word quickly spread of the success of this procedure, which led to a number of other surgeons developing further modifications (Soren and Waugh 1980).

The next milestone in tibiotalar arthrodesis was developed by Hellstadius and Greifensteiner (Soren and Waugh 1980). They advocated for compression across the tibiotalar surfaces to promote fusion; nonunion to this point was an ongoing reason for failure of tibiotalar arthrodesis. Charnley is credited with simplifying the procedure using a transverse anterior approach and compressing the joint using clamps and Steinman pins placed in the tibia and talus (Charnley 1951). The main criticism of this approach is that it required the transection of the
anterior compartment tendons and the anterior tibial artery, but a higher union rate was achieved (Charnley 1951, Soren and Waugh 1980).

Two further advancements in tibiotalar arthrodesis occurred in the late 1970s and early 1980s. The late 1970s saw the ability to perform compression tibiotalar arthrodesis with internal fixation methods (Nihal, Gellman et al. 2008). These showed improved rates of union, faster time to union, and decreased rates of infection (Nihal, Gellman et al. 2008). The first arthroscopic tibiotalar arthrodesis was described in 1983 and has demonstrated high rates of union since (Schneider 1983, Gougoulias, Agathangelidis et al. 2007). A variety of techniques and approaches have been described since, with varying levels of success under a variety of conditions.

1.3.5 Surgical Approach to Ankle

There are a number of approaches to the ankle joint. As mentioned earlier, arthroscopic methods exist for accessing the ankle joint for arthrodesis. The anteromedial and anterolateral portals (medial to the anterior tibialis and lateral to the peroneus tertius) are most often utilized; however, a two-portal posterior technique has also been described (posterolateral – 2 cm proximal to the tip of the lateral malleolus and medial to peroneal tendons/lateral to Achilles tendon, posteromedial – medial to Achilles tendon) (Dent, Patil et al. 1993, de Leeuw, Hendrickx et al. 2016). The potential complications of an arthroscopic approach are injury to the saphenous, sural, deep peroneal, and superficial peroneal nerves (Ferkel, Small et al. 2001, Nihal, Gellman et al. 2008). The benefits of an
arthroscopic approach are decreased wound morbidity and length of hospital stay (Myerson and Quill 1991, O'Brien, Hart et al. 1999, Gougoulias, Agathangelidis et al. 2007). Patients also have smaller scars, increased satisfaction with the procedure, and faster times to union with high rates of union (Gougoulias, Agathangelidis et al. 2007). Even marked deformities can be corrected using an arthroscopic approach (Gougoulias, Agathangelidis et al. 2007). A miniarthrotomy approach uses the same anterior portals as for arthroscopy but extends them to a length of 1.5 cm to allow for access to the joint without arthroscopic equipment, and has similar risks and benefits as those of an arthroscopic approach, without the significant learning curve of arthroscopy, distraction of the ankle joint, or the requirement of specialized equipment (Paremain, Miller et al. 1996).

There are a number of more invasive approaches to the ankle, allowing for greater exposure to the tibiotalar joint, correction of larger deformities, and bone grafting, if required (Nihal, Gellman et al. 2008). Drawbacks to these include those associated with significant soft tissue stripping: increased post-operative pain, delayed wound healing, wound infection, wound dehiscence, nonunion, neurovascular injury, and possibly prolonged recovery time and increased time to union (Nihal, Gellman et al. 2008).

The lateral approach to the ankle is a common approach; it requires a 10-12 cm incision directly over the fibula, with an osteotomy of the fibula approximately 6 cm from its distal extent. The fibula can then be removed and discarded, attached with screws to the tibia and talus to act as a lateral strut, or
morselized into bone graft (Mann, Van Manen et al. 1991). The sural nerve sits posterior in this approach, while the superficial peroneal nerve lies just anterior. A second incision can be made on the medial aspect of the ankle if it is felt that the medial aspect of the joint cannot be adequately prepared from the lateral approach (Nihal, Gellman et al. 2008).

There are a number of different options for an incision when approaching the ankle anteriorly. Charnley advocated a transverse incision, transecting the tendinous and neurovascular structures; this provided an excellent exposure, with the downsides being postoperative tendon adhesions, numbness, swelling, and vascular compromise (Charnley 1951, Ratliff 1959). Longitudinal incisions can be made, with dissection between the tibialis anterior and the extensor hallucis longus, or between the extensor hallucis longus and extensor digitorum longus tendons (Nihal, Gellman et al. 2008, Dekker and Kadakia 2017). The advantage of these approaches is that they protect the neurovascular bundle. Like the lateral approach, a second incision can be made to augment the anterior approach; the incision is made between the extensor digitorum longus and peroneus tertius, or in some cases, between the peroneus tertius and peroneal tendons (Nihal, Gellman et al. 2008). Due to the proximity of the incisions, there is a risk for skin bridge necrosis (Nihal, Gellman et al. 2008).

The posterior approach requires the patient to be placed in the prone position. Incisions can be made lateral or medial to the Achilles tendon; if a lateral incision is utilized, the sural nerve must be protected. The Achilles tendon can then be transected in a Z-plasty formation or the tendon can be released with
a small bone block from its insertion on the calcaneus and reattached at the end of the procedure (Gruen and Mears 1991, Swärd, Hughes et al. 1992). To access the ankle joint, a posterolateral approach is utilized: dissection between the peroneal tendons and flexor hallucis longus. An advantage of this approach is the subtalar joint may also be exposed and fused at the same time and the Achilles tendon can be lengthened if a fixed equinus deformity is noted pre-operatively (Nihal, Gellman et al. 2008).

A medial approach involves an incision over the medial malleolus, either directly medial or slightly anterior (Schuberth, Cheung et al. 2005). The medial malleolus is osteotomized and can be removed or reattached, similar to the lateral malleolus in the lateral approach (Schuberth, Cheung et al. 2005). The main structures at risk during this approach are the saphenous vein and nerve.

1.3.6 Fixation Techniques

The first tibiotalar arthrodeses relied on plaster casts for immobilization. Early internal fixation methods included silver wire, ivory pegs, or structural bone grafts (Soren and Waugh 1980). The difficulty with ivory pegs and bone grafts were that they often resorbed, leading to a loss of fixation; in many cases, these techniques did not include denuding the cartilage from the surfaces that were being fused (Soren and Waugh 1980). Further study led to the conclusion that these methods could only be useful in concert with careful preparation of the tibial and talar surfaces (Soren and Waugh 1980).
Charnley developed a method of external fixation in which Steinman pins were placed in the tibia and talus, and bars connecting the pins with clamps allowed for compression across the construct (Charnley 1951). A Calandruccio frame provided slightly more stability than the Charnley method – two Steinman pins placed in both the tibia and talus – and similarly provided compression across the arthrodesis (Malarkey and Binski 1991). These two methods have given way to more rigid frames developed by a number of manufacturers, as well as new techniques, including a triangular arrangement with a metatarsal pin that provides more stability to the construct (Berman, Bosacco et al. 1989). Ilizarov fixation can also be utilized. These techniques, especially Ilizarov fixation, are extremely useful in the setting of significant soft tissue disruption, bone loss, and even in failed fusion (Johnson, Weltmer et al. 1992, Hawkins, Langerman et al. 1994). The reason external fixation has largely been abandoned is due to its complexity and the requirement for regular adjustments that tax both the system and the patient (Nihal, Gellman et al. 2008). Nevertheless, external fixation remains an important option in tibiotalar arthrodesis.

Internal fixation is generally the fixation of choice in modern tibiotalar arthrodesis. There is a myriad of options available including screws, plates, blade plates, intramedullary nails, and combinations of these devices (Nihal, Gellman et al. 2008). Intramedullary nails may be used to fuse the tibiotalar joint alone or in combination with the subtalar joint (Mückley, Hofmann et al. 2007, Thomas, Guyver et al. 2015). In many cases, the time to fusion and complication rate are lower than external fixation (Pfahler, Krodel et al. 1996). Internal fixation can be
used in a variety of clinical situations and is not as time-consuming as external fixation, making it the first choice in most tibiotalar arthrodeses.

1.3.7 Gait/Biomechanics Following Ankle Arthrodesis

Gait studies after tibiotalar arthrodesis have determined the optimal position of the foot in tibiotalar arthrodesis, with the study by Buck et al. oft-quoted. The position of the foot is neutral plantar/dorsiflexion, 5-10° of external rotation, 0-5° of valgus, and slight posterior translation of the talus in relation to the tibia. This position allows for a gait pattern that more closely resembles a normal gait pattern. If the foot is anteriorly translated or in plantar flexion, there is compensatory recurvatum of the knee, and if the foot is in neutral rotation, there is excess strain on the medial aspect of the knee, leading to stretching of the medial collateral ligament and potential instability of the knee. If the foot is placed in varus, there is a significant decrease in the amount of varus/valgus range of motion available during gait; slight valgus positioning allows for unlocking of the joints of the midfoot, permitting a more normal gait. Even when the foot is placed in the proper position, stride length and overall velocity are decreased (Mazur, Schwartz et al. 1979). The midfoot joints of the foot see increases in the amount of force through them and their ranges of motion increase to compensate for the loss of motion at the ankle; subsequently, they are more likely to develop arthritis and eventually decreased range of motion (Coester, Saltzman et al. 2001, Fuentes-Sanz, Moya-Angeler et al. 2012). The knee and metatarsophalangeal joints, however, are no more likely to develop osteoarthritis following a tibiotalar
arthrodesis (Coester, Saltzman et al. 2001). Proper orthopaedic footwear post-operatively may be helpful in managing the gait abnormalities after this procedure (Trouillier, Hänsel et al. 2002, Thomas, Daniels et al. 2006). It should be remembered that patients often have gait abnormalities prior to their operations; tibiotalar arthrodesis tends to improve these abnormalities, at least in the short term (Brodsky, Kane et al. 2016).

1.3.8 Outcomes

There are a number of outcome measures described in the literature for tibiotalar arthrodesis. The most reported measures are the union/nonunion rate and complication rate; patient reported outcome scores are also commonly utilized.

Union rates quoted in the recent literature are generally >85% with higher rates of nonunion in complex cases (Van Bergeyk, Stotler et al. 2003, Nihal, Gellman et al. 2008, Fragomen, Borst et al. 2012). Infection is also a major reason for reoperation (0-6.1%), as is hardware irritation (Ahmad, Pour et al. 2007, Colman and Pomeroy 2007, Nielsen, Linde et al. 2008, Gordon, Zicker et al. 2013, Chalayon, Wang et al. 2015). Studies with longer follow-up tend to have higher overall rates of reoperation than those with shorter courses of follow-up (Ferkel and Hewitt 2005, Winson, Robinson et al. 2005, Fragomen, Borst et al. 2012).

Undoubtedly, patient satisfaction and function are important when evaluating the outcomes of tibiotalar arthrodesis. Yasui et al. tabulated a number
of scores from a variety of studies, which generally show that patients do well and are satisfied after tibiotalar arthrodesis (Yasui, Hannon et al. 2016). However, studies with the longest-term follow-up tend to find patients who are increasingly disabled due to pain and are unable to participate in the activities and employment they once enjoyed (Coester, Saltzman et al. 2001, Thomas, Daniels et al. 2006).

1.4 AIM OF THIS THESIS

Tibiotalar arthrodesis, when successful, provides significant pain relief and stability to patients with end-stage tibiotalar arthrosis and instability. However, when it fails, it can lead to further reoperation and adverse patient outcomes. The rate of reoperation in tibiotalar arthrodesis to the ipsilateral lower limb is not well-established or reported in the literature. Two of the most common reasons for reoperation in tibiotalar arthrodesis are nonunion and infection; few patient and/or surgical factors have been found to be associated with these outcomes.

Hence, the first experimental part of this thesis, presented in Chapter 2, is a retrospective review of the patients who underwent tibiotalar arthrodesis in our centre to determine the rate of reoperation to the ipsilateral lower limb. The study was carried out in a diverse population in order to determine the risk factors associated with reoperation for nonunion and infection in tibiotalar arthrodesis.

While patient factors may play a role in the failure of tibiotalar arthrodesis, surgical factors may also be involved. Various approaches and techniques have
been developed for tibiotalar arthrodesis, with variable success rates. Total hip and knee arthroplasty are two procedures with a demonstrated high rate of success in various populations; a part of the reason for this is the use of jigs and alignment guides that standardized these procedures. Therefore, the second part of this thesis, presented in Chapter 3, undertook the development and testing of a jig and alignment guide for use in tibiotalar arthrodesis. The objective was to design a system that would improve the contact area between the tibia and talus, reliably place the foot in the proper position, and decrease the time taken to perform the procedure.

1.5 REFERENCES


CHAPTER 2

DETERMINING THE RATE OF REOPERATION AND THE PREDICTORS OF REOPERATION IN TIBIOTALAR ARTHRODESIS.
CHAPTER 2. DETERMINING THE RATE OF REOPERATION AND THE PREDICTORS OF REOPERATION IN TIBIOTALAR ARTHRODESIS

2.1 INTRODUCTION

Tibiotalar arthrodesis is the standard surgical procedure for treating end-stage ankle arthrosis, even in the era of total ankle arthroplasty (Bloch, Srinivasan et al. 2015). Modern techniques have generally pushed the union rate to >85%; however, overall reoperation rates remain high, especially in comparison to the gold standard in orthopaedics, total hip arthroplasty (Nihal, Gellman et al. 2008, Labek, Thaler et al. 2011).

researchers. A recent multicentre study in Canada by Younger et al. (Younger, Glazebrook et al. 2016) identified a 14.1% overall reoperation rate.

While much of the focus is on determining nonunion rates using a specific technique or approach, few studies have attempted to quantify the effect that patient-related factors have on reoperation for nonunion or infection. A study by Chalayon et al. (Chalayon, Wang et al. 2015) was the largest one to-date, involving 215 arthrodeses. The results indicated that patients with preoperative varus alignment and previous subtalar fusion were found to have higher rates of nonunion than their counterparts (Chalayon, Wang et al. 2015).

One of the first studies to attempt to determine patient-related factors was by Perlman and Thordarson (Perlman and Thordarson 1999). Participants were deemed high-risk for nonunion by the authors; all patients had arthrodeses for post-traumatic arthritis (Perlman and Thordarson 1999). Due to the small sample size (67 patients), the authors were only able to find trends towards significance for smoking, alcohol use, diabetes, psychiatric disorders, and illicit drug use as predictors of nonunion.

In a study on arthroscopic tibiotalar arthrodesis by Jain et al. (Jain, Tiernan et al. 2016), smoking was found to increase time to union, but not nonunion. Moreover, Chalayon et al. (Chalayon, Wang et al. 2015) were unable to find an association between diabetes and smoking and reoperation for infection. In subtalar arthrodesis, infections were related to previous open fracture or infection following open reduction and internal fixation of the initial injury (Dingemans, Backes et al. 2016).
Given the relative lack of data regarding patient-related predictors of nonunion, and the difficulty obtaining overall reoperation rates in tibiotalar arthrodesis in the literature, an in-depth study of these objectives was warranted. Therefore, the primary purpose of our study was to determine the rate of reoperation to the ipsilateral distal tibia and foot in tibiotalar arthrodesis. The secondary objective was to determine the predictors, if any, for reoperation as a result of nonunion or infection.

2.2 MATERIALS AND METHODS

2.2.1 General Overview

The study was approved by the Health Sciences Research Ethics Board (REB) at the University of Western Ontario (Appendix I). A retrospective chart review of the electronic medical records of patients receiving a tibiotalar arthrodesis between the beginning of September 2012 and the end of August 2017 was performed. Patients who were potentially eligible for our study were identified using the billing codes (Ministry of Health and Long-Term Care of Ontario) for tibiotalar arthrodesis (R466), provided by three fellowship-trained orthopaedic surgeons at the London Health Sciences Centre – Victoria Hospital.

2.2.2 Inclusion and Exclusion Criteria

Patients were included in the study if they were 18 years of age or older, and received a primary open tibiotalar arthrodesis, either alone or in combination
with another procedure, including concomitant subtalar fusion. Patients were excluded if they did not have sufficient follow-up to determine if the ankle went on to fusion, or if the procedure was a part of a staged procedure for infection.

2.2.3 Chart Review

Charts were assessed by two reviewers (AR and MC) and information gathered and coded into a standardized data collection form. Patient demographics, diagnoses, operative details, and, in cases of trauma leading to arthritis, the date of injury, type of injury, and management of the injury were recorded, where available. In some cases, the patient's recollection of a previous injury were relied on, as details were unavailable due to the length of time from injury or because the injury was diagnosed and treated in another jurisdiction.

2.2.4 Radiography

Radiographs were examined post-operatively to assess for fusion by one of the authors (AR). The ankle was considered fused if at least part of the tibiotalar joint was crossed by bony trabeculae as seen on plain radiographs or confirmed by CT imaging. A diagnosis of nonunion was given if no bony trabeculae ever crossed the tibiotalar joint after prolonged follow-up either on plain radiographs or CT imaging or the reason for reoperation based on the operative note was nonunion of the tibiotalar arthrodesis. Fusion was considered delayed if radiographic union did not occur within the first 6 months after surgery. In instances where the cause of arthritis leading to tibiotalar arthrodesis was
post-traumatic, radiographs of the injury were classified according to the AO classification for distal tibial/malleolar fractures and simply identified by their anatomy if other bones were involved (e.g. talus fracture). Sprains, multiple inversion injuries, and other soft tissue-related trauma were generally classified as ligamentous injuries; they were considered post-traumatic causes of tibiotalar arthritis leading to the requirement for arthrodesis.

### 2.2.5 Reoperations

Patients were considered to have had a reoperation if there was any further surgery to the distal tibia or foot. Reasons for reoperation were classified into eight categories: nonunion, infection, hardware irritation, soft tissue issues, subtalar arthritis, other aspects of the operation outside of the tibiotalar arthrodesis, malunion, and chronic pain.

### 2.2.6 Statistical Analysis

Statistical analysis was conducted using Excel 365 for Mac (Microsoft, Bellevue, WA). Two-sided Fisher’s exact testing was utilized to test the correlations between 14 independent variables and reoperation for nonunion and infection. The 14 variables were: age ≥ 65, sex (male), ASA class >2, BMI >30, psychiatric condition, current smoking status, diabetes, cardiovascular disease including hypertension, renal disease, previous surgery, hindfoot nail, and post-traumatic arthritis. In patients with post-traumatic arthritis, whether the injury was open and whether an external fixator was utilized as part of management were
also tested. Fisher’s exact testing was used because of the low frequency (<5) of some events, and despite repeated testing, the level of significance was kept at \( p < 0.05 \) (two-sided) given the exploratory nature of this study.

**2.3 RESULTS**

Overall, one hundred and sixty-nine arthrodeses performed on 166 patients were identified to be a part of the study; five were excluded due to insufficient follow-up to determine fusion status, and three were excluded for staged operations for infections, leaving 161 arthrodeses (158 patients) remaining. The patient demographics and characteristics are summarized in Table 2.1; reasons for tibiotalar arthrodesis are summarized in Table 2.2. The average follow-up time was 1.6 years (range: 0.2-5.9 years). The majority of patients underwent tibiotalar arthrodesis through a lateral transfibular approach. A compression-screw only construct was used in 85 (52.3%) patients; a hindfoot nail, the next most commonly utilized construct, was used in 41 (25.5%) patients (Table 2.3).

There were a total of 24 (14.9%) nonunions, of which five (3.1%) were septic nonunions. The average time to radiographic union was 14.2 weeks (range 6.0-61.7 weeks) in the remaining 137 patients; eleven patients had delayed radiographic union.

The data for BMI were only available for 142 of our patients. One hundred and ten patients required a tibiotalar arthrodesis for post-traumatic arthritis,
Table 2.1. Demographics and patient characteristics.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>%</th>
<th>Mean±SD (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥65</td>
<td>60</td>
<td>37.3</td>
<td>57±15.8 years (18-89)</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>87</td>
<td>54.0</td>
<td></td>
</tr>
<tr>
<td><strong>Diabetes</strong></td>
<td>29</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td><strong>Renal disease</strong></td>
<td>10</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td><strong>Cardiovascular disease including hypertension</strong></td>
<td>70</td>
<td>43.5</td>
<td></td>
</tr>
<tr>
<td><strong>Mental health condition</strong></td>
<td>21</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td><strong>Current smoker</strong></td>
<td>22</td>
<td>13.7</td>
<td></td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>145*</td>
<td>90.0*</td>
<td>92.1±23.6 kg (39.5-168.0)</td>
</tr>
<tr>
<td><strong>BMI</strong></td>
<td>142^</td>
<td>88.2^</td>
<td>31.9±8.1 (17.8-63.8)</td>
</tr>
<tr>
<td>&gt;30</td>
<td>71</td>
<td>50.0</td>
<td></td>
</tr>
<tr>
<td><strong>ASA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;2</td>
<td>77</td>
<td>47.8</td>
<td></td>
</tr>
<tr>
<td><strong>Follow-up time</strong></td>
<td></td>
<td></td>
<td>1.6±1.2 years (0.2-5.9 years)</td>
</tr>
</tbody>
</table>

* 145 or 90.0% of patients had weight data available
^ 142 or 88.2% of patients had height and weight data available to compute BMI
Table 2.2. Reasons for tibiotalar arthrodesis.

<table>
<thead>
<tr>
<th>REASON</th>
<th>N</th>
<th>FREQUENCY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-traumatic</td>
<td>110</td>
<td>68.3</td>
</tr>
<tr>
<td>Primary osteoarthritis</td>
<td>20</td>
<td>12.4</td>
</tr>
<tr>
<td>Rheumatoid arthritis</td>
<td>10</td>
<td>6.2</td>
</tr>
<tr>
<td>Charcot arthropathy</td>
<td>5</td>
<td>3.1</td>
</tr>
<tr>
<td>Residual clubfoot</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>Psoriatic arthritis</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>Charcot-Marie-Tooth</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>Hemangioma</td>
<td>2</td>
<td>1.2</td>
</tr>
<tr>
<td>Post-septic arthritis</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Reiter's syndrome</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Neonatal hematogenous/multifocal osteomyelitis</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Fibrous dysplasia</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Juvenile rheumatoid arthritis</td>
<td>1</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Table 2.3. Tibiotalar arthrodesis operation characteristics and time to union.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Frequency (%)</th>
<th>Mean±SD (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Side</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>93</td>
<td>57.8</td>
<td></td>
</tr>
<tr>
<td><strong>Construct</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screws</td>
<td>85</td>
<td>52.8</td>
<td></td>
</tr>
<tr>
<td>Hindfoot nail</td>
<td>41</td>
<td>25.5</td>
<td></td>
</tr>
<tr>
<td>Plate and screws</td>
<td>28</td>
<td>17.4</td>
<td></td>
</tr>
<tr>
<td>Anterior plate</td>
<td>4</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Lateral plate</td>
<td>1</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Hindfoot nail and plate</td>
<td>1</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Ilizarov</td>
<td>1</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td><strong>Time to union</strong></td>
<td>137</td>
<td>85.1</td>
<td>14.2±8.2 weeks (6.0-61.7 weeks)</td>
</tr>
<tr>
<td>&gt;6 months</td>
<td>10</td>
<td>6.2</td>
<td></td>
</tr>
</tbody>
</table>
comprising 68.3% of all patients requiring an arthrodesis. The data were used to calculate the two-sided Fisher’s exact values for soft tissue status and placement of an external fixator as part of management of the injury. Open injuries were based on reports available in the electronic medical record: if the soft tissue status was not mentioned, it was considered closed.

Ten ligamentous injuries were also identified as the cause of tibiotalar arthritis; these were considered post-traumatic causes of arthritis and closed injuries. The types of injuries sustained, and time from injury to fusion are summarized in Table 2.4. Seventy-two patients (65.5%) had had at least one operation to their ankle after their initial injury, and 21 had concomitant injuries to the remainder of the body. Six patients who received a tibiotalar arthrodesis as a result of trauma had their arthrodeses performed within one month of their injuries. Twenty-nine patients had their arthrodeses performed within one year of their injuries. Twenty-six patients had a concomitant operation outside of the area of tibiotalar arthrodesis, four of which had subtalar arthrodeses with compression screw constructs.

The total number of patients requiring at least one reoperation, or a further operation to the distal tibia or foot, was 49 for a 30.4% reoperation rate, with a further 21 (13.0%) of these requiring more than one operation. The reasons for reoperation and their frequencies are summarized in Table 2.5. Six patients (3.7%) ultimately went on to have below knee amputations.
Table 2.4. Injury characteristics in patients with post-traumatic causes of arthritis leading to tibiotalar arthrodesis.

<table>
<thead>
<tr>
<th>Injury</th>
<th>N</th>
<th>Frequency (%)</th>
<th>Mean±SD (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture</td>
<td>100</td>
<td>90.9</td>
<td></td>
</tr>
<tr>
<td>AO 43-A</td>
<td>3</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>AO 43-B</td>
<td>19</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>AO 43-C</td>
<td>9</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>AO 44-B</td>
<td>8</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>AO 44-C</td>
<td>8</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Talus</td>
<td>1</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Talus + AO</td>
<td>42-C2, 44-B</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Unknown</td>
<td>50</td>
<td>50.0</td>
<td></td>
</tr>
<tr>
<td>Ligamentous</td>
<td>10</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>Soft tissue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>24</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>Time from injury to fusion*</td>
<td>98</td>
<td>89.1</td>
<td>10.7±14.6 years (0.0-53.0)</td>
</tr>
<tr>
<td>≤1 year</td>
<td>29</td>
<td>29.6</td>
<td></td>
</tr>
<tr>
<td>1-5 years</td>
<td>30</td>
<td>30.6</td>
<td></td>
</tr>
<tr>
<td>5-10 years</td>
<td>7</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>33</td>
<td>33.7</td>
<td></td>
</tr>
</tbody>
</table>

*33 patients were able to give approximate dates, 12 were unable to provide any dates
Table 2.5. Number and frequency of initial reoperations by reason.

<table>
<thead>
<tr>
<th>REASON FOR REOPERATION</th>
<th>N</th>
<th>FREQUENCY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>49</td>
<td>30.4</td>
</tr>
<tr>
<td>Nonunion</td>
<td>14</td>
<td>8.7</td>
</tr>
<tr>
<td>Infection</td>
<td>12</td>
<td>7.5</td>
</tr>
<tr>
<td>Hardware irritation</td>
<td>8</td>
<td>5.0</td>
</tr>
<tr>
<td>Soft tissue issues</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>Subtalar arthritis</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>Other aspects</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>Malunion</td>
<td>2</td>
<td>1.2</td>
</tr>
<tr>
<td>Chronic pain</td>
<td>1</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Fourteen patients had an initial reoperation for nonunion. Two further nonunions were identified after initial reoperation (both removal of hardware) and required revisions. Three more patients were identified who had nonunions, two of which requested no further surgery, and one of whom is booked for revision. Therefore, our statistical analysis regarding predictors of nonunion was based on the 16 (9.9%) total nonunions that required and received revision operations during the study period.

The average time to reoperation for nonunion was 0.9±0.5 years (range: 0.5-2.0 years). Fourteen out of 16 patients (87.5%) underwent a revision procedure in which iliac crest aspirate/autograft and/or allograft was utilized. Of the 16 patients who had a reoperation for nonunion, six (37.5%) required another operation. Cardiovascular disease showed a statistically significant (p <0.05) association with nonunion, with a two-sided Fisher’s exact test value of 0.0367 (Table 2.6).

Twelve patients (7.5%) underwent reoperation for infection, of which 5 (3.1%) underwent reoperation for septic nonunion. The average time to reoperation for infection was 0.8±0.5 years (range: 0.2-2.0 year). Five patients underwent irrigation and debridement and removal of hardware; five patients underwent irrigation and debridement, removal of hardware, and placement of antibiotic spacer/nail; one underwent irrigation and debridement and placement of free radial forearm flap; one underwent below-knee amputation. Seven patients required at least another reoperation, and further three patients ultimately required below-knee amputations. None of the 14 potential predictors
Table 2.6. Predictor variables for reoperation due to nonunion in tibiotalar arthrodesis.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>TWO-SIDED FISHER’S EXACT OUTCOME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age ≥ 65</td>
<td>0.7866</td>
</tr>
<tr>
<td>Sex (male)</td>
<td>0.1921</td>
</tr>
<tr>
<td>ASA class &gt;2</td>
<td>1.000</td>
</tr>
<tr>
<td>BMI &gt;30</td>
<td>0.4268</td>
</tr>
<tr>
<td>Psychiatric condition</td>
<td>0.4420</td>
</tr>
<tr>
<td>Current smoking status</td>
<td>0.2391</td>
</tr>
<tr>
<td>Diabetes</td>
<td>0.4923</td>
</tr>
<tr>
<td>Cardiovascular disease, including hypertension</td>
<td>0.0367*</td>
</tr>
<tr>
<td>Renal disease</td>
<td>1.000</td>
</tr>
<tr>
<td>Previous surgery</td>
<td>0.4380</td>
</tr>
<tr>
<td>Hindfoot nail</td>
<td>1.000</td>
</tr>
<tr>
<td>Post-traumatic arthritis</td>
<td>0.7778</td>
</tr>
<tr>
<td>Soft tissue (open)</td>
<td>1.000</td>
</tr>
<tr>
<td>External fixator</td>
<td>0.1187</td>
</tr>
</tbody>
</table>

* denotes p <0.05
tested using two-sided Fisher’s exact tests for infection reached the level of significance for association (p<0.05) (Table 2.7).

A summary of the remaining reasons for reoperation and the operations performed is shown in Table 2.8. Two patients went on to have below-knee amputations for chronic pain and eight patients had multiple reoperations.

2.4 DISCUSSION

The primary objective was to determine the reoperation rate to the ipsilateral distal tibia/foot after tibiotalar arthrodesis surgery. The overall rate of reoperation in our cohort of patients was 30.4%. If one removes the three operations performed on the foot outside of those associated with the initial reoperation, the rate was 28.6%. Reoperation for nonunion and infection made up just over half (53.1%) of the reasons for reoperation, with a variety of other causes contributing to the remaining reoperations. The overall reoperation rates for nonunion and infection were 9.9% and 7.5%, respectively. If one included the one nonunion not yet operated on, and the two not wishing to return to the operating room, the nonunion rate jumped to 11.8%. Addition of septic nonunions brought this total to 24, for a 14.9% nonunion rate.

The reoperation rate in our study was approximately 10% higher than that found by Chalayon et al. (Chalayon, Wang et al. 2015), who had studied 209 patients (215 procedures) undergoing uncomplicated primary tibiotalar arthrodesis.
Table 2.7. Predictor variables for reoperation due to infection in tibiotalar arthrodesis.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>TWO-SIDED FISHER’S EXACT OUTCOME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age ≥ 65</td>
<td>0.5373</td>
</tr>
<tr>
<td>Sex (male)</td>
<td>0.1468</td>
</tr>
<tr>
<td>ASA class &gt;2</td>
<td>1.000</td>
</tr>
<tr>
<td>BMI &gt;30</td>
<td>0.7463</td>
</tr>
<tr>
<td>Psychiatric condition</td>
<td>0.6578</td>
</tr>
<tr>
<td>Current smoking status</td>
<td>0.2138</td>
</tr>
<tr>
<td>Diabetes</td>
<td>0.4542</td>
</tr>
<tr>
<td>Cardiovascular disease including hypertension</td>
<td>0.3672</td>
</tr>
<tr>
<td>Renal disease</td>
<td>0.5498</td>
</tr>
<tr>
<td>Previous surgery</td>
<td>1.000</td>
</tr>
<tr>
<td>Hindfoot nail</td>
<td>0.0810</td>
</tr>
<tr>
<td>Post-traumatic arthritis</td>
<td>0.1981</td>
</tr>
<tr>
<td>Soft tissue (open)</td>
<td>0.3361</td>
</tr>
<tr>
<td>External fixator</td>
<td>0.2989</td>
</tr>
</tbody>
</table>
Table 2.8. Summary of other reasons for reoperation and reoperations performed.

<table>
<thead>
<tr>
<th>REASON FOR RE-OPERATION</th>
<th>N</th>
<th>OPERATION PERFORMED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware irritation</td>
<td>8</td>
<td>Removal of hardware</td>
</tr>
<tr>
<td>Soft tissue issues</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Non-healing ulcers</td>
<td>2</td>
<td>Irrigation and debridement and skin grafting (plastic surgery)</td>
</tr>
<tr>
<td>Superficial wound</td>
<td>1</td>
<td>Irrigation and debridement and wound reapproapximation</td>
</tr>
<tr>
<td>Soft-tissue de-gloving injury</td>
<td>1</td>
<td>Irrigation and debridement and flap reconstruction from anteromedial thigh (plastic surgery)</td>
</tr>
<tr>
<td>Subtalar arthritis</td>
<td>4</td>
<td>Subtalar arthrodesis</td>
</tr>
<tr>
<td>Other aspects</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Talonavicular nonunion</td>
<td>1</td>
<td>Revision talonavicular arthrodesis with iliac crest aspirate and bone grafting</td>
</tr>
<tr>
<td>Right great toe first MTP joint arthritis and 2nd-4th toe clawing</td>
<td>1</td>
<td>First MTP joint arthrodesis and bunionectomy and 2nd-4th toes PIP arthrodeses</td>
</tr>
<tr>
<td>Fibular pseudoarthrosis</td>
<td>1</td>
<td>Takedown pseudoarthrosis and removal of hardware; fibula ORIF with iliac crest aspirate and bone graft</td>
</tr>
<tr>
<td>Significant forefoot deformity</td>
<td>1</td>
<td>Great toe DIP osteotomy and realignment arthrodesis and extensor tendon lengthening; 2nd-4th toe flexor tenotomies; 2nd-3rd toe PIP arthrodeses</td>
</tr>
<tr>
<td>Malunion</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Painful ankle arthrodesis</td>
<td>1</td>
<td>Removal of hardware fibula/tibia; fibular osteotomy; valgus and extension producing osteotomy</td>
</tr>
<tr>
<td>Ankle pain and varus deformity</td>
<td>1</td>
<td>Tibia-fibula fusion, calcaneal osteotomy</td>
</tr>
<tr>
<td>Chronic pain</td>
<td>1</td>
<td>Below-knee amputation</td>
</tr>
</tbody>
</table>
Demographics were similar between both studies; however, they excluded a number of patients deemed at highest risk for nonunion: patients with neuropathic arthropathy, previous total ankle replacement, prior nonunion, concomitant subtalar fusion, early post-traumatic infection, major bone loss, and those with talar body fractures without bone healing. Another major difference is that patients with concomitant operations to the foot (triple arthrodesis, etc.) were also not included. The rate of nonunion in Chalayon et al. (Chalayon, Wang et al. 2015) study was 9%, with a total unplanned reoperation rate of 19%. Of the 20 patients who had nonunions, 16 underwent revision surgery. This is similar to our findings, in which 15 of 18 patients underwent revision for nonunion. Chalayon also found removal of hardware at 5.6% (12 procedures) and irrigation and debridement for infection at 5.1% (11 procedures), as the next most common reoperations (Chalayon, Wang et al. 2015). Our reoperation rate for hardware irritation was 5.0%, and infection rate was 7.5%.

A lower reoperation rate was found by Younger et al. (Younger, Glazebrook et al. 2016), which attempted to standardize the classification of reoperations in tibiotalar arthrodesis and tibiotalar arthroplasty. Two hundred and thirteen arthrodeses were followed for a minimum of two years; a total reoperation rate was identified at 14.1%, with rates of revision for nonunion and irrigation and debridement for infection of 3.8% and 0.9% respectively (Younger, Glazebrook et al. 2016). Again, they had similar criteria and demographics as Chalayon et al. (2015), but also excluded patients with uncontrolled diabetes (Younger, Glazebrook et al. 2016). Their amputation rate was 1.4%, but they did
not define the reasons for reoperation in these cases. A unique feature of this study was the inclusion of patients with arthroscopic tibiotalar arthrodesis in addition to open tibiotalar arthrodesis (Younger, Glazebrook et al. 2016).

Many papers reporting reoperation and or complication rates are retrospective studies involving a single approach or fixation technique; however, there are some studies that use multiple techniques (Zvijac, Lemak et al. 2002, Van Bergeyk, Stotler et al. 2003, Kopp, Banks et al. 2004, Ferkel and Hewitt 2005, Schuberth, Cheung et al. 2005, Winson, Robinson et al. 2005, Collman, Kaas et al. 2006, Ahmad, Pour et al. 2007, Colman and Pomeroy 2007, Gougoulias, Agathangelidis et al. 2007, Wera and Sontich 2007, Nielsen, Linde et al. 2008, Akra, Middleton et al. 2010, Mohamedean, Said et al. 2010, Zwipp, Rammelt et al. 2010, Fragomen, Borst et al. 2012, Gordon, Zicker et al. 2013, Mongon, Garcia Costa et al. 2013, Flint, Hirose et al. 2017). Table 2.9 summarizes the studies since the year 2000 involving primary tibiotalar arthrodesis, in which the overall reoperation rate, nonunion reoperation rate, and infection reoperation rate could be calculated. Generally, the most common reasons for reoperation in these studies were nonunion, infection, and hardware irritation. Although a number of studies explored whether there was a reoperation for subtalar arthritis, no studies included information on other procedures in the ipsilateral foot (Winson, Robinson et al. 2005, Collman, Kaas et al. 2006, Colman and Pomeroy 2007, Gougoulias, Agathangelidis et al. 2007, Wera and Sontich 2007, Zwipp, Rammelt et al. 2010, Gordon, Zicker et al. 2013, Flint, Hirose et al. 2017).
Table 2.9. Summary of studies since 2000, where overall reoperation rate, nonunion reoperation rate, and infection reoperation rate could be calculated.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Technique</th>
<th>Follow-up time</th>
<th>Overall reoperation rate (%)</th>
<th>Nonunion reoperation rate (%)</th>
<th>Infection reoperation rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalyaon et al.</td>
<td>215</td>
<td>Variable open</td>
<td>Minimum 6 months</td>
<td>19.0</td>
<td>7.4</td>
<td>5.1</td>
</tr>
<tr>
<td>Younger et al.</td>
<td>213</td>
<td>Variable</td>
<td>56.9 months ± 22.7</td>
<td>14.1</td>
<td>3.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Zwipp et al.</td>
<td>94</td>
<td>4 compression screws</td>
<td>5.9 years (4.8-7.8)</td>
<td>4.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Nielsen et al.</td>
<td>107</td>
<td>Not stated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>Open</td>
<td>Minimum 6 months</td>
<td>26.5</td>
<td>4.1</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>Arthroscopic</td>
<td>Minimum 6 months</td>
<td>29.3</td>
<td>3.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Gordon et al.</td>
<td>82</td>
<td>Anteromedial approach</td>
<td>4 years (7 months-8.3 years)</td>
<td>14.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Mongon et al.</td>
<td>17</td>
<td>Tension band</td>
<td>Minimum 6 months (26-122)</td>
<td>72.8</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Kopp et al.</td>
<td>46</td>
<td>Chevron technique</td>
<td>Minimum 6 months (2-20)</td>
<td>7.3</td>
<td>4.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Van Bergeyk et al.</td>
<td>7</td>
<td>Modified Blair technique</td>
<td>median 20 months (12-112)</td>
<td>28.6</td>
<td>28.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Flint et al.</td>
<td>60</td>
<td>Anterior dual locked plating technique</td>
<td>Minimum 6 months (16 weeks-4 years)</td>
<td>1.1</td>
<td>15.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Wera et al.</td>
<td>17</td>
<td>Custom blade plate technique</td>
<td>37.3 months (2-96.7)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Zvijac et al.</td>
<td>21</td>
<td>Arthroscopic</td>
<td>Minimum 6 months (18-60)</td>
<td>4.8</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Winson et al.</td>
<td>118</td>
<td>Arthroscopic</td>
<td>Minimum 6 months</td>
<td>31.4</td>
<td>5.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Study</td>
<td>Patient No.</td>
<td>Method</td>
<td>Follow-up</td>
<td>Weighted Mean</td>
<td>Weighted Standard Deviation</td>
<td>Weighted Standard Error</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------</td>
<td>--------------------------------</td>
<td>-----------</td>
<td>---------------</td>
<td>----------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Gougoulas et al.</td>
<td>78</td>
<td>Arthroscopic</td>
<td>21.1 months (6-68)</td>
<td>14.6</td>
<td>2.1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>Minimal deformity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>Marked deformity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fragomen et al.</td>
<td>92</td>
<td>Ilizarov</td>
<td>median 65 months (27-134)</td>
<td>23.1</td>
<td>13.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Collman et al.</td>
<td>39</td>
<td>Arthroscopic Union</td>
<td>1 year; nonunion: 610 days</td>
<td>17.9</td>
<td>7.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Mohamedea et al.</td>
<td>29</td>
<td>Anterior plating (LDCP)</td>
<td>14 months (12-18)</td>
<td>17.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Schuberth et al.</td>
<td>13</td>
<td>Medial malleolar approach</td>
<td>Not stated</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Akra et al.</td>
<td>26</td>
<td>Lateral transfibular</td>
<td>15.04 months (12-36)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ferkel et al.</td>
<td>35</td>
<td>Arthroscopic</td>
<td>72 months (24-167)</td>
<td>34.3</td>
<td>2.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Ahmad et al.</td>
<td>18</td>
<td>Proximal humeral locking plate (TTC)</td>
<td>21.9 months (8-39)</td>
<td>5.6</td>
<td>0.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Colman et al.</td>
<td>48</td>
<td>Transfibular/onlay strut grafting</td>
<td>36 months</td>
<td>19.0</td>
<td>4.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Our secondary objective was to determine if any of 14 predictors led to reoperation for nonunion or infection. In our study, cardiovascular disease demonstrated a statistically significant association with nonunion. This is contrary to the findings of Chalayon et al. (Chalayon, Wang et al. 2015), where cardiovascular disease was not found to contribute to nonunion. Interestingly, a large cohort inception study by Zura et al. (Zura, Xiong et al. 2016), examining the effects of a number of factors on healing in 18 different bones, found a slightly protective effect of cardiovascular disease against nonunion; the authors offered no explanation of a potential mechanism for this finding. Although altered or diminished tissue oxygenation, coupled with changes in nutrition delivery/waste removal as frequently seen in cardiovascular disease could explain an increased risk of nonunion, no studies could be identified that would report on the effect of cardiovascular disease and bone healing.

Unique to our study is the inclusion of patients who received additional operations at the time of their primary arthrodesis, as well as reporting further operations to the ipsilateral foot as reoperations. Over one quarter (25.3%) of the tibiotalar arthrodeses included some form of subtalar arthrodesis, and a further 13.7% included a simultaneous operation to the distal tibia or foot. Given that our patient demographics are similar to those found in other studies, it is likely that many patients undergo multiple procedures at the same time as their arthrodesis. Therefore, our findings could be a better reflection of the true reoperation rate in primary tibiotalar arthrodesis and may be of use when discussing the expectations with patients undergoing an arthrodesis.
Another important finding of our study that has implications on setting expectations with patients is the below-knee amputation rate, which was 3.7% or nearly one in 25. This number should be communicated to patients as part of providing them with fully informed consent as it is not an entirely uncommon outcome that for many patients would be considered catastrophic and would certainly be something any “reasonable person” would want to know. It is unknown what effect discussing this rate with patients would have on the willingness of patients to undergo this procedure.

Our study was not without limitations; these are those inherent to any retrospective review. First, we relied on patient recall to determine if they had had a previous injury and when that injury occurred in cases where an injury could not be confirmed by the patient’s electronic medical record. Second, in cases of non-acute injury, we assumed patients had post-traumatic arthritis, unless a more convincing diagnosis was available, assuming that injury necessarily led to arthritis. Finally, given the low frequency of some events, fitting our data to more predictive models was not necessarily advisable; therefore, only associations between our chosen predictors and reoperation for nonunion and infection could be determined.

In summary, the overall reoperation rate to the distal tibia or foot after primary tibiotalar arthrodesis in our study was 30.4%. We feel this better reflects the true reoperation rate in the population our centre serves. To-date, few studies have shown any significant associations between patient/surgery related factors and reoperation for nonunion or infection in tibiotalar arthrodesis. Cardiovascular
disease was found to be associated with reoperation for nonunion in tibiotalar arthrodesis, while the remaining 13 predictors tested did not have a statistically significant association with reoperation for nonunion or infection. This is a novel finding in the literature related to nonunion in tibiotalar arthrodesis and may be worth exploring further with prospective studies.

2.5 REFERENCES


CHAPTER 3

DEVELOPMENT OF A NOVEL JIG AND ALIGNMENT GUIDE FOR USE IN TIBIOTALAR ARTHRODESIS.
CHAPTER 3. DEVELOPMENT OF A NOVEL JIG AND ALIGNMENT GUIDE
FOR USE IN TIBIOTALAR ARTHRODESIS

3.1 INTRODUCTION


Despite its drawbacks, tibiotalar arthrodesis remains the gold standard procedure for alleviating pain related to tibiotalar arthrosis (Nihal, Gellman et al. 2008). Two such drawbacks are nonunion and malunion. Modern techniques
have pushed the nonunion rate to less than 15% in many cases, however, when nonunion does occur, it often leads to further operations and ongoing pain for patients (Cooper 2001, Nihal, Gellman et al. 2008). Malunion can have a significant impact on gait, perhaps leading to worsening midfoot, subtalar, and knee joint arthritis, and, in some cases, it requires revision, particularly where the deformity is severe (Cooper 2001, Nihal, Gellman et al. 2008, Yasui, Hannon et al. 2016, Sabine, Sascha et al. 2017).

Many of the operations reported in the current body of literature have been performed by specialty foot and ankle surgeons. Interestingly, a recent study by Sabine et al. (2017) compared outcomes in patients receiving a tibiotalar arthrodesis from a specialty foot and ankle surgeon to those receiving a tibiotalar arthrodesis from a general orthopaedic surgeon. The authors found that, on average, general orthopaedic surgeons took longer to perform the procedure, had more complications including nonunion and malunion; in addition, their patients had slightly lower quality of life than their counterparts who had been operated on by foot and ankle specialists (Sabine, Sascha et al. 2017).

While tibiotalar arthrodesis may be the gold standard procedure for end-stage tibiotalar arthrosis, hip and knee arthroplasty (as an example) could also be considered the gold standard operations in all of orthopaedics (Hawker, Wright et al. 1998, Learmonth, Young et al. 2007). These arthroplasties are frequently performed, with highly reproducible results: their revision rates at five- and ten-year time points are low, while the patient satisfaction is very high (American Orthopaedic Association 2017). Part of the reason for this success,
especially with total knee arthroplasty, was the introduction of jigs and guides in the 1970’s and 1980’s (Laskin 1984). Since then, total knee arthroplasty has become much more reliable, and has improved the quality of life of millions of patients.

Given the success of total knee arthroplasty, particularly its use of jigs and alignment guides, it was suggested that the use of such surgical aids could also improve the outcomes of tibiotalar arthrodesis. Therefore, the purpose of this study was to design and create a jig and alignment guide that would assist with tibiotalar arthrodesis, thereby decreasing or maintaining the current operative time and reducing the nonunion and malunion rates, especially in patients operated on by general orthopaedic surgeons. Fresh-frozen, below-knee cadaveric specimens were utilized for the testing of the jig prototype, using the contact area between prepared tibial and talar surfaces as a surrogate for nonunion. Moreover, procedure time and foot positioning were also directly measured.

3.2 MATERIALS AND METHODS

The study was carried out in two separate phases, summarized in Figure 3.1: (1) Phase I – the initial concept and design of the jig and alignment guide, with testing on Sawbones® specimens and informal testing on fresh-frozen below-knee cadaveric specimens; (2) Phase II – formal testing of the jig and alignment system on fresh-frozen below-knee cadaveric specimens.
Figure 3.1. Workflow for each experimental phase of the tibiotalar jig design and testing. The experiment was divided into two phases:

(A) Phase I – jig design and informal testing; (B) Phase II – formal jig testing.
3.2.1 Phase I: Design of the Jig

3.2.1.1 Concept Draft, Digitization and Production

The original design of the jig was conceptualized by one of the authors (MM), while the development of the alignment guide and testing of the combined system was performed by two of the authors (AR, AG). The original design, as drafted by MM, and later digitized by an outside contractor, is shown in Figure 3.2.

There were a number of features essential to the design of the jig. First, the use of jig was designated for use in tibiotalar arthrodesis through a lateral transfibular approach. As such, it contains a central curved slot that allows a 0.25” burr to pass through it with minimal play. In addition, there are four holes (two at the top and two at the bottom) through which 0.062” Kirschner wires pass to secure the jig to the tibia and talus. The jig has six feet (four proximal and two distal): the proximal feet are longer than the distal ones, to accommodate the anatomy of the lateral tibiotalar joint. Finally, there is also a trapezoid-shaped slot in the proximal aspect of the jig, designed to accommodate a screw placement across the joint to accept a component of the alignment guide. The 0.25” burr was restricted from moving past it’s cutting surface using an adjustable drill stop attached to the shank of the burr.

Following computer-aided design (CAD) rendering of the original drawings, the jig was printed using three-dimensional (3D) printing technology; the initial three prints were completed by two independent contractors, while the remaining 3D prints were produced in-house, using standard grey resin (Form 2, FormLabs,
Figure 3.2. Schematic diagram of the tibiotalar jig. (A) Initial sketch; (B) actual CAD drawing of the proposed design.
SolidWorks (Dassault Systèmes, France) software was used to modify and update the design following each test on the Sawbones®. An example of the printed jig, along with a distractor component, is shown in Figure 3.3.

### 3.2.1.2 Sawbones® Testing

A total of ten tests was carried out on the Sawbones® models. All of these were left-side below-knee specimens, with a soft, smooth articulating surface on the dome of the talus. The tibiotalar articulation was held in place by rubber bands; all other articulations were fixed. Common to all tests was the removal of the distal fibula with an oscillating saw, 6 cm above the distal tip of the lateral malleolus. This was followed by securely mounting the tibia and foot with clamps or vices, and an attempt at positioning the foot with use of a transparent goniometer. The foot positioning was that according to the parameters identified by Buck et al. (1987): 5° valgus, 5° external rotation (tibial crest lined up with first metatarsal), neutral plantar/dorsiflexion, and slight posterior translation (Buck, Morrey et al. 1987).

Following the initial testing of the jig, an alignment guide was added, with the intent that it could improve the alignment of the foot while assisting with the maintenance of its position during the jig placement. In its simplest form, the guide consisted of two adjustable clamps that attached securely to the tibial shaft (given that the fibula was removed distally, there was no longer any support for the clamp from this structure as there were no soft tissues to stabilize it) and a
Figure 3.3. One of the 3D-printed tibiotalar jig prototypes: (A) front view; (B) top view.
long bar that would line up with shaft of the tibia, while remaining perpendicular to the tibiotalar joint surface. The jig connected to the bar through two adjustable fixtures that were held in place by removable pins (Figure 3.4).

3.2.1.3 Progression of the Optimal Jig Design

The jig underwent a number of design changes throughout the process, as shown in Figure 3.5. Following the first prototype testing, the follow-up design added a curve to the bone-facing aspect of the jig, in order to provide some control of rotation of the jig in the axial plane, and to allow the burr visualization starting past the slot, as not to cause any damage to the jig. Eventually, this curve was abandoned due to its bulk; the use of appropriate-length jig feet also made this feature redundant.

The initially designed jig contained a single slot for the burr that needed to be reset to burr the talus. As a result, the second design of the jig that fit into the first using slots seemed a reasonable solution. Moreover, the talar jig was also offset anteriorly, to attempt to position the foot posteriorly. Although this modification would have provided the ability to use the jig on both right and left ankles, it added to the bulk of the jig, making it difficult to apply; therefore, this modification was abandoned in the subsequent redesign.

The follow-up jig modification added two slots with the offset found in the previous version. It also contained a tibial slot that was set on a 5° angle to place the ankle in a 5° valgus position. Despite controlling a number of parameters with
Figure 3.4. Testing of the first tibiotalar jig prototype on Sawbones® specimen: (A) lateral view; (B) superior (top) view.
Figure 3.5. Progression of the tibiotalar jig prototype development. See section 3.2.1.3 for detailed description.
the jig and alignment guide, the appropriate positioning of the guide remained elusive. In an attempt to solve this difficulty, a guide jig was implemented. To provide more degrees of freedom to adjust to different anatomy, multiple K-wire slots were also created for a variety of fittings.

The final adjustments made to the jig were to the width of the slots for the burr. In order to protect the jig, and to improve control over the burr (the burr being initially powered by a commercial die grinder, followed by a commercial drill, both unwieldy to operate, especially on the soft Sawbones® models), a metal guide sleeve was placed over the burr and a 3D-printed handle attached to the assembly. As a result, the handling of the burr was significantly improved. An actual example of the use of this model (i.e. tibiotalar jig and alignment guide) is shown in Figure 3.6.

3.2.1.4 Informal Cadaveric Testing

Prior to the formal cadaveric testing of the jig and alignment guide, the tibiotalar fusion technique using the jig and alignment guide were informally tested on thawed, fresh-frozen below-knee cadaveric specimen. Due to concerns about soft tissue, an attempt was made to use a 5.5 mm arthroscopic burr (Dyonics Bonecutter, Smith & Nephew, London, UK) instead of the 0.25” burr that had originally been used. As it became apparent that the guard would not allow the burr to progress across the joint, a decision was made to use the original burr unguarded. The slot was kept at the same width, despite discarding the guard, as the tight slot would lead to excessive wear around it, due to the
Figure 3.6. An example of jig and alignment guide use on Sawbones® specimen. (A) anterior view; (B) lateral view.
speed of the burr. At this stage, the distractor/alignment jig was discarded, since it did not work in the cadaveric specimen as originally intended. Better visualization than expected was achieved. The holes allowing fixation to the tibia and talus were also increased in diameter, to allow for the placement of more stable pins from a total knee arthroplasty set. The drawback of this setup, however, was the necessity to use of the burr without a depth stop. At this stage of experimentation, no further major changes were made to the alignment guide except a swap of the smaller adjustable clamps for larger ones. As a result, and due to the time constraints placed on the experimentation, only left-ankle jig system could be produced at this time.

3.2.2 Phase II: Formal Jig Testing

The study was approved by the Human Research Ethics Board at the University of Western Ontario and the Lawson Health Research Institute (Appendix I). All human cadaveric specimens used in the study were authorized for use by the Division of Anatomy and Cell Biology at the University of Western Ontario and were stored at the Canadian Surgical Technologies and Advanced Robotics (CSTAR), London Health Sciences Centre, at -20°C until utilized. The tibial and talar jigs utilized in this phase of testing can be seen in Figure 3.7.
Figure 3.7. Tibial and talar jigs utilized in Phase II (A) top view; (B) side view; (C) front view
3.2.2.1 General Considerations

Prior to testing, four matched pairs of fresh-frozen below-knee cadaveric specimen were thawed overnight. None of the specimens had any identifiable surgical intervention involving the leg, ankle, or foot. No specimen had obvious identifiable arthritis on pre-procedural radiographs taken with a portable fluoroscopy machine. Although one specimen did not receive pre-procedural imaging, no obvious signs of wear were noted upon direct inspection of the ankle joint.

Following initial radiography, an 8cm longitudinal incision was made laterally along the ankle, centered over the fibula in the sagittal plane, and ending at the distal tip of the lateral malleolus. Sharp dissection was used to free the distal aspect of the fibula. A disposable ruler was then used to measure 6cm from the tip of the lateral malleolus; a sagittal saw was used to make a horizontal cut through the fibula at this level. This was followed by sharp dissection, to completely remove the fibula (Figure 3.8, panels A-C). Once the fibula was removed, the timing of the procedure was initiated.

The procedure was considered “completed” when the surgeon felt the tibial and talar surfaces were adequately prepared and foot position was deemed as close to ideal as possible. A Birmingham hip resurfacing guide pin was placed longitudinally through the calcaneus into the tibia, or a 0.062” Kirschner wire was placed obliquely from the tibia into the talus, to secure the positioning of the arthrodesis for transfer to another laboratory for foot positioning and joint surface analyses.
Figure 3.8. Tibiotalar fusion procedure using the prototype of the tibiotalar jig on cadaveric specimen. (A) lateral longitudinal incision over fibula; (B) measurement of length of fibula to osteotomize (6cm from distal tip of lateral malleolus); (C) osteotomization the distal fibula; (D) medial view of jig and alignment guide; (E) lateral view of jig and alignment guide.
3.2.2.2 Surgical Procedure Specifics: Traditional Method

For the traditional method, a sagittal saw to prepare the tibial and talar surfaces, followed by curettes, osteotomes, and rongeurs were used. The sagittal saw available was one used in total hip arthroplasty, making larger and more aggressive than the saws typically used for the procedure. This led to the complication of producing a medial malleolar osteotomy in three of the specimens. Outside of this, no major complications were noted. Once the surfaces were prepared, the foot was held in position, and the length of time it took to carry the procedure was recorded. A Birmingham hip guide pin/0.062” Kirschner wire was then placed, to keep the foot in position.

3.2.2.3 Surgical Procedure Specifics: Procedure Using Jig and Alignment Guide

With the tibiotalar joint exposed, the alignment guide was affixed to the tibia and fibula above the level of the fibular osteotomy (Figure 3.8, panels D and E). The proximal clamp was placed on the surgical table rather than the specimen, due to the lack of space, given the amount of tibia and fibula left on the specimen. The alignment rod was then aligned with the tibial crest and a goniometer was used to place the foot in appropriate plantar/dorsiflexion. The fixtures were placed on the alignment rod, while the tibial jig was attached to these fixtures. The jig was then set down on the tibiotalar joint, pinning it into place on the tibia and talus with the removable total knee arthroplasty jig pins using a battery-powered AO drill. The alignment guide was removed. Initially, an AO drill with the 0.25” burr was used, but it had to be changed to a corded
commercial drill due the lack of power to burr the tibial surface. Although it took significant time, burring of the tibia was accomplished.

The tibial jig was switched out for the talar jig, preparing the surface similarly to that of the tibia. A rongeur was required to remove some remaining bone on the tibial side (a cantilever of bone from the medial malleolus had not been removed fully with the burr). The foot was then placed in the position it was felt as most appropriate, pinning it in place.

The second run at the surgical procedure also took significantly longer than expected: halfway through, the commercial drill was changed to a die grinder; as a result, the operative time was significantly decreased for the test. The remaining specimens were prepared using the die grinder.

It is important to note that two major complications were encountered while using the die grinder: significant heat generation, and a need for a substantially larger amount of power. As such, moisture had to be added at regular intervals; also, there was some loss to the medial malleolus in one of the specimens. Although this deviation in procedure most likely affected the validity of the results, the use of jig and alignment guide would not have been viable without it.

### 3.2.3 Tests and Measurements

#### 3.2.3.1 Foot Position Analysis

Before measuring the foot position, the soft tissues were sharply dissected from tibia and fibula proximally, to the level of the talus, just below the arthrodesis
distally. The fibula was completely removed. The foot position in the sagittal and coronal planes, as well as about the longitudinal axis, was measured using a goniometer (Figure 3.9).

The sagittal position was expressed as degrees of dorsi-/plantar- flexion. One arm of the goniometer was held along the length of the fifth metatarsal (i.e. central black line on goniometer), and the second arm was held in line with the posterior tibia (i.e. edge of goniometer).

The coronal position was measured as degrees of varus/valgus of the hindfoot. The axis of the goniometer was held at the level of the arthrodesis, with arm in line with the hindfoot, while the second arm was placed in line with the posterior aspect of the tibia.

The position of the foot in the longitudinal axis was measured as the forefoot in relation the tibial crest. For ease, descriptors such as “first web-space” and “first metatarsal” were used.

3.2.3.2 Instron Testing

Following the recording of the foot position, the proximal tibia was potted in cement inside of a square metal ring, allowing one hour of it to dry. The foot was then securely attached to a board with 3” wood screws, through the midfoot. A hole had been drilled to allow the Birmingham hip guide pin to pass through; the board had four holes on the corners allowing the passage of four metal rods. The rods were secured to the base of the Instron Universal Testing System and were used to centre the board and the foot in the testing system (Figure 3.10).
Figure 3.9. Goniometric measurement of the foot positioning in a cadaveric specimen post-procedure. (A) rotation; (B) plantar/dorsiflexion; (C) varus/valgus.
Figure 3.10. Cadaveric specimen set-up in Instron Universal Testing System.
The proximal tibia was then secured in the testing system and the Birmingham pin or 0.062” Kirschner wire were removed.

A 6x6 cm square of Fujifilm pressure-sensitive (Prescale Ultra Super Low Pressure) film was then placed in a plastic bag to protect it from contamination by fluid; this setup was then placed between the tibia and talus through the surgical site. The border of the medial malleolus was the end point medially; there was overhang anteriorly, posteriorly, and laterally. The tibia was lowered onto the talus and the tibia was traced with a marker from the medial malleolus anteriorly, working laterally, to the lateral malleolus distally. This provided a surface for value normalization, allowing the calculation of percent contact area.

Axial pressure was then applied to the specimen at 10Ns⁻¹, until 700N was achieved. The 700N load was maintained for 60 seconds, following which it was gradually released. The Fujifilm was then removed from the tibiotalar arthrodesis site. At the conclusion, the specimens were removed from the testing system; photographs were taken of the tibial and talar surfaces for the determination of the potential area for fusion between the two surfaces.

3.2.3.3 Pressure-Sensitive Film Analysis

The Fujifilm samples were taken and scanned at a resolution of 1200 dpi (Figure 3.11). The images were imported into ImageJ Fiji (GitHub, San Francisco, CA). They were calibrated for size, by measuring the border of the film (6cm). Images were then converted to black-and-white using a built-in algorithm in the software.
Figure 3.11. An example of Fujifilm pressure-sensitive film analysis. (A) original (before transformation); (B) after conversion into black-and-white image; (C) tracing outline of tibia (faint yellow line/arrow).
The inside of the recorded lines on the film were traced using the cursor. Contact area was calculated by measuring all black pixels within the area traced by the cursor. Percent contact area, in relation to the tibia, was obtained by dividing the contact area by the total area traced. Each measurement was traced in triplicate.

### 3.2.3.4 Joint Surface Analysis

The photographs, taken after removal from the Instron Universal Testing System (Figure 3.12, Figure 3.13) were analyzed using the ImageJ Fiji software. A 1 cm marker was placed in all of the photographs as a means of standardization. The perimeter of the medullary area of the tibia and talus were then manually traced, obtaining an average area of the three specimens (Figure 3.14). All measurements were performed in triplicate.

### 3.2.5 Statistical Analysis

The length of time to carry out the surgical procedure was expressed as hour:minute:second (HH:MM:SS). All remaining parameters were expressed as means ± standard error of the mean (SEM) and analyzed using t-test (MS Excel 2016 for Mac, Bellevue, WA). The length of time of the procedure, and the percentage contact area of the tibial area were assessed by t-test using unequal variance; the prepared surface area was compared by a paired t-test. p<0.05 was considered statistically significant.
Figure 3.12. Tibial and talar surfaces after use of the jig and alignment guide method of preparation for the tibiotalar arthrodesis. Photographs were taken after loading on Instron Universal Testing System.
Figure 3.13. Tibial and talar surfaces prepared with the traditional method for the tibiotalar arthrodesis. Photographs were taken after loading on Instron Universal Testing System.
Figure 3.14. Tibial and talar surface imprints on pressure-sensitive Fujifilm after use of (A) jig and alignment guide, and (B) traditional method of tibiotalar arthrodesis.
3.3 RESULTS

3.3.1 Length of Surgical Procedure

The average time taken to perform the procedure using the jig and alignment guide was 00:52:26, while the time taken to perform the procedure using the traditional method was 00:11:36 (p=0.10, not significant). In order to account for the unexpected equipment troubleshooting, thus discarding the data from the first two tests, the average time to perform the procedure using the jig was 00:25:46, over a two-fold increase over the traditional method (Table 3.1).

3.3.2 Foot Position

The foot positions during the jig and alignment guide use versus those in the traditional method are summarized in Table 3.2. A brief overview demonstrates that both methods were similar in obtaining a valgus position of the foot, excepting that of the first specimen done with the jig and alignment guide (20° valgus). The traditional method was superior in obtaining the placement of the foot closer to neutral plantar/dorsiflexion and rotation, where the positioning closer to the 1st metatarsal was more common.

3.3.3 Contact Area

The use of the jig and alignment guide produced the total contact area (as a percentage of the distal tibia) of 22.0±7.8%, while that obtained by the traditional method was 25.0±7.9% (p=0.60, n.s.) (Table 3.3, Figure 3.12 and Figure 3.13).
Table 3.1. Time taken to perform procedure on cadaveric specimen.

Tibiotalar fusion, performed by the traditional versus jig and alignment guide method was compared.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Time (hr:min:sec)</th>
<th>Specimen ID</th>
<th>Time (hr:min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-left</td>
<td>1:37:13</td>
<td>1-right</td>
<td>0:09:43</td>
</tr>
<tr>
<td>2-left</td>
<td>1:00:58</td>
<td>2-right</td>
<td>0:15:51</td>
</tr>
<tr>
<td>3-left</td>
<td>0:25:18</td>
<td>3-right</td>
<td>0:12:19</td>
</tr>
<tr>
<td>4-left</td>
<td>0:26:13</td>
<td>4-right</td>
<td>0:08:30</td>
</tr>
</tbody>
</table>
Table 3.2. **Angles measured by goniometry post-procedure in cadaveric specimen.** Tibiotalar fusion, carried out by the traditional versus jig and alignment guide method was compared.

*MT*, metatarsal; *WS*, webspace; *deg.*, degree.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>JIG AND ALIGNMENT GUIDE</th>
<th>TRADITIONAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plantar/ Dorsi-Flexion (deg.)</td>
<td>Varus/ Valgus (deg.)</td>
</tr>
<tr>
<td>1-left</td>
<td>5 plantar</td>
<td>20 valgus</td>
</tr>
<tr>
<td>2-left</td>
<td>22 plantar</td>
<td>6 valgus</td>
</tr>
<tr>
<td>3-left</td>
<td>neutral</td>
<td>6 valgus</td>
</tr>
<tr>
<td>4-left</td>
<td>20 plantar</td>
<td>6 valgus</td>
</tr>
</tbody>
</table>
Table 3.3. **Total area in contact between tibia and talus, following tibiotalar arthrodesis.** Tibiotalar fusion, performed by the traditional versus jig and alignment guide method was compared. All measurements, taken in triplicate, were obtained from the Fujifilm pressure-sensitive film and normalized to percent area of distal tibia.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Average Area of Tibia (cm²)</th>
<th>Average Contact Area (cm²)</th>
<th>Percent Normalized to Tibia (%)</th>
<th>Specimen ID</th>
<th>Average Area of Tibia (cm²)</th>
<th>Average Contact Area (cm²)</th>
<th>Percent Normalized to Tibia (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-left</td>
<td>10.34</td>
<td>1.69</td>
<td>16.32</td>
<td>1-right</td>
<td>11.28</td>
<td>3.39</td>
<td>30.03</td>
</tr>
<tr>
<td>2-left</td>
<td>13.03</td>
<td>1.96</td>
<td>15.00</td>
<td>2-right</td>
<td>15.11</td>
<td>3.03</td>
<td>20.07</td>
</tr>
<tr>
<td>3-left</td>
<td>11.20</td>
<td>3.53</td>
<td>31.60</td>
<td>3-right</td>
<td>9.79</td>
<td>3.24</td>
<td>33.13</td>
</tr>
<tr>
<td>4-left</td>
<td>13.86</td>
<td>3.45</td>
<td>24.88</td>
<td>4-right</td>
<td>12.43</td>
<td>2.07</td>
<td>16.68</td>
</tr>
</tbody>
</table>
The average prepared area of the tibia using the jig and alignment guide was 14.1±3.3 cm², while that of the traditional method was 14.9±1.0 cm² (p=0.54, n.s.). The average prepared areas of the talus were 7.5±1.7 cm² and 7.2±2.2 cm² using the jig and alignment guide versus the traditional method, respectively (p=0.79, n.s.) (Table 3.4, Figure 3.12 and Figure 3.13).

3.4 DISCUSSION

Tibiotalar arthrodesis remains the gold standard therapy for alleviating pain related to tibiotalar arthrosis (Nihal, Gellman et al. 2008). The procedure itself, however, is not without complications, particularly those relating to non-union or malunion (Nihal, Gellman et al. 2008, Sabine, Sascha et al. 2017). In addition, tibiotalar arthrodesis requires orthopaedic surgeons with very specialized training – an option not always present in the general community. As such, we undertook the development of tibiotalar jig that would not only assist with the proper surgical technique but would also provide a means of tibiotalar arthrodesis standardization.

Once the optimal prototype of the device was created, testing on cadaveric specimen was undertaken. It was found that the jig and alignment system increased the time taken to perform the procedure nearly four-fold during testing. Part of the reason for this was the fact that the burr did not effectively remove bone when used in the AO drill and commercial drill. The commercial drill, previously used during testing of the jig on the Sawbones® specimens, was
Table 3.4. Prepared surface area of tibia and talus in cadaveric specimens for tibiotalar arthrodesis. Tibiotalar fusion, carried out by the traditional versus jig and alignment guide method was compared.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Tibia Area (cm²)</th>
<th>Talus Area (cm²)</th>
<th>Specimen ID</th>
<th>Tibia Area (cm²)</th>
<th>Talus Area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-left</td>
<td>10.54</td>
<td>5.30</td>
<td>1-right</td>
<td>14.20</td>
<td>5.25</td>
</tr>
<tr>
<td>2-left</td>
<td>18.07</td>
<td>9.33</td>
<td>2-right</td>
<td>16.36</td>
<td>6.85</td>
</tr>
<tr>
<td>3-left</td>
<td>12.43</td>
<td>7.97</td>
<td>3-right</td>
<td>14.08</td>
<td>6.30</td>
</tr>
<tr>
<td>4-left</td>
<td>15.17</td>
<td>7.53</td>
<td>4-right</td>
<td>14.80</td>
<td>10.37</td>
</tr>
</tbody>
</table>
found to be too aggressive, causing the Sawbones® to loosen from the clamp/vice setup. As such, as well as the need for soft tissue protection, led to the use of the Dyonics Bonecutter burr. Unfortunately, the guard on this device would not allow for an effective crossing of the joint to reach as far as the medial malleolus – which is normally needed to effectively prepare the surfaces for arthrodesis. Believing that the AO drill and commercial drill would have enough power to burr through the cadaveric bone because of how it had handled the Sawbones® was the single greatest error.

Elimination of the burr problems still resulted in two-fold increase in time required to perform the procedure with the jig and alignment system, as opposed to that of the traditional procedure. This may have been due to the fact that the cadaveric specimens available to us only included the distal aspect of the leg; given that the design of our alignment guide included a proximal clamp intended to be affixed to the leg at approximate level of the tibial tubercle (unavailable on our specimen), it made it difficult to control the specimen and keep the alignment guide in place. Moreover, the large sagittal saw available to us for preparing the joint surfaces by the traditional method is intended for use in total hip arthroplasty; although this allowed for quick surface preparation, it made it dangerous to the soft tissues, and also contributed to the observed overshoot past the medial malleolus.

Outside of the issues with the burr and limited equipment, two other factors may have played a role in the time taken to perform the procedure. The first is the expected learning curve with any new technique. Learning how to
manage the soft tissues and other anatomical variabilities along with the equipment requires practice – outside of a single test of the jig and alignment guide on a cadaveric specimen, no further tests were performed before proceeding with Phase II. Another factor that may have played a role in the time taken to perform the procedure in the experimental group versus the control group was physician handedness. It is relatively common for surgeons to find that operating on one side of the body (i.e. right or left) is easier than operating on the other. This could have played a role in the time taken to perform the procedure as the specimens were divided into either the experimental group or the control group based on which side of the body they came from.

Foot positioning during the use of the jig and alignment guide was not optimal, in comparison to that of the traditional method. The curved nature of the surface that the jig prepared left some ability for the foot to rotate in the transverse axis. Rotation during the jig use was also not as expected. Ideally, during the pin placement, the foot should be held with the first metatarsal colinear with the tibial crest. During the jig use, however, we found it challenging to hold the foot in the proper rotation during the placement of talar pins, most likely due to the curved nature of the prepared surfaces. We did have some success in placing the foot in the correct varus/valgus position, with three specimens positioned in 6° valgus, close to the original aim of 5°. This was likely the result of the 5° slope built into the tibial jig.

The contact area, determined by Fujifilm pressure sensitive film, is a widely used technique in the foot and ankle literature (Millington, Grabner et al.
The Prescale Ultra Super Low Pressure product is noted to best detect pressure differences between 0.2 MPa and 0.6 MPa, much lower than the 700 N applied in our experiment. The purpose of using such sensitive film in our experiments was to achieve the goal of determining the contact area between the tibial and talar surfaces rather than the pressure exerted on any one specific area. Using a pressure sensitive film sensitive to low pressures is an established experimental method for determining contact area between two surface in the biomechanical literature (Zdero 2016).

Using pressure sensitive film to determine contact area does have a number of drawbacks, including the requirement to dissect the joint in order to insert the film, and susceptibility to film crinkling, slippage, and shearing. As such, the technique can produce erroneous results. However, several others have used Fujifilm previously for testing different methods of tibiotalar arthrodesis (Ogilvie-Harris, Fitsialos et al. 1994, Connor and Nabhani 2004, Jeng, Baumbach et al. 2011). Of these, the outcomes of Jeng et al (2011) were similar to those found in our study, namely the small percent contact area (11%). Unlike in our study, however, the authors normalized the data to the size of the Fujifilm and did not actually prepare the surfaces for arthrodesis (Jeng, Baumbach et al. 2011). On our part, an attempt was made to normalize data to the distal tibial surface to account for the differing sizes of cadaveric specimens. Tracing the distal tibial surface was challenging, given its uneven shape and a lack of flat surface to trace on. Residual soft tissue may also have affected the tracings.
Seven hundred Newtons of force was utilized in our experimental setup as this is a physiologic load (force exerted by 70 kg person in single limb stance) often used in similar experiments (Krause, Windolf et al. 2007, Hunt, Goeb et al. 2015, Choi, Lee et al. 2016). Interestingly, Jeng et al. found that the maximum compressive force produced between the tibia and talus when putting in compression screws across the tibiotalar joint in cadaveric specimens was approximately 1.1 MPa (Jeng, Baumbach et al. 2011). This finding is important for two reasons: the first is that patients who undergo tibiotalar arthrodesis are rarely allowed to weight bear for the first 8-12 weeks of their recovery, therefore, a physiologic load is almost never placed on the construct while healing; the second is that this value acts a benchmark for future testing of a screw placement guide that will eventually be developed as part of our system. It is also possible that the lower compressive force provided by compression screws may lead to an overall decrease in the contact area between the tibia and talus as compared to the physiologic load that was placed on it in our experiment.

The cadaveric specimen was loaded at a rate of 10 Ns\(^{-1}\) to avoid the effects of viscoelasticity on the Fujifilm. The maximum force of 700 N was applied for 60 seconds to allow the polymer component in the Fujifilm to reach a steady state. These are commonly used parameters in the literature regarding the use of Fujifilm in biomechanical studies (Zdero 2016).

In our study, we found no statistically significant differences in the average prepared areas of the tibiae. There was some element of uncertainty in tracing the prepared surface areas of the tibae and tali, especially since it was not
always clear where the medullary bone was. In some cases, because a medial malleolar osteotomy was performed in error, the distal tibial area may have been over-estimated.

We were unable to test whether our jig and alignment system had a direct impact on nonunion, given that cadaveric specimens were used. The surrogate markers were the area of prepared surfaces of the tibae and tali, as well as the contact area between the two surfaces. Undoubtedly, improperly prepared surfaces with remaining cartilage and subchondral bone can lead to nonunion, hence our desire to use this as a surrogate marker. The gaps remaining between the surfaces could also lead to a delayed union or nonunion, as demonstrated by Claes et al. (1998) in experiments carried out in sheep. This group found that with increasingly large osteotomy gaps, there was greater interfragmentary movement, periosteal callus, and connective tissue in the fracture gap (Claes, Heigele et al. 1998). The authors concluded that the gap size of the calcified surface was one of the factors that affected bone healing. Obviously, there are patient-related factors outside of the surgeon’s control that also impact nonunion rates (Perlman and Thordarson 1999, Chalayon, Wang et al. 2015, Younger, Glazebrook et al. 2016). Even with perfect technique, it is likely that nonunion will always remain a concern in tibiotalar arthrodesis.

The results of our tests have led us to consider a number of crucial changes to the jig and alignment guide, as well as to the overall method of its use. One absolutely critical redesign will need to focus on development of a reliable method for prevention of heat damage to the bone during the preparation of the
Another will be a re-design with the ability to place a depth stop on the shank of the burr to improve control of the burr. Moreover, starting with an initial burr of the tibial and talar surfaces, with the ability to further refine these surfaces with additional jigs, improvements to the adjustability of the clamps on the alignment guide, a method/device for protecting the soft tissues, as well as a development of a system to compress and hold the joint in the proper alignment will also have to be addressed.

With these improvement in mind, it is noted that a significant amount of time was spent testing the jig and alignment guide on Sawbones® specimens. Given the results of Phase II of our study, Sawbones® testing may not have been entirely warranted. Perhaps the most crucial difference between testing on the Sawbones® and testing on the cadaveric specimens was the difference in burr power required to prepare the tibial and talar surfaces – while the Sawbones® could be prepared easily with a commercial drill, a die grinder with significantly more torque and a higher revolution rate was needed to prepare the surfaces of the cadaveric specimens. Also, without soft tissue present, the alignment guide was much easier to align with the tibial crest and affix to the tibia than in the cadaveric specimens where soft tissue made it difficult to keep the alignment guide firmly in place. Further development of the jig and alignment guide will focus primarily on cadaveric testing rather than testing on Sawbones®.

Before commencement of testing in patients, a number of significant revisions will have to be made to the jig. Ultimately, the jig and alignment guide pathway of Phase II (Figure 3.1) will need to be revisited, until the jig has been
improved enough and is safe for use patients. Eventually, a design of the guide should also address the screw placement. Once all of these are accomplished, the jig and alignment guide will need to be fabricated out of durable, sterilisable materials and trialled on a small-scale basis in patients to determine its usability and safety. Surgeons involved in these initial trials would need to be educated on the product and its use. Further revisions to the jig would likely be necessary throughout the process. Only then would the jig and alignment guide be ready for the final step of testing it in a randomized controlled trial (i.e. phase III of jig testing) (Figure 3.15). Outcome measures, such as procedure time, foot position (both clinical and radiographical), and patient-reported outcome scores could be collected and analyzed to determine which method of tibiotalar arthrodesis would be superior.

Although initially not a great success, testing the jig and alignment guide under conditions similar to those of an operating room has provided us with significant insight into how the system can be improved. Further modifications will be made to the jig and alignment guide, with the ultimate goal of testing the system in surgical patients.
Figure 3.15. Proposed workflow for the final phase (Phase III) of the tibiotalar jig design and testing.
3.5 REFERENCES


CHAPTER 4

GENERAL DISCUSSION AND CONCLUSIONS
CHAPTER 4. GENERAL DISCUSSION AND CONCLUSIONS

4.1 OVERVIEW OF RESULTS

Tibiotalar arthrodesis is the standard surgical procedure for treating end-stage ankle arthrosis (Bloch, Srinivasan et al. 2015). Despite the success of the procedure, significant complications can occur, particularly when patients develop nonunion. Nonunion remains one of the most common reasons for revision in tibiotalar arthrodesis, yet few studies have determined any links between patient/surgical factors and nonunion (Chalayon, Wang et al. 2015). Another major reason for revision or reoperation is infection; even fewer studies have explored the correlation between patient/surgical factors and this outcome.

Given the relative scarcity of patient/surgical factors correlated with nonunion in the literature, another possibility for nonunion could be the operator technique. A study by Sabine et al. (2017) demonstrated that patients operated on by general orthopaedic surgeons had higher rates of complications including malunion and nonunion. Operations, on average also took 74 minutes longer (Sabine, Sascha et al. 2017).

We felt these outcomes could potentially be improved by standardizing the procedure through the use of a jig and alignment system, much like how total hip and knee arthroplasty were improved with these devices in the past (Laskin 1984).
4.1.1 Determining the Rate of Reoperation and the Predictors of Reoperation in Tibiotalar Arthrodesis

The purpose of this study was to determine the overall reoperation rate to the operative leg or foot after tibiotalar arthrodesis and if there were any patient/surgical factors that were correlated with nonunion and/or infection. Our overall rate of reoperation was 30.4%, with nonunion and infection making up just over half (53.1%) of the primary reasons for reoperation. Of the 14 pre-determined possible predictors of nonunion and infection, cardiovascular disease was associated with reoperation for nonunion, while none of the 14 factors were associated with reoperation for infection.

Reoperation rates are difficult to determine from the literature, given the varying definitions on what constitute reoperations and the lack of reporting of this figure. Reoperation rates calculated from a variety of sources where statistics were available vary from 0-34.3% (Ferkel and Hewitt 2005, Schuberth, Cheung et al. 2005, Wera and Sontich 2007, Akra, Middleton et al. 2010, Mongon, Garcia Costa et al. 2013). Higher reoperation rates were generally found in studies with longer average patient follow-up and those with more patients included (Ferkel and Hewitt 2005, Winson, Robinson et al. 2005, Fragomen, Borst et al. 2012).

Ours is one of the larger studies in the field, with a large variety of patients included. This makes the results more widely applicable to a diverse population. In our patient cohort, cardiovascular disease was found to be of significance, associated with nonunion. This is a unique finding in the literature surrounding tibiotalar arthrodesis; it was suggested that altered or diminished tissue
oxygenation may play a role in fracture healing, although this has not been explored in our study.

### 4.1.2 Development of a Novel Jig and Alignment Guide for Use in Tibiotalar Arthrodesis

The purpose of this part of the thesis was to develop a jig and alignment guide that would decrease operative time, lower the nonunion rates, and reliably place the foot in the proper position for arthrodesis. As this was a cadaveric study, the contact area between the prepared tibial and talar surfaces was used as a surrogate for nonunion. Unfortunately, our newly developed jig and alignment system led to a procedure time five times longer on average compared to the traditional method. It did not reliably position the foot in the optimal position, nor did it increase the contact area between the prepared tibial and talar surfaces. However, the practical approach to the use of the jig suggested the necessary modifications for the next generation of the prototype.

### 4.2 LIMITATIONS AND FUTURE DIRECTIONS

While we did not focus on the physical mechanisms of tibiotalar arthrodesis failure, further study in the field should focus on reducing the rates of reoperation in tibiotalar arthrodesis and on the link between cardiovascular disease and nonunion. A better understanding of the reasons why certain
patients develop nonunions and infections is warranted. Ultimately, decreasing rates of nonunion and infection in tibiotalar arthrodesis will have a substantial impact on the reoperation rate in this procedure, with obvious benefits to patients and the health care system.

Pertaining to the use of the jig in tibiotalar arthrodesis, the procedure length in the experimental group could partially be explained by the equipment not working as planned; even with two of the longest procedure times removed, the jig and alignment system still doubled the procedure length. As such, substantial improvements will need to be made to our jig and alignment system before use in patients. Proposed modifications include the ability to add a depth-stop to the shank of the burr to provide more control of the burr, improvements to the adjustability of the clamps on the alignment guide, a method/device for protecting soft tissues, and a system for compressing and holding the joint in the proper alignment.

Another potential study arising from our findings would be related to the contact area between the tibia and the talus and whether increasing this area is important in achieving union rates and improvement in patients’ outcomes.

4.3 CONCLUSION

Nonunion and infection in tibiotalar arthrodesis remain critical issues. We found that cardiovascular disease was correlated with nonunion in tibiotalar arthrodesis. The first prototype for the jig and alignment guide did not reliably
fulfill our criteria of decreasing procedure time, improving contact area between
the prepared tibial and talar surfaces, or consistently placing the foot in the
proper alignment. As such, further work will be required to make our jig and
alignment guide a viable product that would improve the outcomes in tibiotalar
arthrodesis.

4.4 REFERENCES

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Bloch, B. B. M. F., S. M. M. S. D. N. B. Srinivasan and J. M. S. F. Mangwani

Chalayon, O., B. Wang, B. Blankenhorn, J. B. Jackson, T. Beals, F. Nickisch and
C. L. Saltzman (2015). "Factors Affecting the Outcomes of Uncomplicated


"Complex Ankle Arthrodesis Using the Ilizarov Method Yields High Rate of


"Tibiotalar Arthrodesis in Posttraumatic Arthritis Using the Tension Band

Sabine, K., A. Sascha, B. Peter, M. Clemens, C. Michel and T. Hans-Joerg
(2017). "Comparative study of outcomes after ankle arthrodesis shows higher
complication rates in cases operated upon by general orthopaedic surgeons." Int


APPENDICES
APPENDIX I: RESEARCH ETHICS BOARD APPROVAL – CHART REVIEW

STUDY

I.1 University of Western Ontario REB Approval Letter – Chart Review

Date: 19 July 2018
To: Dr. Abdel-Rahman Lawendy
Project ID: 112334
Study Title: Determining the rate of re-operation and predictors of re-operation in tibiotalar arthrodesis
Application Type: HSREB Initial Application
Review Type: Delegated
Meeting Date / Full Board Reporting Date: 07/Aug/2018
Date Approval Issued: 19/Jul/2018
REB Approval Expiry Date: 19/Jul/2019

Dear Dr. Abdel-Rahman Lawendy

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

Documents Approved:

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No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB, except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Daniel Wyzyński, Research Ethics Coordinator, on behalf of Dr. Joseph Gilbert, HSREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).
LAWSON FINAL APPROVAL NOTICE

LAWSN APPROVAL NUMBER: R-18-404

PROJECT TITLE: Determining the rate of re-operation and predictors of re-operation in tibiotalar arthrodesis

PRINCIPAL INVESTIGATOR: Dr. Abdel-Rahman Lawendy

LAWSN APPROVAL DATE: Friday, 20 July 2018

ReDA ID: 5572

Overall Study Status: Active

Please be advised that the above project was reviewed by Lawson Administration and the project:

Please provide your Lawson Approval Number (R#) to the appropriate contact(s) in supporting departments (eg. Lab Services, Diagnostic Imaging, etc.) to inform them that your study is starting. The Lawson Approval Number must be provided each time services are requested.

Dr. David Hill
V.P. Research
Lawson Health Research Institute
II.1 University of Western Ontario REB Approval Letter – Cadaver Study

Dear Dr. Abdel-Rahman Lawendy

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

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No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB, except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPs 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Patricia Sargeant, Ethics Officer (ext. 85990) on behalf of Dr. Marcelo Kremenchutzky, HSREB Vice-Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).
II.2 Lawson Health Research Institute Approval Letter – Cadaver Study

LAWSON FINAL APPROVAL NOTICE

LAWSON APPROVAL NUMBER: R-18-151

PROJECT TITLE: Design, development and testing a jig for use in tibiotalar arthrodesis

PRINCIPAL INVESTIGATOR: Dr. Abdel-Rahman Lawendy

LAWSON APPROVAL DATE: Wednesday, 21 March 2018

ReDA ID: 4216

Overall Study Status: Active

Please be advised that the above project was reviewed by Lawson Administration and the project:

Please provide your Lawson Approval Number (R#) to the appropriate contact(s) in supporting departments (eg. Lab Services, Diagnostic Imaging, etc.) to inform them that your study is starting. The Lawson Approval Number must be provided each time services are requested.

Dr. David Hill
V.P. Research
Lawson Health Research Institute
VITA

Name: Adam Mathew Ropchan

Post-secondary Education and Degrees:

University of Waterloo
Waterloo, Ontario, Canada
2007 – 2011 BSc (Hon. Biomedical Sciences)

University of Western Ontario
London, Ontario, Canada
2011 – 2015 MD

University of Western Ontario
London, Ontario, Canada
2015 – present FRCSC (Orthopaedic Surgery)

University of Western Ontario
London, Ontario, Canada
2017 – present MSc (Surgery)

Honours and Awards:

University of Waterloo President's Scholarship
2007

Western Graduate Research Scholarship
2017 – 2018

Related Work Experience:

Orthopaedic Surgery Resident
London Health Sciences Centre
2015 – present

Publications:
