THE EFFECT OF ANKLE ARTHRITIS ON HINDFOOT KINEMATICS DURING HEEL RISE

by

David Joshua Mayich

A thesis submitted in conformity with the requirements for the degree of Masters of Science
The Institute of Medical Science
University of Toronto

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ABSTRACT

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The act of raising the heel up is an essential portion of the gait cycle in humans, comprising the third rocker in the gait cycle. This act further demands specific motions from the hindfoot, and the surrounding structures. These motions have been previously studied and are reasonably well understood. End-stage osteoarthritis of the ankle (or ESOA) has been theorized to affect not only the ankle joint, but the same joints required for heel rise. (i.e. - hindfoot, lower leg, and foot) In the present research, the powerful effect that ESOA has on the lower leg, hindfoot and forefoot biomechanical relationship was demonstrated as significantly different from that of healthy age and sex-matched controls. This has implications not only for further research, but potentially treatment as well.
ACKNOWLEDGEMENTS

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The author would like to remember the ultimate sacrifice made by his grandfather, Stanley Mayich. Without his willful sacrifice to Canada and his (and others) willingness to pay the ultimate price for his/their loyalty to our country, the opportunity and privilege we all enjoy to freely pursue knowledge and a better world would never exist.

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God love yas all.
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References
CO-AUTHORSHIP

This thesis contains materials from several works currently submitted for publication.


*Chapter 2*: Novak A, Mayich DJ, Brodsky J, Daniels TR. Gait Analysis in Orthopaedic Foot and Ankle Surgery. Part 2: Modern Approaches to modeling the foot and ankle.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Abd</td>
<td>Abduction</td>
</tr>
<tr>
<td>Add</td>
<td>Adduction</td>
</tr>
<tr>
<td>AOFAS</td>
<td>American orthopaedic foot and ankle society</td>
</tr>
<tr>
<td>AVN</td>
<td>Avascular necrosis</td>
</tr>
<tr>
<td>CCJ</td>
<td>Calcaneo-cuboid Joint</td>
</tr>
<tr>
<td>DF</td>
<td>Dorsiflexion</td>
</tr>
<tr>
<td>ESOA</td>
<td>End-stage osteoarthritis of the ankle</td>
</tr>
<tr>
<td>Ev</td>
<td>Eversion</td>
</tr>
<tr>
<td>IREDs</td>
<td>Infrared emitting diodes</td>
</tr>
<tr>
<td>Inv</td>
<td>Inversion</td>
</tr>
<tr>
<td>OA</td>
<td>Osteoarthritis</td>
</tr>
<tr>
<td>PF</td>
<td>Plantarflexion</td>
</tr>
<tr>
<td>PTOA</td>
<td>Post-traumatic osteoarthritis</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of motion</td>
</tr>
<tr>
<td>STJ</td>
<td>Subtalar (or talo-calcaneal) Joint</td>
</tr>
<tr>
<td>TNJ</td>
<td>Talo-navicular joint</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>TAR</td>
<td>Total ankle replacement</td>
</tr>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 - Introduction

The hindfoot is a complex anatomic and biomechanical structure. Each bone, ligament, tendon, blood vessel, nerve has an exact location and character that imparts a functionality that is a requirement for the normal functioning of the hindfoot. This all culminates in the performance of normal bipedal human motion or gait. Attempting to understand the interplay between these complex structures by teasing out meaning from the in vitro study of the individual components can yield abstract data that is often very difficult to contextualize or apply to the in vivo or clinical environment. On the other hand, study of overall function, as in the case with gait analysis, without a detailed understanding of the anatomic and biomechanical components of the hindfoot can be equally ineffective at discerning precise information from what is often combined efforts from different anatomic and biomechanical structures. A critical balance between detailed understanding as well as a grasp of overall function must be struck for research of this form to be of any use to the clinical community.

Given these difficulties, attempting to understand and describe motion of the hindfoot is not easy. This is well exemplified by the research that shows the highly coordinated motion of the shank (tibia and fibula), hindfoot, midfoot and forefoot segments of the human foot and ankle. Furthermore within the
hindfoot segment itself, an interdependent relationship between bones is critically important for normal function.\textsuperscript{113} The talus itself has no muscular attachments and relies on articular relationships and ligamentous connections with all of the surrounding bones for the indirect transfer of forces and guided motion to function normally. This is exemplified by the calcaneofibular ligament (CFL) and deltoid ligament.\textsuperscript{19,30,39,72,84,87,90,91,103-105,115,126,127,133,134,146,160,162,178} Both of these ligaments span multiple joints about the talus, and are in direct contact with muscular tendons.\textsuperscript{90} These ligaments of the hindfoot that are in contact with multiple bones and tendons help transfer forces, guide motion and ensure biomechanical relationships throughout the physiologic range of motion (or ROM).\textsuperscript{90} This is evidenced by an immense body of \textit{in vitro} research, and is increasingly being recognized with \textit{in vivo} research, as the ability to rigorously track motion between different bones improves.\textsuperscript{19,30,39,50,71,72,79,84,87,90,91,103-105,115,120,121,126,127,133,134,137,146,160,162,178,205}

When the ankle becomes arthritic there are significant changes that occur within the ankle joint.\textsuperscript{35} The effect that this disease has on the anatomy and biomechanical characteristics of the ankle does vary somewhat with the causative etiology, but does have some common features in each case.\textsuperscript{35,184} It is critically important, despite the complexity it imposes, to keep in mind the effect that ankle dysfunction has on the joints surrounding it in the hindfoot.\textsuperscript{113} Due to the inter-dependency of all of the joints of the hindfoot, end-stage ankle arthritis (or ESOA) has a profound effect on the anatomy and biomechanics of the subtalar (or STJ) and talonavicular (TNJ)
joints and their related anatomy. This is most commonly recognized in the clinical world as “marching arthritis” or “adjacent joint disease” (or arthritis development in the joints adjacent to the ankle over time), which can be commonly seen after the diagnosis of ESOA has been made, and the ankle has been successfully treated. How the subsequent development of arthritis in the STJ and TNJ (hereby known as the “adjacent joints”) is mediated, and how it is initiated, at this point in medical history, remains an unsolved question.

Despite the controversy around this subject several critically important observations have been made. In some obvious instances trauma or inflammatory arthritis directly affects the joints in question and arthritis develops in the adjacent joints as a result of this direct bony and cartilaginous injury. In some cases, with varus talar neck malunions being the most obvious example, a residual anatomic abnormality directly mediates known abnormal biomechanical behavior and leads to abnormal joint loading of the STJ and cartilage and degeneration can result. In more isolated cases of ESOA aberrations in what one would assume to be relatively normal functioning adjacent joints, have been shown, upon more detailed analysis, to show subtle alterations in the axis of motion of the subtalar joint. Similar changes in the behavior of the STJ have been found after successful ankle fusion. These consistent changes likely point to adaptations occurring in the biomechanical behavior of the adjacent joints, presumably in response to the changes in the ankle joint, and not from previous injury.
Gait analysis, in the case of ESOA, offers a unique and dynamic method of measuring the effects of the ESOA on not only the ankle itself, but also on the other joints of the foot and leg. This, to a certain extent has been done, and has shown significant alterations in the motion of the individual suffering from the ESOA as well as those who have been treated for ESOA.\textsuperscript{21,31,93,107,143,153,183} Furthermore detailed research utilizing more detailed models of the foot and ankle joints have gathered further information about the compensatory mechanisms utilized by the foot joints in an attempt to overcome ESOA.\textsuperscript{93,143} This offers the orthopaedic foot and ankle community a chance to begin to understand how the foot and ankle compensates and behaves in the setting of ESOA. Although advancing in its depth and scope, this area of research is in its infancy. Significant areas of foot and ankle biomechanics that have direct bearing on research have yet to be elucidated or confirmed with \textit{in vivo} research.

\textbf{1.2 - Thesis Outline and Intent}

The overall intent of this thesis was to obtain a thorough grasp of normal foot anatomy and function (e.g. – gait) in the normal state and, using this knowledge, investigate and describe the mechanisms by which the foot compensates for end stage ESOA. To address this a thorough literature review on the anatomy and biomechanics of the hindfoot, the science and methodology of gait analysis, and the effects of ESOA on hindfoot and gait was completed (Chapter 2) Secondly, a study of the normal foot kinematics during heel rise, an activity that requires significant
mobility within the foot, was undertaken. (Chapter 3) This allowed the researchers to understand the full range of normal hindfoot motion that is required during physiologic in vivo function. The thesis concludes with a summary and general discussion in Chapter 4, including future directions for clinical research and practice.
CHAPTER 2

LITERATURE REVIEW

Chapter 2.1: Principles & Uses of Kinematic Gait Analysis

2.1.1 - What is gait analysis?

Documented observation of the human gait for clinical purposes has been practiced for thousands of years, and has been noted in the writings of Hippocrates and Aristotle. In recent times, the meaning and usages of the terms “gait analysis,” and “biomechanics” have been occasionally confused, poorly defined, or even used interchangeably. This is perhaps attributable to the increasing complexity of the science, and inappropriate application of these commonly used terms. As the field of biomechanics expands, so too does the need for the orthopaedic foot and ankle surgeon to have a basic understanding of gait and of foot and ankle biomechanics. A requirement for a basic understanding of gait likely also pertains to the general orthopaedic surgeon as well.

The foot and ankle is the terminal appendage to the lower extremity. It is subjected to large forces and variable terrain. To adapt to this environment a closely linked system of joints is necessary to provide a construct, which is both stable and robust. Any alteration in this system may have adverse effects on the entire limb, both proximally and distally. (See Table 2.1)
Table 2.1 - Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Meaning</th>
<th>Where does this (typically) occur?</th>
<th>Primary purpose?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Gait Evaluation</td>
<td>Visual observation of the gait of patients to aid in clinical evaluation and decision-making</td>
<td>In clinics &amp; offices of orthopaedic surgeons</td>
<td>Clinical evaluation and decision-making</td>
</tr>
<tr>
<td>Gait Analysis</td>
<td>The use of scientific methodology to observe and record objective variables of human gait.</td>
<td>In specialized facilities designed for gait analysis.</td>
<td>Objective, scientific characterization of the variables of human motion</td>
</tr>
<tr>
<td>Biomechanics</td>
<td>The discipline that describes, analyzes and assesses human movement and the involved forces.\textsuperscript{207}</td>
<td>In facilities specialized in biomechanical evaluation of a subject or target object. (e.g. – living humans, cadaveric portions of human anatomy, tissue samples, etc.)</td>
<td>Scientific characterization and modeling of forces and motion</td>
</tr>
</tbody>
</table>

Both general orthopaedic and orthopaedic foot and ankle surgeons have been historically taught the importance of observing gait as a means to assess the cause of effect of musculoskeletal disease.\textsuperscript{33,82} Visual gait evaluation is based in clinical context and is done solely for the clinical benefit of the observed patients. This is quite different from “gait analysis,” which is performed in a specialized motion analysis laboratory. This occurs outside of the clinical realm, and usually presents no potential for clinical benefit to the subject, which is reflected in the necessary
ethical documentation process required from the scientists and their consenting subjects. “Gait analysis” objectively records, and quantifies human motion. The purpose of gait analysis is to scientifically measure human motion (whether normal or diseased) in order to achieve two major goals: (1) to understand the biomechanical properties of human gait (e.g. – characteristics of normal and/or diseased gait;\textsuperscript{35,93,196} and (2) to analyze the components of human gait (e.g. – studying the biomechanical components of the foot and their relationship to one another during gait.\textsuperscript{110}). This ideally leads to clinically meaningful inferences regarding anatomic and biomechanical function. (e.g. – to objectively measure the effect of treatment.\textsuperscript{11,21,154})

2.1.2 - Commonly used terms in Gait analysis

The gait cycle is defined to be all events involved in achieving forward motion occurring during one full step - in most cases beginning when the foot of one limb contacts the floor, and ending once this same limb strikes the ground for the same purpose again. The gait cycle has been divided into phases, periods and events in order to allow identification and isolation of different aspects of the gait cycle to facilitate communication. Although varied terminology has been used to describe the gait cycle, there are some standardized terminologies that allow clinicians, surgeons and scientists to communicate effectively. The gait cycle is divided into the stance and swing phases. The stance phase comprises approximately sixty percent of each gait cycle, while the swing phase accounts for roughly forty percent.\textsuperscript{95} Both
phases are sub-divided into periods with identifiable events. (See Table 2.2 and Figure 2.1)

Figure 2.1 - the three rockers of gait. (a) during the first rocker the heel strikes the ground, and the foot rotates about this point, and the ankle joint axis to come to rest in the flat foot position. Contraction of the anterior compartment muscles (*) controls this motion; (B) during the second rocker of gait tibia (& body) is brought over the talus rotating around the ankle joint. The intrinsic muscles of the foot & tibialis posterior fire (*) to maintain a medial longitudinal arch; (C) during the terminal portion of the 2nd rocker the powerful triceps surae fires (*); (D) During the 3rd rocker the ankle plantarflexes over a fixed forefoot (about the metatarsophalangeal joints – often termed “heel rise”) ending in toe off, initiating the swing phase of gait.
Table 2.2 - Phases, periods and events of the normal human gait cycle

<table>
<thead>
<tr>
<th>Phase</th>
<th>Period</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance</td>
<td>1st Rocker</td>
<td>Heel Strike</td>
</tr>
<tr>
<td></td>
<td>2nd Rocker</td>
<td>Foot Flat</td>
</tr>
<tr>
<td></td>
<td>3rd Rocker</td>
<td>Heel rise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toe off</td>
</tr>
<tr>
<td>Swing</td>
<td></td>
<td>Foot clearance</td>
</tr>
</tbody>
</table>

A working knowledge of these events, and their importance in normal gait is important for understanding and ultimately diagnosing and treating foot pathology. For example, if the event of “foot clearance” cannot occur during the swing phase then the body must expend additional energy to hyperflex the knee and hip, which produces the clinically observed “steppage” gait. Terminology such as this (“steppage gait”) allows the clinician to quickly communicate what is a complex adapted gait pattern in an easily and quickly understood term. Understanding a set of basic terminology around common abnormal gait patterns is an important tool required for effective communication amongst musculoskeletal health care professionals.

2.1.3 – The phases of gait: Stance phase

The stance phase is responsible for weight bearing while allowing the pelvis to rotate and translate over the planted foot. This process of forward motion of the body over a planted foot places the proximal leg muscles under tension, functionally storing energy that can be later utilized for energy efficient limb advancement in the swing phase. During the stance phase, the foot progresses through three
“rocker” periods, beginning with heel strike and ending with toe off. (See Table 2.2 and Figure 2.1) In the first rocker the heel touches the ground. Eccentric contraction of the ankle dorsiflexors allows plantarflexion to occur in a controlled manner. This plantar flexion occurs as a rotation with the point here the heel is in contact with the ground as the axis of rotation. In the second rocker the tibia rolls forward over the ankle to permit continual forward movement of the body. The foot remains planted throughout the second rocker. The primary rotation at this point occurs about the ankle, although some associated motion of the peritalar joints does occur. In the third rocker, the foot is dorsiflexed around the metatarso-phalangeal (or MTP) joints, which is often summarized as “heel rise.” This event culminates in toe-off. Here rotational axes can be found at both the MTP and the ankle joints.

The function of several muscle groups is critical during stance phase, allowing for the efficient process of human gait to occur.33,74 (See Table 2.3)
Table 2.3 - The Muscles Utilized during the Gait Cycle

<table>
<thead>
<tr>
<th>Phase of Gait</th>
<th>Period</th>
<th>Muscles</th>
<th>Contraction type</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- Anterior muscle group</td>
<td>Eccentric</td>
<td>Control the plantarflexion of the foot, preventing the foot from slapping against the ground</td>
</tr>
<tr>
<td>First Rocker</td>
<td></td>
<td>- Intrinsic muscles of the foot</td>
<td>Eccentric</td>
<td>- Intrinsic foot muscles and Tibialis posterior maintain the longitudinal arch of the foot throughout the second rocker - Posterior muscle group contracts to control the forward rolling of the tibia over the ankle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(utilizing the plantar fascia\textsuperscript{32})</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Peroneus longus</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Posterior muscle group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second Rocker</td>
<td></td>
<td>- Posterior muscle group</td>
<td>Concentric</td>
<td>- To lock the Chopart’s joint, permitting the heel to rise, rotating about the MTP joints - Provide a small forward propulsive force.</td>
</tr>
<tr>
<td>Third Rocker</td>
<td></td>
<td>- Peroneus brevis</td>
<td></td>
<td>Dorsiflexion of the foot on the ankle to allow for foot clearance and to prepare the foot for heel strike.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Anterior muscle group</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The “anterior muscle group” here refers to: Tibialis anterior, extensor digitoum longus, extensor halicus longus; the “Posterior muscle group” in this instance refers to = Tibialis posterior, flexor digitorum longus, flexor Hallicus longus, and the Gastrocnemius & soleus muscles.

The predictable timing and intensity of activity during normal gait has been well established and abnormalities have been correlated to disease states, making a basic understanding of this sequence of activity an important consideration during clinical assessment of normal and pathologic gait\textsuperscript{33,203} An example of this would be the patient with flexible posterior tibial tendon dysfunction. Lack of effective contraction of the tibialis posterior prevents locking of the transverse tarsal joints,
which is essential in order to convert the normally flexible hindfoot and midfoot segments into a rigid single segment. The creation of this rigid hindfoot-midfoot structure is needed to efficiently transmit the force of the triceps surae contraction to the rising heel and forefoot. Concentric contraction of the posterior musculature occurs during the third rocker as the heel rises up and the foot rapidly advances to toe off. The energy expenditure required to perform steady state gait is increased in the setting of flexible pes planus. This is due in part to the loss of mechanical advantage that is created when the transverse tarsal joints lock to make the midfoot into a more rigid lever arm. This process can be somewhat mitigated with appropriate orthotics, which help to restore the lever arm that normally occurs in the mid- to terminal portions of the stance phase.

Motion at the level of individual bones and joints in the foot (specifically in the hind- and mid-foot) during gait, is difficult to study. The bones of the feet are small, have a close association to neighboring bones, and often have functional arcs (or paths) of motion that are very small. To further add to the difficulty in analysis, the capacity for adaptation by the multiple joints in the foot, as well as the complex and variable configuration of the supporting static and dynamic stabilizers about the foot contribute to the complexity of the functional behavior of the foot and ankle. Because of these characteristics, the role that motion in each of the bones of the foot or their associated active and passive supportive structures plays during the stance phase of gait is not yet fully understood. This is exemplified in post-ankle fusion
gait. It has been demonstrated that although differences do exist, surprisingly normal global gait patterns can exist, despite the elimination of tibiotalar joint motion. This was reflected in the spatiotemporal and kinematics research published by Thomas et al, who showed that cadence was decreased by only 8.5 steps/minute, stride length was decreased by 16cm, and stance time was unaffected. The ability of individuals with a fused ankle to walk with such a surprisingly normal outward appearing gait is presumably because the gait cycle progresses through three rockers and doesn’t specifically rely on tibiotalar motion for the entirety of the foot and ankle motion. The peritalar joints as well as the other larger proximal joints, compensate through their own capacity for adaptation, likely play a role in this effective compensatory mechanism.35,56,113,183,198 Cadaveric research demonstrated a 12.5° arc of motion in plantar- and dorsiflexion following ankle fusion where conceptually little motion would be expected.192 In vivo radiologic research further demonstrated the capacity for adaptation by the peritalar joints, which developed a 10.8% increase in sagittal plane motion of the foot and ankle, following ankle fusion.172 This was termed by Sealey et al. as “hypermobility.” In the Thomas et al. post ankle fusion gait study, significant, but smaller than was perhaps expected, reductions in sagittal plane motion were also noted in both the hindfoot (6.8°) and forefoot, (6.5°). A reduction in hindfoot motion of less than 7° following fusion was thought to point to contributions from compensatory mechanisms during sagittal plane foot and ankle motion, like those presented by Sealey et al. The reductions noted in forefoot motion were thought to indicate that the forefoot was
either involved in the arthritic process, or was involved in a compensatory mechanism in response to ESOA.

2.1.4 – The phases of gait: Swing phase

The swing portion of gait is responsible for bringing the foot from a plantar-flexed position at toe off, to a neutral or slightly dorsiflexed position through the concentric contraction of the anterior leg musculature and peroneus brevis. This allows the foot to clear the floor as the leg is pulled forward by the energy that was stored in the previously tensioned pelvic and proximal thigh musculature. Changes in hindfoot/peritalar and midfoot alignment, from a supinated, and relatively unstable position to a pronated and highly stable position also occur. This brings the entire hindfoot, with the ankle included, into a position developed to accept and dissipate the high loads that are observed during heel strike. Other not as well studied as the stance phase, abnormalities in this phase can lead to significant changes in the biomechanics of the ankle, and lead to demonstrable gait abnormalities.

2.1.5 – The variables of gait analysis: Kinematics

There are four main variables of gait analysis. These are: (1) Temporal-spatial variables; (2) Kinematic variables; (3) Kinetic variables; (4) and EMG. For the purposes of this thesis, the focus will be placed on kinematic variables.
Kinematics, or the study of motion, refers to the measurement of the movement of a body or bodies with respect to time in isolation of the forces that generate the movement. This is most often measured as displacement (either linear or angular), velocity or acceleration. Kinematic measures may be observed in many ways, but are most commonly recorded using motion tracking devices and/or cameras to derive limb trajectories and joint angles. Modern gait analysis utilizes optical cameras. Although this can be done using either two-dimensional (or 2D) or three-dimensional (or 3D) technology, for the purposes of this review only 3D gait analysis will be discussed. In the 3D methodology a defined volume or space is calibrated so that the position of markers within this space can be tracked in 3D with high accuracy. The motion between defined segments, as well as a defined “global coordinate system” (or a defined set of planes that relates the segments to the surrounding environment, with usually level ground as a starting point) is observed.

Tracking markers are placed on the skin over palpable landmarks to allow the measurement of one “segment” (or portion) of the body of interest in accordance with a validated model, like the model put forward by Leardini et al. (See Figure 2.2)
Figure 2.2: An instrumented foot utilizing the four segment model initially described by Leardini et al. The segments of this model are the hallux (Ha), forefoot (F), midfoot (M) and the hindfoot (H).

They can be either active markers (which transmit a signal, like those shown in Figure 2.2) or passive markers (that reflect a signal from a transmitting and receiving camera). Attaching markers on the skin of the foot over palpable landmarks is not without limitations. Skin motion has been documented as a source of significant error with the skin moving as much as 16.4mm ±16.7 mm over the navicular and 12.1 ± 0.3 mm over the calcaneus at toe-off. Further issues related to other soft-tissue artifact and exaggeration of motion has also been demonstrated and will be discussed in greater detail in part two of this article. Error has also been recognized in reliably marking the complex anatomy of the foot.
Anatomic variation in the normal state or in pathologic states contributes to potential issues regarding the accuracy and reproducibility of marker placement.  

Despite these shortcomings, given the invasive nature of fixation of markers to bone in normal healthy subjects, and considering the subcutaneous location of the osseous anatomy of the foot, skin-mounted markers are the likely the most acceptable marker arrangement at this time.

The foot and ankle is a collection of a large number of small bones (26) that function in complex and very close anatomic relationships. These characteristics make separating the motion of the different bones and joints of the foot a practical impossibility, given our currently available technology. These factors were among the dominant considerations that lead to the initial treatment of the foot as a single segment, as is the case with the “modified Helen Heyes” configuration that has been widely utilized in the literature. Despite this widespread use, single segment foot models provide limited and over simplistic data regarding the foot. This is highlighted by the practical observation that the foot is not clinically treated as a “single segment.”

With improved technology there has been an emerging trend to treat the foot as one anatomic area made up of many functionally related but distinct segments, mainly the hindfoot, midfoot, forefoot, hallux etc. (See Figure 2.2) The information that can be gained by breaking foot function into (or segmenting) different functional units for the purposes of gait analysis can yield important information.
about the different and clinically significant parts of the foot. Using this approach, a wealth of information can be gathered about clinically relevant differences like motion,\textsuperscript{40,75,111} observed ground-reaction forces,\textsuperscript{22,75} plantar pressures,\textsuperscript{40,56} etc. between the different segments. The increased resolution allows one to differentiate behavior of the foot with respect to normal or pathological gait.\textsuperscript{96} ESOA, as discussed earlier, is one such example.\textsuperscript{35,143,175} This knowledge is likely critical to gain an understanding of how different functional areas of the foot adjust in the face of injury and/or dysfunction or the consequences of treatment. This information is poised to, and already has in some cases, help inform clinical decision-making and serve as a tool for measuring outcomes following intervention.\textsuperscript{48,118}

2.1.6 – Conclusions

Gait analysis, and specifically the study of the kinematics of gait, has enjoyed a rapid development over the past 50 years. A wealth of information regarding the movements that occur within the foot and ankle to constitute normal gait is becoming increasingly available in the orthopaedic foot and ankle literature. This has traditionally involved the normal or healthy condition, but is increasingly involving the kinematics of abnormal/diseased states, such as ESOA as well. This has had a profound effect on how we view the pathophysiology of the diseases that effect the foot and ankle and will ultimately guide the development and validation of the treatments we use.
Chapter 2.2 - Modeling of the foot and ankle

2.2.1 - Introduction

Motion of the ankle-foot complex has been traditionally investigated by modeling the foot as a single rigid segment that interacts with the lower leg, typified by the modified Helen Hayes foot model.\textsuperscript{21} Such an analysis permits identification of angular motion (kinematics) and forces/moments and powers (kinetics) generated about the ankle in normal\textsuperscript{117,206} and pathological populations.\textsuperscript{21,183} Although relatively easy to perform and analyze, the basic information from single segment foot modeling, does not allow for observation of the complex motion that occurs within the foot during human gait.\textsuperscript{16,24,112} Multi-segmented foot modeling attempts to overcome this limitation by providing a more precise analysis of the motion that occurs within the foot. Several segmented models of the foot have been developed to date and are increasingly used in clinical gait analysis and biomechanics research.\textsuperscript{26,83,110,112,124} The choice of an appropriate model used will depend on many factors, including the questions to be answered, the patient population and/or analytical needs.

This portion of the literature review will provide: (1) An introduction to methods of multi-segmented foot modeling – with a focus on the “IOR” model of the foot and ankle; (2) Limitations associated with multi-segmented foot modeling; and (3) Clinical application of the multi-segmented foot model. With multi-segmented foot modeling being reported with increasing frequency in the literature in the past few years, it is important for clinicians and researchers involved in assessment of
foot and ankle dysfunction to gain, at a minimum, a basic understanding of the strengths and limitations of multi-segmented foot modeling. This will assist in allowing clinicians and researchers alike to accurately assess and interpret gait data presented in the literature, and to inform the planning of relevant clinical research similar to that performed in this thesis.

2.2.2 – Foot and Ankle Anatomy – The basics

The human foot is comprised of, normally, 26 bones, 33 joints, 107 ligaments, 19 muscles and tendons. (See figures 2.3 and 2.4) There are some defined variations that have been well-described in the literature. The tibia and fibula, and their ligamentous connections are often referred to as the “shank” in the biomechanical literature. The large number of bones of the feet are often grouped into functional components: The hindfoot includes the calcaneus and talus; the midfoot includes the navicular, cuboid, medial, intermediate and lateral cuneiforms; the forefoot includes the metatarsals and the phalanges.

2.2.3 - Methods of multi-segmented foot modeling

Understanding the complex anatomic regions of the foot biomechanically is not without problems. This is exemplified when the foot, with all of its complexity is treated as a single segment. To address the shortcomings of the single-segment foot model, several multi-segmented foot models have been developed in recent years to describe normal and pathological movement using 3D motion capture systems. These models can vary according to the number of segments analyzed, definition of
the neutral (or “reference” position), definition of the functional (segment) coordinate systems, and/or determination of inter-segmental motion

Figure 2.3 - A (A) Clinical, (B) Composite; and (C) Radiographic image of normal foot and ankle anatomy from a side (or sagittal) view. The Tibia (A), Fibula (B), Talus (C), Calcaneus (D), Navicular (E), Cuboid (F), Medial Cuneiform (G), 1st (H) and 5th (I) Metatarsals, as well as the phalanges (J) are depicted.
Figure 2.4 - A (A) Clinical, (B) Composite; and (C) Radiographic image of normal foot and ankle anatomy from a side (or sagittal) view. The Talus (C), Calcaneus (D), Navicular (E), Cuboid (F), Medial (G), Intermediate (K) and lateral (L) cuneiforms, 1st (H) and 5th (I) Metatarsals, as well as the phalanges (J) are depicted.

(kinematics).\textsuperscript{156} Intra-cortical bone pins with attached markers is the theoretically ideal method for tracking bone movement of the foot, as this type of modeling tracks direct motion of individual bones.\textsuperscript{122,139} Not surprisingly, \textit{in vivo} measurement using bone-anchored markers is not widespread given the relatively invasive nature of the technique.\textsuperscript{7,122,159} 3D motion tracking of the segments of the foot using skin-mounted markers is much more commonly utilized (Figure 2.2).

Multi-segmented foot models can vary from two, three or commonly more segments to describe partial or whole foot kinematics. Given the variation of properties
associated with multi-segmented foot models, an accurate and detailed description of the segment (or local) coordinate system (SCS) is required. The SCS is generally a right-handed, orthogonal system that is fixed within a body or segment and moves with that body/segment. Thus, the SCS describes the position and orientation of the segment.\textsuperscript{163} Definition of the SCS is dependent on placement of the digitized or tracking markers secured on the body or segment. Therefore, accurate and discernable description of the anatomical landmarks used for marker placement, anatomical reference frames, and reference position is critical (further discussed in the limitations section of this review paper). This is necessary to ensure the reproducibility of the study, to determine the appropriateness of the selected model, to allow comparison with published results, and most importantly, and to guide the clinical interpretation of the data.

2.2.4 - The Leardini (IOR) Foot Model

Leardini and colleagues\textsuperscript{110} developed an anatomically-based four-segment foot model with particular clinical focus on frontal plane alignment of the hindfoot, and transverse and sagittal plane alignment of the forefoot. This model places single tracking markers directly mounted on the skin surface over relevant anatomical landmarks to track the (1) shank (tibia, fibula), (2) hindfoot (calcaneus), (3) midfoot (including the navicular, lateral, middle and medial cuneiforms, and the cuboid bones), and (4) forefoot (includes five metatarsal bones). In order to overcome several limitations known with direct marker placement, this model uses more dorsal locations for the fore-foot markers (i.e. forefoot defined by base of 2\textsuperscript{nd}}
metatarsal, head of 1st metatarsal, head of 5th metatarsal to form a triangle which defines the orientation of the segment), so as to permit easier and more reliable application of markers in normal and pathologic feet alike. Additionally, the choice of forefoot marker locations, which are along relevant joint lines, reduced the number of markers required. The IOR model of Leardini et al.\textsuperscript{110} also had a particular clinical focus on frontal plane alignment of the hindfoot, given the functional importance of hindfoot alignment in relation to the shank and forefoot in common foot pathologies, like ESOA. The hindfoot was defined with direct marker placement on the medial apex of sustentaculum tali, lateral apex of peroneal tubercle (with the midpoint of these segments calculated and used for SCS orientation) and the upper central ridge of the calcaneus posterior surface (which also depicts the origin of the segment), seeking a clinically oriented definition of the segment. Unlike the oxford foot model, SCS definition of the hindfoot is not dependent on a standardized static pose but rather the use of the three landmarks gives the hindfoot SCS an inversion offset. However, the standardized static or “standing neutral” pose was used to calculate offset values for all joint angles (similar to other models). See table 2.4 for more detailed SCS definitions. In addition to the 3D foot segments, the proposed model further describes the 2D orientation of the line segments representing the first, second and fifth metatarsal bones and the proximal phalanx of the hallux. These line segments permit calculation of several planar or “functional” angles, such as the medial longitudinal arch, navicular drop, and first ray mobility. This theoretically allows for useful the direct and absolute measurement of the position of the parts of the foot to one another. This
development was thought to be important as it theoretically brought the utility of
the gait lab beyond the measurement of relative motion (one segment against
another). It also theoretically allowed for the direct measure of the absolute
relationships of the segments of the foot. This is in distinction to measuring joint
motion where the measured planar angles are not offset from the neutral or
standing/"resting" position. Despite this promise, caution must be exercised
because the use of the absolute planar angles may have a significant impact on
variability of the reported results.\textsuperscript{44}

A recent study reported difficulty and increased variability in measuring the
planar angles described by Leardini, including the medial longitudinal arch angle,
the angle between the second and first metatarsus and the angle between the
second and fifth metatarsus.\textsuperscript{44} In these cases, reliance on the range of motion in the
sagittal plane, rather than peak plantarflexion angle (for example), improved
variability of the reported data considerably. Although not conclusive, this study did
deal this attempt at advancement a significant setback. Using multi-segmented foot
models to measure absolute foot position in space, therefore, is likely not reliably
possible with this model at this time. In fact, the disappointing reliability results
from this study likely this show the significant limitation of this type of model
(external/skin marker) when trying to measure absolute position and motion of the
foot.\textsuperscript{44}

In addition to small inter-session and inter-examiner variability in healthy
individuals\textsuperscript{24} repeatability and validity of the IOR foot model has also been recently
reported in the presence of foot deformities. Higher variability of the 3D rotations was detected when the midfoot was involved in defined pathology, although as suggested by the authors, both relative and absolute 3D rotations and planar angles can be measured. This helps the model maintain definable clinical utility in the presence of a wide variety of foot deformities.

2.2.5 - Limitations of Multi-segmented Foot Models

There are several limitations which must be considered with respect to 3D multi-segmented foot modeling, including, but not limited to, difficulties in: (1) locating anatomical references (i.e. - bony landmarks); (2) repeatability of marker placement; (3) exaggerations in reported motion; (4) movement artifact of skin-mounted markers; and (5) limited investigation of the kinetics of the foot segments. These limitations can all have a significant effect on the reliability of reported data, and clinical applicability. It is therefore important for the authors of research using multi-segmented foot models to report this, and to demonstrate how these limitations were addressed, if at all. Without such information, the validity and ultimately the value of such research are uncertain.
Marker placement variability, repeatability

Discrepancies in marker placement have been demonstrated to be a significant factor related to reported variability in repeatability studies of multi-segmented foot models.\textsuperscript{24,34,182} Multi-segmented foot models utilize anatomic locations that are accessible to palpation on healthy feet. Utility of the models becomes more challenging in setting of anatomic variation and even more so when attempting to study pathological populations. Caravaggi et al\textsuperscript{24} recently reported greater inter-session variability over the stance phase, associated with tracking the hindfoot segment using the 2007 IOR model.\textsuperscript{110} The observed variability was thought to be associated with significant differences between sessions in the positioning of the markers representing the sustentaculum tali and lateral apex of the peroneal tubercle (i.e. - the medial and lateral landmarks used to define the hindfoot segment). This is not surprising given the variability in the peroneal tubercle’s presence (24-99\% of studied cases) and morphology (enlarged tubercles were reported present in 20\% to 24\% of cases).\textsuperscript{77,90} Indeed, because of the close proximity of the landmark locations, small deviations in marker placement can result in large deviations of the hindfoot segment’s coordinate reference frame and subsequent joint angles.\textsuperscript{24} In patient populations, difficulty in identifying these bony landmarks may contribute to an even greater degree in the variability of reported results. To improve accuracy, radiographic landmark definitions in conjunction with surface markers have been utilized. However, this is not feasible in most clinical gait laboratories and exposes the subject to radiation.\textsuperscript{136,138} Alternatively, the use of marker clusters to track segments may provide a solution in the presence of foot
deformities. In the 1999 IOR model previously described, the use of markers attached to rigid clusters provided consistent patterns of joint motion. However, as discussed by the authors, the technique resulted in uncomfortable marker clusters and required time-consuming anatomical landmark calibration. Additionally, inertial properties associated with cluster movement at contact may also introduce unnecessary error. More easily implemented, simple and careful training of examiners should be used to minimize the variability of the measurements at the intrinsic joints of the foot. The experience and training of the individuals performing this portion of the study should also then, be clearly reported in the methods section of any study using this approach. Without this information, a critical factor in the validity and in the end, the value of the research is unaccounted for.

**Skin marker movement & segment rigidity**

Marker error induced by the underlying skin movement has been given significant consideration in the biomechanics literature. For example, skin marker movement of the subtalar joint in various positions has been quantified using a single subject with radiograph and surface marker measurements. Considerable, non-uniform skin movement occurring at the four identified anatomical landmarks (medial and lateral malleoli, medial and lateral aspects of the talus) was reported. Despite this, the effect of the skin artifact on the inter-segmental angle calculations was substantially less (effect of 1° in the sagittal and transverse planes, 5° in the frontal plane), suggesting that skin-mounted markers
could be likely used to assess subtalar joint motion. Using a more critical evaluation method, however, Reinschmidt et al demonstrated that external or mounted markers consistently overestimated observed kinematics when compared with bone pins.¹⁵⁹ Because of these observations, most notably the significant overestimation of motion from external markers, in vivo assessment of the bone using markers attached to intra-cortical pins is still considered the “gold” standard to track bone movement and eliminate soft tissue artifact.¹²²,¹³⁹,¹⁵⁹ However, the invasive nature of this technique limits its usability and applicability in many clinical gait laboratories. Studies which have compared bone-anchored markers to skin-mounted markers have reported discrepancies between rotation magnitudes in all planes of movement, with the latter showing particularly greater magnitudes in the frontal and transverse planes of ankle movement. Despite this, the authors report a reasonable match between kinematic data from skin and bone-mounted markers.¹³⁹,²⁰¹ Skin-mounted markers, either placed directly on bony landmarks or on rigid clusters, are commonly used in foot and ankle research and are assumed to provide a reasonable representation of the underlying segmental motions. It should be noted that rigid body assumptions (i.e. - considering many bones to act together as one segment) will increase the degree of reported error in kinematics and thus clinicians and researchers must be cognizant of possible sources this assumption as a possible source of error when generating multi-segmented foot data.¹⁴⁰
2.2.6 - Clinical Application of the Multi-segmented Foot Model

The current difficulty facing gait analysis with the purpose of investigating foot and ankle function, pathology and treatment is the almost irreducible complexity of the foot and ankle complex. Initially, motion of the ankle was modeled to act as a simple “hinge” joint, with the foot described as a rigid body. Increased understanding of the anatomic and biomechanical behavior of the foot and ankle has led an appropriate drive by the scientific community to more accurately describe and demonstrate motion of the different segments of the foot and ankle. This has logically followed a progression, in the setting of gait analysis, to an increasing division of the foot into its different constituent biomechanical parts, or segments. This ever-increasing complexity in the analysis, however, can have several effects on the ultimate utility of the obtained information. In today’s scientific and academic setting, it may be challenging to understand fully the terms, mathematics and science behind the more current gait analysis articles. However, an over-arching understanding of the principles, the advantages and the drawbacks to the current methods in gait analysis presented throughout this review are critical for the clinician to understand.

Examples of the improved quality of the information obtained by using multi-segmented foot models and it’s clinical utility have been well demonstrated in the literature. It is very well recognized that injury or pathology to one area of the foot and ankle, like ESOA, often causes adaptive changes in other areas of the foot. Although this compensatory mechanism has a powerful effect on what a
patient feels, and how necessary and successful an intervention will be, until recently both the magnitude and nature of these adaptations have been very poorly understood. By being able to separate the foot and identify the behavior of portions of interest (e.g. hindfoot motion in patients with ESOA) the true impact of the pathology and more accurate interpretations of the effect of treatment can be quantified. This improved understanding could be of a definable benefit to the orthopaedic foot and ankle surgery (or OFAS) community and the patients it serves. It is therefore critical for the OFAS, who must read, interpret and translate this information into patient-care, to have a basic understanding of the advantages, disadvantages and limitations of this advancing science. With this in mind, it is the important to ensure that all data relevant to a clinical audience is presented in a way that is both accessible and interpretable to the anticipated audience.

2.2.7 - Conclusions

Clinical gait analysis has become increasingly more widespread given the advances in technology and greater ease by which to obtain 3D biomechanical data. Use of single-segment foot models has many limitations, particularly when attempting to understand movement within the foot. Multi-segmented foot modeling provides an alternative approach to gain insight into the intricate motion of the individual foot segments.
(1) To date several 3D multi-segmented foot models, like the presented IOR model have been proposed. The clinical utility of these models lies in the ability of the researcher to appropriately match the model used, with its unique strengths and limitations, with the population, pathology or disease state that is being studied. Optimizing this “matching process” will allow the model to provide meaningful biomechanical data, which can be interpreted by the researchers into meaningful findings.

(2) Some limitations are unavoidable when using external marker-based multi-segmented foot models. (e.g. – over estimation of motion from external marker placement) There are some factors, however, that can be controlled (e.g. – decision where to place markers & associated skin motion artifact, error in marker placement, etc.). The decision-making process in selecting the correct model must be made carefully. Furthermore, when reporting the data, clear and appropriate description of techniques is necessary to provide a transparent path for evaluation.

(3) Although this field of science is complex and quickly evolving, a basic understanding of the foot models that are being increasingly utilized by the clinical gait analysis community, like the IOR model, is important for the modern OFAS.
Chapter 2.3 – the Kinematics of Normal Heel Rise

The motion of heel rise, or lifting the heel of a planted foot off of the ground, is a critically important component of normal human gait.\textsuperscript{92,95,203} Specifically, it is considered to be the “third rocker” of normal human gait, where the center of pressure on the human foot continues to move forward from the heel to the area under the first and second metatarsophalangeal joints.\textsuperscript{33} The biomechanical importance of this event during normal gait has been evidenced by its demonstrated contribution to minimizing displacement of center of mass during steady-state gait as well as the disability imparted by individuals not able to perform this task.\textsuperscript{41,92}

The biomechanics behind how this task is achieved are complex.\textsuperscript{29,53,67,68,76,157,170} In the simplest terms, it involves a predictable and reproducible chain of events: (1) posterior musculature (e.g. – triceps surae, tibialis posterior and the extrinsic toe flexors) contraction; (2) the resulting supination of the hindfoot; (3) the subsequent “locking” of the midfoot joints; (4) the rising of the heel (brought about by the relative dorsiflexion of the ankle joint, and metatarsophalangeal joints) (See Figure 2.1D, Figure 2.5 and Figure 2.6) This chain of events, and the order in which they occur is critical biomechanically because it turns the supple and highly mobile human hind- and mid-foot into a more rigid construct that can be conceptualized as a lever-arm.\textsuperscript{33,53,67,90,170} This gives the muscular action of the posterior musculature an enhanced mechanical advantage.\textsuperscript{90} This results in a reduced force requirement from the posterior muscles, and allows the heel to rise
Figure 2.5 - The sequence of events that culminate in heel rise.

about the metatarsophalangeal joint rotational axis with as little active energy expenditure as possible. There are several anatomic structures (most notably the ligamentous support of the hindfoot, the tibialis
posterior,\textsuperscript{13,68,80,88,101,141,157,181,186,191,205} and the plantar fascia\textsuperscript{25,54,73,97,98,100,135,171} that have been shown to be of particular importance in coordinating this event.

Figure 2.6 – The appearance of the joints and osseous components of the hindfoot during heel rise in the normal state. Note the consistent congruence in the talonavicular (A), calcaneocuboid (B) and subtalar (C) joints. Also note that the alignments of the medial arch relationship, and specifically the calcaneal pitch, which increases in the sagittal plane during heel rise. This is in distinction from the arthritic images shown later in fig. 2.5.

The anatomic structures, particularly the plantar fascia, and the midfoot joints, produce a coupled motion between the different segments of the foot.\textsuperscript{167,171} This implies that during the predictable motions of heel rise, motions of the hindfoot produce predictable motions, in predictable proportions, of the mid and
forefoot. This "automatic" (or passively driven) coupled motion provides a critical component to the mechanical and energetic efficiency during the task of heel rise. Ultimately these motions are powered by inertia from previous movement in the gait cycle, and by muscular contraction. The actions of the tibialis posterior, the Achilles’ tendon and to a lesser extent the intrinsic musculature of the foot and peroneal muscles provide needed additional force and guidance to continue the gait cycle. The normal function of these muscles, similar to the passive structures, is also critically important for the progression through heel rise to toe-off. This is well supported by clinical findings from some disease states, specifically in the settings of pes planus as well as Achilles tendon pathology.

Due to the clinical importance of this activity, as well as the recognized anatomical structures responsible for its motion, heel rise has been studied closely in both in vitro and in vivo. Previous research has shown that the high degree of coordinated motion, mediated by bony alignment, exact articular relationships as well as the ligaments of the mid- and hindfoot, is responsible for a significant proportion of the observed motion of the hindfoot during heel rise. Furthermore, the contribution of active contraction of muscles plays a critical role in the coordination and function of heel rise. Despite the fact that tracking the motion and activation of these individual bones and muscle groups in vivo in the midst of this complex motion is not easily performed, a significant body of literature surrounds this event in the gait cycle.
Furthermore, it is theorized and has been demonstrated that the hindfoot, through the movement of its constituent joints, is able to compensate for disease. In the setting of ESOA, this has been specifically demonstrated during the heel rise motion, where normal motion between the hindfoot and forefoot has been observed to be significantly effected. As was mentioned previously, a significant portion of motion still occurs in the hindfoot following ankle fusion in vitro. In the setting of successful ankle fusion, Sealey et al observed radiographic increases in subtalar motion in vivo. This significant (10.8%) increase was thought to be a compensation for the fused ankle, and this prospective increase in motion was termed "hypermobility." This has been theorized to be of specific importance in the case of ESOA where significantly improved and surprisingly normal gait can occur after definitive procedures (i.e. ankle fusion) that take away significant motion. These findings are in powerful distinction to the (in some cases pre-operative) arthritic state. How this surprisingly normal gait in the presence of a fused tibiotalar articulation is accomplished, is not well understood beyond the observations mentioned above. Although considerable peritalar joint changes, specifically the association with peritalar arthritis with ESOA both pre and post-treatment have been demonstrated and are theorized to be at least in part responsible for this. Understanding and characterizing a clinically significant motion like heel rise in the setting of ESOA in vivo would likely shed significant light as to how the hindfoot compensates for abnormal motion in the setting of ESOA. Furthermore, gaining a more detailed understanding of how the constituent
portions of the normal lower leg-hindfoot-forefoot mechanism are altered or affected by arthritis would likely help in understanding how the hindfoot adapts to ESOA.
Chapter 2.4 – The effect of Osteoarthritis on Ankle Mechanics and Gait

Although attempting to determine the overall prevalence of the ESOA is difficult, it has been observed that the number of patients with ESOA is increasing. While research has demonstrated the pain experienced by ESOA patients, the amount of disability individuals with ESOA experience has not been so well evaluated. The aspects of their day-to-day lives that give them the most trouble, or the activities that they simply are not able to perform due to the pain and stiffness from their ESHA have not been well described. This has been echoed in a recent rigorous review of the current patient questionnaires and rating scales that are in use commonly. Qualitative research that has occurred at our institution (St Michael’s Hospital, Toronto, ON, Canada) has shown, with preliminary results, that patients with ESOA have significant difficulty with the heel rise event. This clinically manifests itself as a very noticeable limp, as well as other functional limitations. (I.e. – difficulty navigating stairs)

The true impact of ESOA on the variables of gait and how the hindfoot functions during these specific events have only recently received specific attention in the scientific literature. These studies have been largely selected and modeled after the formative analyses performed on normal controls. These studies predominantly used formal gait analysis that, as discussed previously, use force plates for pressure measurement,
optical and digital tracking systems to measure joint motion, gait symmetry and gait velocity, and in some cases, EMG to measure muscle activity throughout the gait cycle.\textsuperscript{21,93,196}

This independent research has all shown significant effects of ESOA on gait in human subjects. Specifically, Valderrabano et al, Khazzam et al, and Brodsky et al have all shown shortened stride length, decreased walking velocity, and walking cadence in the setting of ESOA.\textsuperscript{21,93,196} Significant decreases in range of motion, specifically sagittal plane motion (or dorsi- and plantar-flexion of the ankle) as well as transverse plane motion were observed.\textsuperscript{93,196} Although these variables remain constantly observed, others have shown some inconsistency. Stance phase length has been recorded as trending to be, but not significantly longer (p > 0.001),\textsuperscript{21,93} and as significantly shorter. (p = 0.01)\textsuperscript{196} Reasonable explanations for both have been offered. Khazzam et al examined the biomechanical evaluation of the foot, utilizing 12 markers about the foot and ankle, allowing for biomechanical evaluation of the hindfoot, forefoot and hallux as independent segments.\textsuperscript{93} Using the data from this analysis, they were able to detect decreased rigidity of the lever arm of the foot, which caused a decreased biomechanical advantage for the foot at push off in their 35 studied foot and ankles in 34 patients. This then lead to decreased forward motion during heel rise and push off, and, in their minds, contributed to the trend to prolonged stance phase that they observed. Valderrabano et al, however, explained the statistically significant \textit{decreased} stance phase time in the 15 ankles in 15 patients that they studied as likely due to “the presence of joint pain and the
protective strategy to reduce loading in the arthritic joint.” This dichotomy in conclusions from what should be a very similar patient population creates many questions. As there was no formal power analysis completed on the stance phase analysis from either study, though, no definitive conclusions from either study can be made.

This particular research highlighted the complexity in the response of the human foot and ankle to ESOA. At least part of this complexity likely arises from the compensatory mechanism of the hindfoot and the movement of its constituent joints. In the setting of ESOA, this has been specifically demonstrated during the heel rise motion, where normal motion between the hindfoot and forefoot has been observed to be significantly effected. This has been theorized to be of specific importance in the case of ESOA where significantly improved and surprisingly normal gait can occur after definitive procedures (i.e. ankle fusion) that take away significant motion. These findings are in distinction to the (in some cases pre-operative) arthritic state. How this surprisingly normal gait in the presence of a fused tibiotalar articulation is accomplished, is not well understood. Although considerable peritalar joint changes have been demonstrated and are theorized to be at least in part responsible for this, there still is a wide gap in the understanding of the kinematics of normal heel rise in the setting of ESOA. (See figures 2.6, 2.7 and 2.8)
Fig 2.7 – The appearance of the joints and osseous components of the hindfoot during heel rise in the arthritic state. Note the significant alterations in the talonavicular (A), calcaneocuboid (B) and subtalar (C) joints. Also note that the alignments of the medial arch relationship, and specifically the calcaneal pitch, which remains relatively static. This is in distinction from the normal images shown previously in Fig 2.4.
Figure 2.8 – Likely as, at least in part, a result of the diminished tibiotalar joint motion (white arrow), significant differences in the observed motion of the talonavicular (A), calcaneocuboid (B) and subtalar (C) joints can be observed in the arthritic (A) versus the normal (B) state. Also note that the alignments of the medial arch relationship, and specifically the calcaneal pitch, which remains relatively flat in the arthritic state.

Although some attempts have been made to correlate objective gait characteristics to specific activities of daily living (or ADLs)\textsuperscript{31} these have been preliminary and limited to in-direct measures of disability. Most studies have used gait velocity as the outcome of primary interest. This is likely in part due to the fact that gait velocity has been independently shown to reflect the function of the other joints in the lower extremities and pelvis,\textsuperscript{14} and to indirectly represent disability in elderly populations.\textsuperscript{149} Other indirect measures of functional ability, like the “Timed Get-Up and Go” test and the 4-square step test have been done; but, they remain indirect performance measures.\textsuperscript{149,202} Other previously used performance tests such as the
6-minute walk; the self-paced walk; and the stair-test have not been utilized in the setting of ESOA. The timed get-up and go and the 4-square step test have been found to have poor correlation with other evaluation methods of patient’s functional abilities.\textsuperscript{31} The research was preliminary, however, and in the knee these measures, have been shown to be predictive of physical capacity, while allowing for a more comprehensive assessment of well being in patients with osteoarthritis.\textsuperscript{180} But these timed tests, alone have been shown to inadequately measure functional status as a whole.\textsuperscript{179} Correlated patient outcomes scores, are likely required for a more global assessment. It is important to note that literature linking these tests of performance and global patient assessments is lacking for ESOA.

Biomechanically and functionally, ESOA has a significant effect on the gait of normal individuals.\textsuperscript{1,35,175} It has been demonstrated that this abnormal gait is the result of both pain, from the arthritis itself, as well as likely also from the biomechanical disturbances cause from the abnormal motion of the ankle.\textsuperscript{1,35,196} As previously mentioned, gait research in the setting of ankle fusion for ESOA has shown significant improvements in gait.\textsuperscript{183} Given these results, it has been increasingly understood that the gait disturbances from pain may in fact be one of the most significant drivers for the abnormalities seen in gait in patients suffering with ESOA.\textsuperscript{196} The effect of this combined source of difficulty, however, is what is clinically important. This is what is combining to cause the disability that causes patients to seek treatment by OFAS. More fully understanding the functional effects that ESOA has on the foot and ankle, and specifically the hindfoot-shank and
hindfoot-forefoot kinematic mechanism would provide a crucial advance into beginning to, in a more evidence-based way, approach the treatment of this debilitating condition in a rationale way.
2.5 - Research Aims and Hypotheses

2.5.1 – Research Aims

Understanding and characterizing a clinically significant motion like heel rise in the setting of ESOA *in vivo* would likely shed significant light as to how the hindfoot compensates for abnormal motion in the setting of ESOA. Furthermore, gaining a more detailed understanding of how the constituent portions of the normal lower leg-hindfoot-forefoot couple are altered or affected by arthritis would likely help in understanding how the foot and ankle adapts to ESOA. This would advance the current understanding of the true impact of ESOA on foot and ankle motion. Getting a more detailed and realistic understanding of how the constituent parts of the lower limb and foot are affected by ESOA could better inform diagnosis and treatment of this condition.

The purpose of this thesis was to document the *in vivo* motion of the segments of the foot and lower leg during bilateral (or “double limb”) heel rise in the normal, aged and arthritic states.

2.5.2 – Hypotheses

The null hypotheses were:
(1) The absolute motion occurring between the shank-hindfoot and hindfoot-forefoot segments is unaffected by ESOA.

(2) The coupling relationships between shank-hindfoot and hindfoot-forefoot motion are unaffected by ESOA.
CHAPTER 3

METHODS

3.1 – Studied Population identification & ethical recruitment

3.1.1 – Research Ethics Board approval and the consent process

Research Ethics review board approval was obtained prior to the conduct of this study. All subjects provided informed consent, and a final pre-study confirmation of consent. This involved a documented process by which the understanding of the proposed study was probed and in most cases enhanced prior to participation in the study.

3.1.2 - Healthy Normal Subjects

Between June and November of 2012, 15 healthy subjects were recruited and enrolled in this study. The subjects were all between the ages of 18 and 40 and had no identified foot and ankle, orthopaedic or related medical condition that precluded normal gait. Relevant demographic information was collected to ensure comparative populations were compared.
3.1.3 - Arthritic and matched subjects

Seven individuals with end-stage ankle arthritis, identified through an orthopaedic foot and ankle surgery clinic, were recruited to participate. Inclusion and exclusion criteria outlined in Table 3.1 were applied to each potential subject. Relevant demographic and clinical information was collected to ensure comparative populations were studied, and that a representative sample of ankle arthritis was chosen. Immediately prior to the gait analysis, a fellowship-trained orthopaedic foot and ankle surgeon clinically examined all subjects. This ensured no subjects with undiagnosed pathologic conditions of the foot and ankle were inadvertently included in the study.

Following completion of the data collection, the seven arthritic individuals were age and sex-matched to six healthy volunteers. Two individuals with ankle arthritis were the same age and sex and were matched to the same control subject. Similar exclusion criteria were applied, and a similar pre-study examination by a fellowship-trained orthopaedic foot and ankle surgeon was performed. One matched individual with undiagnosed arthritis of the first metatarsophalangeal joint and individual with coronal deformity of the lesser toes were identified. Both individuals were excluded. An additional individual was recruited giving seven arthritic individuals and to six age and sex matched individuals.
Table 3.1 - The Inclusion and exclusion criterion applied

<table>
<thead>
<tr>
<th><strong>Inclusion criteria</strong></th>
<th><strong>Exclusion criteria</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis of ankle osteoarthritis</td>
<td>Bilateral ankle disease</td>
</tr>
<tr>
<td>Preexisting diagnosis of orthopaedic condition</td>
<td>History of operatively or non-operatively treated condition of the foot and ankle</td>
</tr>
<tr>
<td>(previously treated or not)</td>
<td>bilaterally</td>
</tr>
<tr>
<td>affecting the back and lower extremities</td>
<td>History of inflammatory arthropathy</td>
</tr>
<tr>
<td>History of operatively or non-operatively</td>
<td>History of neuropathy of the feet and ankles (including a diagnosis of diabetic</td>
</tr>
<tr>
<td>treated condition of the foot and ankle</td>
<td>neuropathy either known or demonstrated on sensory examination immediately prior to the</td>
</tr>
<tr>
<td>bilaterally</td>
<td>trial)</td>
</tr>
<tr>
<td>History of any recognized medical condition</td>
<td>History of any recognized medical condition affecting balance</td>
</tr>
<tr>
<td>affecting gait</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 - Instrumentation and data collection:

Motion of the foot and ankle complex was tracked according to a three-dimensional multi-segment foot model validated by Leardini et al.\(^1\)\(^1\)\(^2\) (See Figure 2.2). According to this model, infrared emitting diodes (IREDs) were skin mounted directly over subcutaneous landmarks by a fellowship-trained orthopaedic foot and ankle surgeon (see Table 3.2). Additionally, clusters of four IREDs were secured bilaterally on the shank and hallux segments.\(^1\)\(^0\),\(^1\)\(^2\) Finally, an instrumented probe embedded with four IREDs fixed relative to the tip identified virtual landmarks representing locations on the hallux and shank segments not tracked directly with markers, from a static standing reference trial.
Throughout the heel rise task, bilateral kinematic data were acquired at a sampling rate of 60 Hz using four active optical motion capture camera banks (Phoenix Technologies Inc., Burnaby, BC) positioned around the subject (see Figure 3.1 and Figure 3.2). Bilateral data were collected for all three groups. In addition to the heel rise data, subjects were asked to ambulate across level and sloped surfaces instrumented with multiple force platforms. This was performed using the identical marker and motion-capture set up. For the purposes of the thesis these data will not be included in the analysis. (See Figure 3.1)

Figure 3.1 - A standard modern gait analysis facility. Cameras are located throughout the facility (in the four sides of the analysis area in this photo) to allow for fluid and reliable collection of data. The floor is also equipped with force plates, which allow the simultaneous collection of kinetic data as well.
Figure 3.2 - A schematic diagram of the experimental set-up highlighting the dimensions of the setup and optical tracking camera location.
Table 3.2 - The locations of the skin-mounted markers placed by the orthopaedic foot and ankle surgeon.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Location of included landmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forefoot</td>
<td>Medial head of 1(^{st}) MT</td>
</tr>
<tr>
<td></td>
<td>Medial base of 1(^{st}) MT</td>
</tr>
<tr>
<td></td>
<td>Lateral head of 5(^{th}) MT</td>
</tr>
<tr>
<td></td>
<td>Dorsal skin surface above 2(^{nd}) MT joint</td>
</tr>
<tr>
<td>Midfoot</td>
<td>Navicular Tuberosity</td>
</tr>
<tr>
<td></td>
<td>Base of the 5(^{th}) MT</td>
</tr>
<tr>
<td></td>
<td>Base of 2(^{nd}) MT</td>
</tr>
<tr>
<td>Hindfoot</td>
<td>Superior aspect of the Calcaneal Tuberosity</td>
</tr>
<tr>
<td></td>
<td>Sustentaculum tali</td>
</tr>
<tr>
<td></td>
<td>Peroneal tubercle</td>
</tr>
</tbody>
</table>
Table 3.3 - Reference-landmarked sites required for the rigid body-tracked segments

<table>
<thead>
<tr>
<th>Segment</th>
<th>Landmarked Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hallux Segment</td>
<td>Medial head of proximal phalanx of 1st toe</td>
</tr>
<tr>
<td></td>
<td>Lateral head of proximal phalanx of 1st toe</td>
</tr>
<tr>
<td></td>
<td>Medial base of proximal phalanx of 1st toe</td>
</tr>
<tr>
<td>Shank Segment</td>
<td>Medial malleolus</td>
</tr>
<tr>
<td></td>
<td>Lateral Malleolus</td>
</tr>
<tr>
<td></td>
<td>Medial femoral epicondyle</td>
</tr>
<tr>
<td></td>
<td>Lateral femoral epicondyle</td>
</tr>
</tbody>
</table>
Figure 3.3 – (TOP) A side view of the heel rise event. (BOTTOM) A posterior view of the heel rise event.
Table 3.4 - Marker locations and segment coordinate system definition from the IOR/Leardini et al model. (excluding shank segment)

<table>
<thead>
<tr>
<th>Model</th>
<th>Hindfoot</th>
<th>Midfoot</th>
<th>Forefoot</th>
<th>Hallux</th>
</tr>
</thead>
</table>
| Leardini Foot Model (Leardini et al., 2007) | Tracking marker locations:  
- Calcaneus (CA)  
- Medial apex, Sustentaculim Tali (ST)  
- Lateral apex, Peroneal Tubercle (PT)  

SCS:  
- Origin: CA  
- x-axis: joins origin with mid-pt between ST & PT  
- z-axis: lies in transverse plane defined by x-axis and ST  
- y-axis: orthogonal to x-z plane | Tracking marker locations:  
- Apex, Navicular Tuberosity (TN)  
- Apex, Cuboid Tuberosity (TC)  
- Prominence, dorsal aspect Middle Cuneiform (MC)  
(assumed to coincide with base of 2nd metatarsal, SMB)  

SCS:  
- Origin: mid-pt between TC and TN  
- x-axis: joins origin with MC  
- z-axis: lies in transverse plane defined by x-axis and TN  
- y-axis: orthogonal to x-z plane | Tracking marker locations:  
- Head of 1st metatarsal (FMH), dorso-medial aspect of 1st MTP jt.  
- Head of 2nd metatarsal (SMH), dorso-medial aspect of 2nd MTP jt.  
- Base of 2nd metatarsal (SMB), dorso-medial aspect of 2nd metatarsal-cuneiform jt.  
- Head of 5th metatarsal (VMH), dorso-medial aspect of 5th metatarsal-cuboid jt.  

SCS:  
- Origin: SMB  
- x-axis: joins origin with SMH, on transverse plane defined by origin, FMH, VMH  
- z-axis: lies in transverse plane as defined above, orthogonal to x-axis  
- y-axis: orthogonal to x-z plane | - ** Motion of hallux determined using planar angles (ie. angle between 2D orientation of line segments)  
- ** Line segments representing 1st, 2nd and 5th metatarsal bones permit calculation of additional planar angles also reported for this model |
3.3 – Performance of the heel rise

Once instrumented and landmarked, and following a trial of gait each subject was asked to go into a double limb heel rise. (See Figure 3.3) Specific verbal instructions were supplied to the individual. A demonstration of a normal double limb heel rise was performed for each subject. The subjects were then asked to perform this heel rise to their own personal maximal capacity at a rate comfortable for them. The subjects were instructed to not attempt to maintain maximal heel rise. They were instead told to simply go up until they reached their comfortable maximum and then immediately begin the downward portion of the activity. They were asked to reproduce this motion four times. Verbal cues of “up,” “down,” and “rest” were given to each subject on the first trial to re-enforce the requested motion. The rest portion in between each heel rise event was for a minimal of two seconds for healthy normal and matched controls. It is important to note that the subjects were offered longer rest periods when necessary, and in the arthritic group, the rest periods were notably longer. (Although not timed) This was done to ensure that each individual heel rise event was as unaffected by the previous one as possible.

3.4 - Data processing and analysis:

3.4.1 – General data processing and analysis

All kinematic data were interpolated and filtered (fourth order, low pass, Butterworth, cutoff frequency 6 Hz) using post-processing software (Visual 3D, C-
Motion, Inc., Rockville, MD). Reference frames of the individual segments of the foot (Hindfoot, midfoot, forefoot and hallux) were defined as previously described.\textsuperscript{10,11} (See Table 3.4) The shank segment was defined using the probed landmark locations identifying the proximal and distal end of the segment (epicondyles and malleoli, respectively). All reference frames were oriented such that motion about the x, y and z axes represented flexion/extension, abduction/adduction and transverse rotations, respectively. During resting stance, a mean of the position of the calcaneal markers was taken. Initiation of the task was then determined when vertical displacement of the calcaneus marker exceeded two standard deviations above the mean baseline or resting stance position. Completion of task was identified as the minimum vertical position of the calcaneus marker. Data were time-normalized to 100\% of the heel rise portion of the task. Data are reported for the dominant side (healthy adults), dominant and non-dominant sides (matched controls) as well as for affected and non-affected sides (arthritis subjects).

3.4.2 – Analysis of kinematic data from the Heel Rise

For the purposes of this study, three-dimensional rotations were calculated using Visual 3D (C-Motion, Inc., Rockville, MD) between the shank-hindfoot, and hindfoot-forefoot segments. Joint angles were normalized to a static standing reference trial. This practically meant that all marker displacements were determined relative to the static stance position. Sagittal and frontal plane peak values and joint ranges of motion (ROM) were obtained from the individual angular displacement profiles and then averaged for each subject.
3.5 – Kinematic coupling analysis

Kinematic coupling ratios were used to assess the relationship between the motion of the shank-hindfoot and the hindfoot-forefoot segments in specific planes of motion during the heel rise task. Consistent with previous work, coupling ratios were determined as the absolute change in the total observed range of motion over a specified interval (or the observed difference between the maximum and minimum, or peak, relative segment positions from a specified start to end point)\textsuperscript{137,205}

Two main coupling relationships were quantified. They were completed using the previously utilized methods published in the orthopaedic literature. The path of motion of the proximal segment (from the point of initiation of heel rise, to the point of maximal displacement) in a plane of interest was divided by the path of motion of the distal segment in a plane of interest. The first coupling ratio assessed axial rotation of the shank coupled with coronal plane motion of the hindfoot.

\[ \text{Coupling Ratio} = \frac{\text{Shank (axial path of motion)}}{\text{Hindfoot (frontal path of motion)}} \]

Axial rotation of the shank segment was determined as the motion of the shank with respect to the hindfoot in the transverse plane. Hindfoot inversion/eversion was determined as the coronal plane motion of the hindfoot expressed relative to the
shank. Coupling ratios less than one indicates greater motion of the hindfoot compared to axial rotation of the shank.

Sagittal plane motion of the hindfoot coupled with sagittal plane motion of the forefoot was also evaluated. Sagittal plane motion of the forefoot was expressed relative to the hindfoot, whereas sagittal plane motion of the hindfoot was determined with respect to the shank.

Coupling Ratio = Hindfoot (sag. path of motion) ÷ Forefoot (sag. path of motion)

Coupling ratios less than one indicates greater forefoot motion compared to hindfoot motion during the specified interval.

3.6 - Statistical Analysis

Descriptive statistics (means and standard deviations) were calculated for all outcome measures (SPSS version 21.0, San Rafael, CA). Differences in categorical data were compared using a χ² test of independence analysis between the arthritic and age and sex-matched control group. Because four trials were utilized per trial, a two-way ANOVA for repeated measures was utilized to analyze the heel rise data. Levene's test for equality of variances was applied to each data set. In cases where the three groups were compared, this was performed utilizing a one-way between groups ANOVA. The level of statistical significance was set a p < 0.05 for all analyses.
CHAPTER 4
RESULTS

4.1 – Study population demographics and clinical characteristics

The clinical characteristics of the recruited subject with ankle arthritis are included in table 3.5. The average age of the arthritic group was 66 ± 7.94, while in the control group the average was 67 ± 8.85; p = 0.83. The average age for the young control group was 29.6 ± 3.73. This represented a statistically significant difference from the other two groups. (p < 0.001) A similar distribution of comorbidities was noted in the matched control group and in the arthritic group, indicating that as a group there was not likely any specific confounding influence from comorbidities on the gait of the studied groups. The calculated body mass index (or BMI) for the arthritic group was 27.8 ± 1.8kg/m², while the BMIs for the matched control group and young control group were, 26.2 ± 2.62 kg/m² and 24.1 ± 3.24 kg/m² (p = 0.16) respectively. This represented a non-significant difference between the matched and arthritic groups (p = 0.36), as well as between control groups. (p = 0.20)

The causative etiology of the ankle arthritis studied resembled the reported clinical norm, with the majority of cases (5/7, 71%) being a result of post-traumatic ankle arthritis.195 (See table 4.1) The hindfoot alignment of the majority (5/7, 71%) of arthritic ankles presented in either neutral or physiologic hindfoot valgus. The remaining two (29%) had more significant (> 10°) clinical valgus deformity. This
was somewhat different from the matched control group, who all present in neutral –physiologic valgus alignment.

Table 4.1 - Clinical characteristics of included subjects with ankle osteoarthritis

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>Age</th>
<th>Sex</th>
<th>Side</th>
<th>Diagnosis</th>
<th>Clinical History</th>
<th>Comorbidities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>73</td>
<td>M</td>
<td>L</td>
<td>PTOA</td>
<td>Long history of multiple ankle sprains</td>
<td>colon CA (remote), prostate CA (remote), hernia repair (6 mos previous), Cholelithiasis, HTN</td>
</tr>
<tr>
<td>2</td>
<td>59</td>
<td>M</td>
<td>L</td>
<td>PTOA</td>
<td>Remote ipsilateral tibial fracture</td>
<td>HTN</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>M</td>
<td>L</td>
<td>PTOA</td>
<td>Remote #/dislocation of ankle</td>
<td>Nil</td>
</tr>
<tr>
<td>4</td>
<td>74</td>
<td>M</td>
<td>L</td>
<td>PTOA</td>
<td>Long history of multiple ankle sprains</td>
<td>Nil</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>M</td>
<td>R</td>
<td>Stage IV</td>
<td>Slow deterioration of ankle over years.</td>
<td>HTN</td>
</tr>
<tr>
<td>6</td>
<td>72</td>
<td>F</td>
<td>R</td>
<td>Post Septic arthritis</td>
<td>Generalized sepsis that seeded ankle joint. (3 years ago)</td>
<td>Hypothyroidism, osteoporosis</td>
</tr>
<tr>
<td>7</td>
<td>58</td>
<td>M</td>
<td>L</td>
<td>PTOA</td>
<td>Remote Open Ankle # (1973). Slow deterioration x 2 years</td>
<td>CAD, HTN, T2DM, GERD, HC, mild obesity</td>
</tr>
</tbody>
</table>

*PTOA = post-traumatic osteoarthritis, # = fracture, CAD = coronary artery disease, HTN = hypertension, T2DM = type II diabetes mellitus, HC = hypercholesterolemia, GERD = gastro-esophageal reflux disease, CA = cancer*
Figure 4.1 – An example of the clinical and radiographic appearance of an included case with ankle osteoarthritis. (A) antero-posterior; (B) lateral/side; (C) and posterior/heel alignment views are depicted. All views of the ankle show evidence of ankle arthritis - subchondral sclerosis (intense whitening of the distal tibia and superior talus on the radiographs), anterior osteophytes (or new bone formation) and subchondral cysts of the distal tibia and talar body.
4.2. - Kinematic Data

4.2.1 - Shank - Hindfoot segment motion

The range of motion of the hindfoot relative to the shank was significantly affected by the presence of osteoarthritis of the ankle versus sex and age matched individuals. (see Table 4.2) This loss of 12.4° of motion occurred in both the sagittal (7.3 ± 2.6° versus 19.8 ± 4.2°) as well as 8.6° in the frontal plane. (7.7 ± 2.6° versus 16.3 ± 3.4°) These differences were both statistically significant. (p < 0.001, and p = 0.001, respectively) Age did not seem to have any effect on the total range of motion in either plane.

Plantarflexion sagittal plan range of motion was more drastically affected by arthritis, with peak plantarflexion being 19.5 ± 6.9° in the normal group, and 5.8 ± 8.0° in the arthritic group. (p = 0.01) Dorsiflexion range or motion was somewhat preserved. Peak dorsiflexion was 1.5 ± 6.6° in the arthritic group and 0.2 ± 6.1° in the normal group (p = 0.77). Similarly to range of motion, some loss of peak plantarflexion (1.27°) and dorsiflexion (2.32°) was noted in the control subjects compared to the young healthy subjects.
Table 4.2 - Hindfoot-shank angle (degrees) of the double-limb heel rise task in patients with arthritis (affected side), age/sex-matched controls, and healthy young controls (mean (standard deviation)).

<table>
<thead>
<tr>
<th></th>
<th>Sagittal plane</th>
<th>Frontal Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Dorsiflexion</td>
<td>Peak Plantarflexion</td>
</tr>
<tr>
<td>Arthritis Group</td>
<td>1.5 (6.6)</td>
<td>5.8 (8.0)*</td>
</tr>
<tr>
<td>Matched Control</td>
<td>0.2 (6.1)</td>
<td>19.5 (7.0)*</td>
</tr>
<tr>
<td>Young Control</td>
<td>3.8 (3.5)</td>
<td>21.1 (4.7)</td>
</tr>
</tbody>
</table>

* - indicates a significant difference between arthritis and matched control groups (p<0.05)
† - indicates a trend towards significant difference between arthritis and matched controls (p<0.1)
N.B. - No significant differences were found between matched control and young control groups

In the frontal plane, the range of motion was reduced in inversion, with peak inversions of 15.6 ± 5.5° being observed in the control group and 7.9 ± 7.0° in the arthritic group (p = 0.05). This was a greater reduction than noted in eversion, where 0.6° was noted to be lost in the presence of ankle osteoarthritis. (0.8 ± 4.3° in the control group versus 0.19 ± 5.3° in the arthritic group, p = 0.74) No differences in frontal plane range of motion (12.8 ± 4.1°; p = 0.12), peak inversion (10.5 ± 4.7°; p = 0.10) or eversion (2.3 ± 2.4°; p = 0.44) were noted in the aged control groups versus the young healthy group.

The direction of motion was also considered. In both the sagittal (Figure 4.2) and coronal planes (Figure 4.3) the direction of motion was relatively consistent between the normal and arthritic states. Ankles with ESOA started, and ultimately
returned to, on average, a position of slight dorsiflexion (1.2 +/- 6.6). This position was not significantly different from the matched control group (-0.38 +/- 6.2; p =0.74). In the coronal plane, both groups began and ultimately returned to a position of close to heel-neutral. No differences were noted between the young adult control and age- and sex-matched controls regarding the directions of motion during heel rise.

Figure 4.2 – The sagittal plane motion (degrees) occurring between the shank and the hindfoot during heel rise. Plantarflexion is denoted as negative displacement. The depicted lines, as in the figures 4.3-4.5, represent 1 SD about the observed mean.
Figure 4.3 - The coronal plane motion (degrees) occurring between the shank and the hindfoot during heel rise. Inversion is denoted as positive displacement.

4.2.2 - Hindfoot-forefoot kinematic data

The total range of motion for the hindfoot and forefoot were also significantly affected by the presence of ankle arthritis in both the sagittal (8.97 ± 4.15° in the arthritic group versus 18.3 ± 4.7° in the control group) and in the coronal planes. (see Table 4.3) (3.86 ± 1.45° in the arthritic group versus 11.88 ± 5.65° in the control group) These findings were significant in both the sagittal (p = 0.01) and coronal planes. (p = 0.02) There were no observed differences of significance noted...
in the aged controlled subjects versus the younger control group in either the sagittal \((17.23 \pm 5.46; p = 0.72)\) or frontal plane. \((7.32 \pm 3.54; p = 0.13)\)

Table 4.3 - Hindfoot-forefoot angle (degrees) of the double-limb heel rise task in patients with arthritis (affected side), age/sex-matched controls, and healthy young controls (mean (standard deviation)).

<table>
<thead>
<tr>
<th></th>
<th>Sagittal plane</th>
<th></th>
<th>Frontal Plane</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Dorsiflexion</td>
<td>Peak Plantarflexion</td>
<td>Range of motion</td>
<td>Peak Inversion</td>
</tr>
<tr>
<td><strong>Arthritis Group</strong></td>
<td>3.05 (3.16)</td>
<td>5.92 (4.40)*</td>
<td>8.97 (4.15)*</td>
<td>0.63 (4.80)</td>
</tr>
<tr>
<td><strong>Matched Control Group</strong></td>
<td>2.13 (6.17)</td>
<td>16.15 (7.78)*</td>
<td>18.28 (4.67)*</td>
<td>4.94 (3.85)</td>
</tr>
<tr>
<td><strong>Young Control Group</strong></td>
<td>4.48 (4.10)</td>
<td>12.75 (5.38)</td>
<td>17.23 (5.46)</td>
<td>3.95 (4.95)</td>
</tr>
</tbody>
</table>

* - indicates a significant difference between arthritis and matched control groups \((p<0.05)\)

α - indicates a significant difference between matched control and young control groups \((p<0.05)\)

In the sagittal plane, plantarflexion range of motion was preferentially affected by the presence of ankle arthritis. The peak plantarflexion angle noted was 16.15 ± 7.78° in the control group and was 5.92 ± 4.4° in the arthritic group. This difference was statistically significant. \((p = 0.03)\) Dorsiflexion range of motion, like in the shank-hindfoot segment, was increased in the arthritic group. Peak dorsiflexion was 3.05 ± 3.16° in the arthritic population versus 2.13 ± 6.17° in the control group. This difference was not statistically significant. \((p = 0.94)\) Similarly differences in peak plantarflexion (3.4°) and dorsiflexion (2.35°) noted between the young versus aged controls were not significant. \((p = 0.37\) and \(p = 0.43\), respectively)
In the coronal plane, differences in eversion and inversion ranges of motion were relatively evenly distributed. Peak inversion was 0.6 \pm 4.8^\circ in the arthritic group and 4.9 \pm 3.9^\circ in the control group. This did not represent a significant difference. (p = 0.15) In eversion, a peak angle of 3.2 \pm 3.5^\circ was noted in the arthritic group, this is compared to 6.9 \pm 3.2^\circ in the control group. The differences noted were not significant. (p = 0.12) The peak ranges of motion in the young control group were noted to be smaller in both inversion (4.0 \pm 5.0^\circ) and eversion. (3.4 \pm 2.6^\circ) The difference were not significant in inversion, (p = 0.7) but was statistically significant in eversion. (p = 0.05)

The direction of the motion between the hindfoot and forefoot segments produced notable findings. In the coronal plane the pattern of motion was exactly reversed in the arthritic versus the healthy normal state. (See Figure 4.4) Initial eversion gave way to inversion during the heel rise event. This is the opposite of what was observed in the matched subjects. In the sagittal plane, this motion was not reversed, but noted to be comparatively restricted in the arthritic state. (Figure 4.5) Age appeared to have no effect on the direction or observed magnitude on the observed motion in the foot.
Figure 4.4 - The coronal plane motion (degrees) occurring between the hindfoot and the forefoot during heel rise. Inversion is denoted as positive displacement. Here the reversal or “flipping” of the expected relationship of the forefoot to the hindfoot in the coronal plane was observed.
Figure 4.5 – The sagittal plane motion (degrees) occurring between the shank and the hindfoot during heel rise. Plantarflexion is denoted as negative displacement.

4.3 – Kinematic Coupling Data

4.3.1 – The Shank-Hindfoot couple

No significant relationships in motion between the hindfoot in the frontal plane (inversion-eversion), relative to motion in the shank in the axial plane (internal and external rotation) were demonstrated. The presence of ankle arthritis (see Figure 4.6) similarly showed no statistically significant evidence of a coupling relationship (p = 0.35; see table 4.4 and Figure 4.6).
Table 4.4 – The demonstrated coupling ratios of shank (axial plane range of motion) versus hindfoot (frontal plane range of motion) and hindfoot (sagittal plane range of motion) versus forefoot (sagittal plane range of motion) motion.

<table>
<thead>
<tr>
<th>Coupling ratio</th>
<th>Arthritis Group</th>
<th>Matched Control Group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial rotation of shank and coronal plane motion of hindfoot – Coupling ratio</td>
<td>0.64 (0.16)</td>
<td>0.54 (0.20)</td>
<td>0.365</td>
</tr>
<tr>
<td>Sagittal plane motion of forefoot and sagittal plane motion of hindfoot – Coupling ratio</td>
<td>0.94 (0.57)</td>
<td>1.23 (0.51)</td>
<td>0.394</td>
</tr>
</tbody>
</table>

4.3.2 – *The hindfoot-forefoot couple*

No strong evidence of coupled motion between the hindfoot and forefoot in the sagittal plane was demonstrated. (See Table 4.4) The differences in the coupling relationship between the arthritics and the matched populations were not statistically significant. When the data were plotted, however, in the arthritic populations there was more observed forefoot versus hindfoot motion, which placed the distribution of points above the 1:1 line. This was reversed in the matched group, which demonstrated a predilection for more hindfoot than forefoot motion during the heel rise motion. (see Figure 4.7)
Figure 4.6 - Individual subject data indicating the coupling response (absolute change over the interval) of the axial rotation of the shank segment and coronal plane motion of the hindfoot from the start of the heel rise task to maximum inversion of the hindfoot. The diagonal line represents a theoretical one-to-one coupling relationship of the segments.
Figure 4.7 - Individual subject data indicating the coupling response (absolute change over the interval) of the sagittal plane motion of the hindfoot and sagittal plane motion of the forefoot from the start of the heel rise task to maximum plantarflexion of the forefoot. The diagonal line represents a theoretical one-to-one coupling relationship of the segments.
CHAPTER 5
DISCUSSION

5.1 – The measured effect of ESOA on hindfoot kinematics

5.1.1 – Hindfoot kinematics in relation to the motion of the shank and forefoot

The main and novel findings from this research were the effects that ESOA had on motion of the foot and ankle during heel rise. Specifically, restrictions in motion as well as the changes in the directions of motion of the hindfoot and forefoot segments were observed. This presents an interesting question. Is this alteration in the kinematic function of the foot caused by the ESOA, or is the ESOA a result of the altered kinematics? The etiology of ESOA is, in the majority of cases, caused by traumatic injuries to the foot and ankle. These traumatic injuries result in direct cartilaginous injury, altered bony relationships (e.g. – mal-united tibial fracture), altered ligamentous function (e.g. – syndesmotic injury leading to chronic ligamentous insufficiency of the ankle), or a combination of the above. Following traumatic injuries such as these, altered kinematics of the injured foot and ankle are often an expected result of the injury itself, and in some cases as a complication of the treatment required to treat the injury. (e.g. – long periods of immobilization, etc) In such cases, the changes in the kinematic relationship observed following the eventual development of arthritis could be, at least, in part due to the altered kinematic relationships that result from the injury itself, rather than from the
subsequent development of ESOA. In addition to this, what role the arthritis could or
does play in any further alteration of the kinematic function of the post-traumatic
foot and ankle is unknown. There is likely, in these uncertain circumstances, a
requirement for more rigorous research of the more immediate post-traumatic state
to document and begin to understand the effect of the post-traumatic foot and ankle.

There were noted changes in kinematic behavior of the foot and ankle in both
direction and in magnitude. Specifically there was a change in direction in the
frontal plane demonstrated by both the preferential loss of hindfoot inversion
motion relative to the shank, and in the direction of motion in the hindfoot versus
the forefoot. (Figure 4.4) Not surprisingly the most significant restrictions of motion
occurred at the level of the ankle in both the sagittal (12.44°) and in the coronal
plane. (8.57°) Similarly the restrictions in motion at the level of the hind- and
forefoot segments in the sagittal plane (8.26°; p = 0.007) is also a somewhat
expected result, given the body of research present in the literature.93

5.1.2 – The initiation of heel rise – Further clues to hindfoot and forefoot relationship
changes

Other clues to this loss of the normal coupled relationship of the hindfoot and
forefoot occurred during the initiation of heel rise in the sagittal plane. In the
matched controls the typical initial delay allowing for the initiation of posterior
muscular contraction occurred. During this portion of the activity no sagittal plane
motion occurred. Given the known events of heel rise, as posterior compartment
musculature was contracted the plantar fascia was presumably tightened. This is one mechanism by which the expected increased plantarflexion of the forefoot relative to the hindfoot was likely observed. Observed. This sequence also likely allowed the hindfoot joints to lock the midfoot joints, and the rigid midfoot lever was achieved. This theoretically allowed the heel to rise with an ever-increasing amount of forefoot versus hindfoot motion. This is likely related to the continued and increasing tension in the plantar fascia as the MTP joints dorsiflexed.

In the arthritic population this did not occur. In fact, during the initiation and eventual contraction of the posterior compartment muscles of the lower leg, there was an observed initial dorsiflexion of the hindfoot relative to the forefoot. (See Figure 5.1) Although a subtle change, this likely is indicative of a significant alteration in the relationship of the biomechanical segments of the foot. This can be further seen in plain film radiographs taken during heel rise in arthritic ankle patients, where the normal very close relationships of the peritalar, and specifically transverse tarsal, bones appears to be disrupted. (Figures 2.7 & 2.8) This could also offer en explanation for a similar finding by Khazzam et al, who noted that stance phase was increased by 4.1% (p = 0.0014), and described a decreased rigidity of the lever arm of the foot.93 They theorized, like the author of this thesis, the breakdown in the normal coupled behavior of the hind- and mid-foot, as evidenced by the altered mechanics of the forefoot relative of the hindfoot, led to a less efficient and more time-consuming push off in the 34 patients with ESOA that they studied. The
observation noted here, and in Figure 5.1 may be the first noted confirmation of this theory as far as the author is aware.

![Graph of sagittal plane forefoot-hindfoot angle](image)

**Figure 5.1** – A focused look at the initiation phase of heel rise, where no motion, followed by forefoot versus hindfoot segment plantarflexion (downward) is observed in the normal group. Paradoxical initial dorsiflexion (upward) followed by diminished plantarflexion, by comparison, was seen in the arthritic group.

The alteration in motion in individuals with ESOA has been demonstrated in the past by others *in vivo*. The predilection for hindfoot sagittal plane, and eversion motion loss observed in this study was also previously described. What is lacking in the current body of research available is the impact that these restrictions in motion has on the overall coordination of motion of the lower leg, hindfoot and the remaining components (mid- and forefoot) of the foot. Further
tying such results to the other issues that have been shown to alter the gait of individuals with ESOA, most notably pain, which has been noted to cause an opposite effect of stance phase shortening, must also occur. This study has begun to address this gap in knowledge by beginning to describe the aberrant motion occurring in between the hindfoot and the shank and forefoot during double limb heel rise.

5.2 – The relationship of the lower leg and foot – evidence of a maladaptive response to ESOA?

The highly coupled relationship of the lower extremity to the hindfoot and the hindfoot to the rest of the foot has been well described and demonstrated in the literature in the theoretical, in vitro and in vivo settings. Furthermore the mechanisms by which this coupling occurs have been elucidated in the past. Specifically, in the setting of hindfoot motion, the importance of the normal function of the involved muscles, hindfoot joint conformation and motion, ligamentous and fascial competence, have all been postulated and in some instances proven to play an important role in the normal function of the foot and ankle. Keeping these findings in mind, trying to then pinpoint one specific structure or derangement responsible for the observed abnormalities (adaptive or not) in the kinematics of the foot and ankle in the setting of ESOA is then likely quite difficult if not impossible.
Despite these difficulties, some work has been done to characterize the adaptations of the normal hindfoot coupling mechanisms to ESOA. Kozanek et al. demonstrated using fluoroscopic analysis of hindfoot motion, that the motion of the subtalar joint was reversed in the setting of ESOA in the transverse, frontal and sagittal planes. Their study was unfortunately limited to the subtalar joint in isolation, and did not include other joints or segments of the foot. In contrast to this research, the resolution of the motion of individual joints was not studied in the presented research. This was partly due to the invasiveness of the implanted bone-markers required to do this type of research, and the reasonably acceptable reliability of skin markers for tracking foot motion. This conclusion is based not only on the anatomy of the hindfoot, but also in the observed compensatory motion and complex deformities of the hindfoot that result from the pathologic states that effect it. It therefore would be necessary to study the motion of each individual bone of the hindfoot (i.e. – the tibia, fibula, talus, calcaneus, the navicular and cuboid), as well as the combined motion in order to be able to understand (1) the total effect of hindfoot complex coupling; and (2) the contribution each individual articulation made to this coordinated motion. Such study, given the current available technologies and ethical considerations made this situation a practical impossibility.

Given these limitations then, the demonstrated findings, did fit in reasonably well with the demonstrated foot and ankle adaptations that occurred as a result of ESOA. Khazzam et al in 2006 noted decreased forefoot motion during the heel rise portion
of gait.\textsuperscript{93} Specifically they noted a decrease in coronal plane (varus) rotation in the setting of ESOA. Khazzzam et al. did not note the reversal of the motion in this plane in this area noted by this research. Although statistically insignificant, this potential finding indicates that this potential alteration of the normal relationship should be investigated further. Theoretically, if proved with additional research, this reversal and loss of normal relative forefoot plantarflexion and valgus motion could lead to a loss of the rigidity of the hindfoot-midfoot-forefoot structure that has been identified as essential to normal functioning of the foot during the third rocker, or heel rise. This loss of the normal foot function during this critical portion of the gait cycle could potentially be one of the driving forces behind the observed loss of ankle power, gait speed, and efficiency of gait observed in individuals with ESOA.\textsuperscript{21,93,143,196} The currently demonstrated significant effect of ESOA on the other portions of the foot and the adaption that it commands has been, with few exceptions, largely overlooked until recently. The findings from this research, in concert with the previous research, would command an understanding of ESOA as much more than just a disease of the ankle, rather a disease effecting the entire foot and ankle.
5.3 – The abnormal relationships in the setting of ESOA as an opportunity to optimize treatment

An understanding of the global effects of ESOA on the foot and ankle has obvious and far-reaching effects on how this disease is and likely should be treated. For instance, in the setting of ESOA the “rocker-bottom” sole is commonly prescribed. This shoe modification assists in the loss of sagittal plane motion in an attempt to prevent co-contraction of traversing muscles.\textsuperscript{169} Although evidence is lacking, this theoretically leads to decreases in the compressive forces seen at the ankle joint, and prevents of the increasing contact of the painful bony surfaces. These interventions do not take into account the abnormal relationships within the foot, and the altered mechanics present in the foot suffering from ESOA. The significant and repeatedly demonstrated loss of coronal plane motion is not addressed with this modification. Furthermore, the motion compensated for by the rocker-bottom sole, without any modifications or extensions, is aimed solely at ankle joint motion loss and not at the sagittal plane motion that is demonstrably lost \textit{between} the segments of the foot. Keeping the more detailed, 3D and accurate description of motion loss of the entire foot and ankle complex when re-designing an orthosis for the treatment of ESOA could stand a reasonable chance of improving the effectiveness of this intervention.

Operatively ESOA is treated with interventions aimed primarily at the ankle joint performed while the ankle and foot are not biomechanically active. Most patients
are under either a general anesthesia or a combination of general sedative and local nerve blocks. Some exceptions to this traditional approach to surgery in other parts of the body are well documented. This means a functional assessment of the foot that includes the obviously critical contribution of active motor units and weight bearing are not possible intra-operatively. This places a premium on the surgeons understanding and insight into the biomechanical characteristics of ESOA. Studies like this one, then likely have a role to play in iteratively informing clinicians as to what effect ESOA has on the function of the foot and ankle.

With respect to the foot, the global effect of ESOA has been increasingly recognized recently. In the setting of coronal deformity, increasing attention is being paid to correcting the deformities of the foot outside of the ankle effected by or in conjunction with this condition. These, largely retrospective, case-based and expert-opinion based publications all stressed the critical importance of a well-balanced and plantigrade foot as a required goal of any total ankle replacement surgery.

Understanding how ESOA affects the biomechanical performance of the foot, even in cases where the anatomic appearance may be relatively normal, may and likely should prompt a serious reconsideration in how this clinical entity is approached in the operating room. Intra-operative pedobarography has been shown to aid in the intra-operative assessment of biomechanical function of the foot. Furthermore, “wide-awake” surgeries (surgeries conducted with little or no sedation under local
anesthetic) are commonly performed on the human hand to assist in the real-time assessment of the biomechanical function of tendon and bony repairs of hand injuries.\textsuperscript{108,109} Perhaps the use of the combination of these approaches might allow the foot and ankle surgeon to assess intra-operatively the true biomechanical function of the foot and ankle. This would, at least in theory, allow the foot and ankle surgeon, in real time, to assess the global biomechanical function of a foot and ankle complex likely globally affected by the presence of ESOA.

5.4 – The defined strengths of the research

This study has several strengths. It is an in \textit{vivo} study conducted with age and sex-matched controls, as well as a set of young controls. This allowed for the direct comparison with a comparable population, and also allowed for direct comparison with a “normal” population. In the end little if any difference was noted between the older and younger control populations. This study employed a commonly utilized and validated foot model. The data produced in a gait trial along flat ground showed the observed kinematic curves matched those originally published.\textsuperscript{112} Finally, the event of heel rise is a well-described event. It has been described biomechanically on its own and also as the third rocker or terminal stance phase of gait. The biomechanical information from this vast body of research provides a relatively well-documented sequence of events that have been shown to reliably occur. This allows for both an excellent comparison for the normal data obtained during this
study, as well as a “starting point” from which the abnormal behaviors observed in
the setting of ESOA can be considered.

5.5 – The limitations of the research

Double-limbed heel rise, in the physiologic state demands a great deal of well-
characterized mobility from the human hindfoot. This particular activity was chosen
as a focus for study for this reason. There are however significant limitations
brought about by this approach when trying to apply the observed behaviors to
human gait: (1) although heel rise is the dominant hindfoot motion during the third
rocker of gait, there is typically only one foot in contact on the ground during this
motion; (2) double-limbed heel rise is a quasi-static event, performed while the
subject is standing still. Physiologic gait, by contrast, is a dynamic event. Inertia and
the constant forward motion of the center of gravity is an important part of normal
human gait; and (3) The requirements for the maintenance of balance are likely
different in a standing-still heel-rise activity versus in the steady-state gait scenario.
This could have generated movements and behaviors in the double-limbed heel rise
group that might not be necessary or appear in the setting of normal gait. Keeping
these ideas in mind, in the young control group single and double-limbed heel rise
were compared. Significant differences were demonstrated in some instances
indicating that although a critical first step, the limitations on this research imparted
by the movement that was measured make further study during actual gait an
absolute necessity; (4) EMG was not included in the analysis. The understanding of
the active control of foot and ankle motion in the setting of ESOA is in its infancy. Despite this, it has been shown that the performance of the muscles of the foot and ankle play a dominant role in foot and ankle function. It is therefore a weakness that EMG was not included in the above research.

The issues stemming from a highly complex process occurring in the living state, are only amplified in a disease like ESOA. It is well-documented that ESOA has several etiologies and a wide range of presentations and clinical manifestations. Although some factors, such as a coronal deformity, have been shown to have a small effect on the gait in ESOA, other as yet unidentified factors may play a more significant role in the gait of arthritics. For the purposes of this study non-inflammatory, unilateral ESOA was considered as a single group. Furthermore the presence of systemic diseases both related and unrelated to the musculoskeletal system (e.g. – chronic obstructive pulmonary disease, diabetes mellitus, renal disease, etc.) have been found to have profound implications for human gait. Although ideally avoiding such comorbidities would make for more pure methodological research, practically this information may not be as useful. The incidence of comorbidities in the setting of ESOA, a disease with its highest prevalence in individuals over 50 years of age, is likely relatively high in comparison to the normal, younger and healthier population. Providing a larger sample would help mitigate some of these potential confounding influences.
5.6 - Conclusions:

Based on the research the following conclusions can be made:

(1) ESOA has a profound impact on the observed magnitude of motion of foot segments in multiple planes and differs significantly from the normal state.

(2) ESOA likely has an impact on the biomechanical relationships of the different segments of the foot and ankle. (i.e. – lower leg or shank, hindfoot, forefoot)

This must be substantiated with further research before more significant conclusions can be drawn.
5.7 – Future Directions

The work published in this thesis was not in isolation and is, in fact, the “part one” of a “five part” research program. The next four portions of the continuing study that we are currently undertaking are: (2) biomechanics of the hindfoot-forefoot couple in the setting of ESOA during level-ground walking; (3) the effect of slopes on the gait of individuals with ESOA; (4) what is the optimal incline of an accessibility ramp for individuals with ESOA; and (5) the effect of ESOA on standing balance.

The goal of this research program, which has been underway for the past year and has already had the majority of data collected, is to apply the findings in ways that are useful to society (e.g. – informing building codes for equal access buildings in Ontario).

Another longer-term objective of this body of research is to inform the more evidence-based design of non-operative management interventions for ESOA. This means practically, designing orthotics that have in-built compensatory mechanisms that help overcome the identified aberrations in the foot and ankle coupling mechanisms. This would help better restore normal gait mechanics. Furthermore a hopeful decrease in the pain and disability that individuals with ESOA perceive would be decreased as well.
It is hoped that the information gathered from this research would help to start informing the operative interventions that are commonly performed for ESOA. Practically this means starting a collection of age- and sex-matched patients with arthritis who are going on to be treated. From the group examined, three have already received surgery (total ankle replacements and fusions) and the rest are soon to follow. The data collected here will serve as a critically important “start point” for their treatment course. These individuals will be the first individuals (as far as the author can tell) to have their treatment course followed under such rigorous study, focused on the biomechanical performance of their feet and ankles.

This will allow the foot and ankle surgery community to start to gain information around pressing questions like: (1) Do ankle replacements restore the coupling relationships that are abnormal in the setting of ESOA? (2) Do ankle fusions restore this relationship as well? Or (3) Does the behavior of the foot and ankle change in some other way in response to these procedures? Currently there is no information around these questions and the foot and ankle community has no ability to explain some critical clinical situations that arise as a result of these treatments. This is well represented by the classic and recognized symptoms that can often occur as a result of total ankle replacements. (e.g. – medial malleolar pain following total ankle replacement) Are these symptoms a result of the treatment itself – requiring improvements in the design to treat? Are these symptoms a result of a currently unknown compensation by the foot and ankle to the ankle replacement – requiring
corrective surgery to avoid? Critical questions like these could be, at least in part, be answered by the proposed research program.

Finally, the process of this master’s degree has given the author the impetus to write a text-book/monograph on the topic of the functional anatomy of the hindfoot. Currently the literature is disjointed, poorly organized, in some cases, conflicting. This massive reservoir of information, as it currently stands, can be impossible for a busy clinician to read and decipher.
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