

AN EXPLORATION OF FOOT KINEMATICS AND LOWER EXTREMITY
NEUROMUSCULAR FUNCTION IN MIDDLE-AGED PATIENTS WITH PLANTAR HEEL
PAIN

by

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ABSTRACT

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Plantar heel pain (PHP) afflicts 7.3% of adults over the age of 35, most commonly those aged 45–64, and has an annual treatment cost of \$284 million in the United States. PHP is also associated with significant personal costs such as pain-related interference with work-related activities, low physical activity, and decreased health-related quality of life (HRQOL). PHP is an injury caused from mechanical overload which induces inflammation, and ultimately degeneration, at the origin of the plantar aponeurosis. It is signified by pain felt in the heel especially after the first few steps of the morning or by prolonged standing. Although mechanical overload of the plantar aponeurosis is considered the primary mechanism of PHP, the difference within the foot and lower extremity during gait in middle-aged adults with PHP is poorly understood.

Therefore, the purposes of this exploratory study were to: identify the kinematic (Chapter 2) and neuromuscular (Chapter 3) gait differences within the foot and lower extremity in middle-aged PHP patients; and determine the association between the gait mechanics, PHP risk factors, and PHP in middle-aged adults (Chapter 4). We hypothesized that patients with PHP would demonstrate: (1) foot and lower extremity

differences during loading response, mid/terminal-stance, and push-off phases of gait, (2) lower extremity neuromuscular difference during the early and late stance phases of gait, and (3) the inclusion of gait variables associated with mechanical overload of the plantar aponeurosis with the primary risk factors would improve the ability to predict PHP in middle-aged adults.

A convenience sample of 60 adults (aged 45–64; PHP: $n = 30$; controls: $n = 30$) participated in the study. All participants completed a series of health and activity questionnaires (SF-36, IPAQ, FAAM, MFPDI), followed by lower limb strength and range of motion (ROM) assessment. Participants then completed barefoot walking trials at self-selected and standardized speeds that were captured using a 14-camera motion capture system and three floor embedded force plates. Joint kinematics were calculated for the hip, knee, and foot. During the walking trials, electromyography (EMG) was recorded from five lower limb muscles. Following walking trials, the kinematic and force plate data were used to calculate stance phase hip, knee, and ankle net joint powers.

PHP participants exhibited greater body mass, lower physical activity and HRQOL scores (SF-36, IPAQ, FAAM), and higher pain and disability ratings (MFPDI). They also demonstrated reduced ankle dorsiflexion passive ROM, decreased muscle strength (hip extensors, knee flexor, ankle dorsiflexor, ankle evertor, and hallux flexors), and slower preferred walking speed.

Kinematic analysis revealed significant foot ROM differences in the PHP group during the loading response (reduced rearfoot complex lateral rotation, decreased medial midfoot dorsiflexion, increased medial forefoot dorsiflexion) and midstance-terminal stance (reduced rearfoot complex dorsiflexion) subphases. Most of the

differences were contrary to the hypothesis and may have been compensatory or pain-avoidant strategies to reduce the plantar aponeurosis strain and pain at impact and when pushing off. Patient reports of heel pain during gait supported this interpretation, with 90% reporting pain at initial contact and during push-off, and 80% reporting heel pain during the gait trials.

With respect to neuromuscular function, there were no significant differences in mean lower extremity muscle activation amplitudes between the PHP and uninjured participants, but the PHP patients did exhibit significantly lower peak eccentric plantar flexor ankle power. The peak occurred during the late mid/terminal stance subphase and may function to decrease plantar aponeurosis strain and pain as the activity of the plantar flexors transition from eccentric to concentric activity.

Logistic regression analysis examined associations between key kinematic, neuromuscular, and intrinsic/extrinsic risk factors and PHP across six domains: gait kinematics, neuromuscular activation, joint ROM, muscle strength, physical activity, and BMI. Significant predictors of PHP included reduced rearfoot sagittal plane ROM during mid/terminal stance, reduced eccentric ankle plantar flexor power, decreased ankle dorsiflexion passive ROM, and lower physical activity levels. Muscle strength and BMI were not significantly associated with PHP.

Collectively, these findings advance the understanding of PHP related gait dysfunction and provide potential outcome measures for interventions aimed at modifying foot mechanics and neuromuscular patterns in patients with PHP. Future prospective studies will be needed to determine if the changes identified in the current study are the cause, or effect, of PHP.

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DEDICATION

I hereby dedicate this work to my family—father, mother, brothers, and sisters—whose unwavering support has served as a foundation throughout this intellectual endeavor. Both my father and mother encouraged me to complete my undergraduate degree and pursue graduate studies, and so with this, I have fulfilled their ultimate goal. To my wife Um Naif, her boundless love, patience, and encouragement have been indispensable to the realization of this achievement. I also dedicate this work to my kids Naif, Dalia, Raghad, and Badr, with the hope that they come to appreciate the profound value of education, perseverance, and the relentless pursuit of their aspirations, especially in balancing my academic commitments with family life. Although my father and brother Saad and Haasen have passed away, may Allah grant them eternal mercy, I remain profoundly grateful for the principles and values they imparted to me, as they have been essential in the pursuit of my life's aspirations. Their unwavering support, along with their teachings on commitment and diligence, empowered me to persevere in the face of life's challenges. The enduring legacy of their example, characterized by a bold challenge to conventional norms and an unwavering embrace of life's journey, continues to inspire both my personal and professional development.

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LIST OF ABBREVIATIONS

General Abbreviations

ABBREVIATIONS	Nomenclatures
BMI	Body Mass Index
CON	Uninjured Group
EMG	Electromyographic
FAAM	Foot & Ankle Ability Measure
GRF	Ground Reaction Force
HRQOL	Health-Related Quality of Life
IPAQ	International Physical Activity Questionnaire
MFPDI	Manchester Foot Pain and Disability Index
MVIC	Maximum Voluntary Isometric Contractions
PHP	Plantar Heel Pain
ROM	Range of Motion
SF-36	36-Item Short Form Survey Instrument
STP	Spatiotemporal

Abbreviations of Foot Bones and Multi-Segment Foot Model

ABBREVIATIONS	Nomenclatures
CALC	Calcaneus
CUB	Cuboid
HAL	Hallux
LFF	Lateral Forefoot Functional Articulation
LMF	Lateral Midfoot Functional Articulation
MFF	Medial Forefoot Functional Articulation
MMF	Medial Midfoot Functional Articulation
MSFM	Multi-Segment Foot Model
1MTP	First Metatarsophalangeal Functional Articulation
NAV	Navicular
RC	Rearfoot Complex

Plantar Heel Pain

In this work, the term plantar heel pain (PHP) rather than plantar fasciitis or plantar fasciosis is used. PHP is used to describe the condition since the presence/absence of inflammation in the plantar aponeurosis is unclear (Riel et al., 2017). As part of the study procedures, the etiology of plantar heel pain associated with pathology of the plantar aponeurosis was to be confirmed, and other potential sources of plantar heel pain were ruled out.

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CHAPTER ONE: INTRODUCTION

A recent large-scale study investigating the population prevalence of plantar heel pain in the United States estimated that 1.1% of adults over the age of 18 were diagnosed with plantar fasciitis in the previous year and that the prevalence was greatest in those between the ages of 45 and 64 (Nahin, 2018). In the United States, the severity of the pain and disability associated with plantar heel pain results in approximately one million patients per year seeking physician consultation (Riddle and Schappert, 2004), and the annual economic burden of treatment is \$284 million (Tong and Furia, 2010). Further, the pain associated with plantar heel pain takes an average of 6 to 96 months to resolve (Davis et al., 1994), and 44% of patients continue to report symptoms 15 years later (Hansen et al., 2018).

The prevalence and persistence of plantar heel pain, even in those receiving treatment/rehabilitation, is also associated with significant and long-term personal burden including pain-related interference with normal work- and walking-related activities (Nahin, 2018; Riddle and Schappert, 2004), low physical activity and participation (Thomas et al., 2019), and decreased health related quality of life (HRQOL) (Fernandez-Lao et al., 2016). Greater levels of depression, anxiety (Cotchett et al., 2016; Thomas et al., 2019), and stress (Cotchett et al., 2016) have also been reported. Additionally, patients with plantar heel pain are known to become more socially isolated, have less energy to participate in their usual activities, and experience a general decrease in the ability to perform numerous physical tasks (Irving et al., 2008). The reduction in mobility, which can lead to inactivity and weight gain, also

increases the risk for many other chronic diseases and makes plantar heel pain a serious public health problem (Irving et al., 2008; Young et al., 2001).

Clearly, current plantar heel pain preventive and management strategies are largely ineffective. This is further evidenced by the multiple treatment options currently being prescribed for plantar heel pain with no single treatment/management strategy standard of care (Klein et al., 2012). A lack of knowledge of mechanical and neuromuscular difference during gait in patients with plantar heel pain is a major gap limiting the development of more effective management strategies. In the absence of such knowledge, creating effective programs to treat and/or prevent development of plantar heel pain will remain largely ineffective and the prevalence, economic, and personal costs associated with plantar heel pain will remain a significant public health problem.

Effect of Plantar Heel Pain on Gait Spatiotemporal Parameters and Kinetics

Although the etiology and pathophysiology of plantar heel pain is not well understood, the general consensus is that increased tension on the plantar aponeurosis (mechanical overload) during loading activities such as gait, leads to repetitive microtrauma and subsequent degeneration of the plantar aponeurosis (Leach et al., 1986; Snider et al., 1983; Tountas and Fornasier, 1996). The bulk of the gait research has focused on identifying differences in spatiotemporal (STP) and kinetic (Ground reaction force “GRF”, plantar pressure) variables in patients with plantar heel pain. When the foot is considered as a single segment, no significant STP differences have been reported between patients with plantar heel pain and uninjured participants (Sullivan et al., 2015a; Wearing et al., 2002, 2010; Bovonsunthonchai et al., 2019).

Additionally, the only kinetic difference reported has been a decrease in the second/active peak vertical GRF in plantar heel pain patients (Chang et al., 2014). However, when the foot is partitioned into regions (e.g., medial and lateral heel, midfoot, medial and lateral forefoot), plantar heel pain patients have demonstrated increased contact time in the midfoot and medial and lateral forefoot (Sullivan et al., 2015a), and decreased hindfoot and midfoot loading (Riskowski et al., 2015; Sullivan et al., 2015a). These studies collectively suggest that partitioning the foot into regions/segments is important in identifying the differences associated with plantar heel pain. While these studies have identified differences in STP and loading (ground reaction, plantar pressure) in patients with plantar heel pain, the variables assessed represent the outcome of the body's neuromuscular response to plantar heel pain. They do not identify the dysfunctional movement and/or neuromuscular dysfunction causing the STP or loading differences.

Further, based on a study that investigated tension in the plantar aponeurosis during walking (Caravaggi et al., 2009), and the auto-supportive mechanisms of the foot during gait (Dananberg, 1993; Bojsen-Moller, 1979; Hicks, 1954), the plantar aponeurosis functions to support the different regions of the foot during the stance subphases. With respect to tension, the plantar aponeurosis is preloaded prior to initial contact, tension is maintained until approximately 30% of stance, and then increases to a peak at approximately 80% of stance (Caravaggi et al., 2009). The preloading of the plantar aponeurosis may function to help control foot pronation during loading response and early midstance as the center of pressure travels from the lateral rearfoot along the lateral midfoot and lateral forefoot. Just prior to heel rise, which occurs between

midstance and terminal stance, the center of pressure moves from the lateral forefoot to the medial forefoot. The transfer of load to the medial forefoot is theorized to further increase tension in the plantar aponeurosis and activate the first auto supportive mechanism, the calcaneocuboid locking mechanism. The increased tension in the plantar aponeurosis is theorized to compress the cuboid into the calcaneus to stabilize the lateral midfoot (Dananberg, 1993; Bojsen-Moller, 1979). The stable lateral midfoot enables the plantar aponeurosis to activate the second auto-supportive mechanism, the “truss” mechanism. Tension in the plantar aponeurosis acts like a tie-rod that assists stabilizing of the midfoot in preparation for propulsion (Dananberg, 1993). Finally, hallux extension in late terminal stance and push-off causes peak tension in the plantar aponeurosis which activates the third auto supportive mechanism, the windlass effect. The increased tension assists the raising of the medial longitudinal arch (supination) to create a stable forefoot, midfoot, and rearfoot for propulsion (Hicks, 1954). Thus, plantar heel pain could cause dysfunction during early, mid, or late stance, but the dysfunction may be masked by models that do not include midfoot and medial and lateral forefoot joints and/or by studies that do not investigate the stance subphases.

Effect of Plantar Heel Pain on Lower Extremity Kinematics

The research investigating lower extremity kinematics in patients with plantar heel pain has been limited. To date, only three studies have investigated the kinematic difference associated with plantar heel pain (Bovonsunthonchai et al., 2019; Chang et al., 2014; Harutaichun et al., 2021).

When the entire stance phase has been assessed, Chang et al. (2014) reported increased rearfoot eversion and medial forefoot dorsiflexion range of motion (ROM)

between initial contact and peak eversion and dorsiflexion, respectively in patients with plantar heel pain. When total stance phase ROM (maximum position – minimum position) has been calculated, Bovonsunthonchai et al. (2019) reported decreased rearfoot frontal plane and forefoot sagittal plane ROM in plantar heel pain patients. Based on the figures presented in the study, the timing of peak eversion for both groups appeared to be around 60% of stance, but the timing of peak inversion in the two groups is not completely clear. Peak inversion positions at initial contact, around 50% stance, and in late stance, all appear similar. Thus, it is difficult to determine if the decreased frontal plane ROM in plantar heel pain patients was due to decreased inversion or eversion ROM. With respect to the forefoot sagittal plane ROM, peak dorsiflexion in both groups appeared to be near 50% of stance, and peak plantar flexion near 60% of stance. Therefore, the decreased sagittal plane ROM in patients with plantar heel pain appeared to be decreased plantar flexion ROM between approximately 50% and 60% of stance. With respect to other significant differences during stance phase, Bovonsunthonchai et al. (2019) found increased peak forefoot dorsiflexion and decreased peak forefoot inversion positions in plantar heel pain patients. Chang et al. (2014) did not report significant differences in peak medial forefoot dorsiflexion between those with and without plantar heel pain, but medial forefoot plantar flexion position at initial contact and first metatarsophalangeal joint extension at the end of stance were increased in patients with plantar heel pain.

Of the studies investigating the kinematic gait difference in plantar heel pain, only Harutaichun et al. (2021) partitioned stance into subphases. This may be important given the different functions that must be accomplished by the foot and lower extremity

within stance (e.g., mobility for load absorption in early stance, stability for propulsion in mid and late stance). During early stance, patients with plantar heel pain demonstrated increased transverse and decreased sagittal plane ROM in the rearfoot and forefoot, respectively. During the middle subphases, plantar heel pain patients exhibited decreased sagittal plane ROM in the midfoot and hip joints, increased frontal plane ROM in the forefoot, and decreased sagittal and transverse plane knee joint ROM. Finally, in the late stance subphase, plantar heel pain patients demonstrated increased transverse and frontal plane ROM in the ankle and hip joints, respectively.

Although it is difficult to directly compare the results of the three studies due to differing methodologies (e.g., participant ages, multi-segment foot model utilized, discrete variables selected, and stance phase periods investigated), the common conclusion of the studies has been that most of the ROM changes in patients with plantar heel pain have been attributed to increased pronation (Chang et al., 2014; Harutaichun et al., 2021), or are consistent with inadequate supination (Bovonsunthonchai et al., 2019).

Previous studies have improved the understanding of the effect of plantar heel pain on gait, however, there are important limitations that need to be addressed. While most kinematic studies have utilized a multi-segment foot model, only one has included an analysis of the midfoot (Harutaichun et al., 2021), and those that have included the forefoot have defined the entire forefoot segment as a single rigid segment, or only defined the medial forefoot. The absence of a midfoot joint and the failure to segment the forefoot into medial and lateral joints may be important given that significant motion has been reported between the rearfoot and midfoot, and that the medial and lateral

forefoot have the ability to function somewhat independent of one another (Wolf et al., 2008). Further, three of the four studies investigating gait kinematics included participants of differing age groups (e.g., young and middle-aged or middle-aged and old) (Bovonsunthonchai et al., 2019; Chang et al., 2014; Greve et al., 2019), and the fourth study only included active young male military recruits (Harutaichun et al., 2021). This may be important given the known changes in gait, neuromuscular function, and strength associated with aging (McGibbon, 2003; McGibbon et al., 2001; Spink et al., 2010). Finally, of the gait kinematic studies conducted, only one examined the function of joints proximal to the ankle (Harutaichun et al., 2021). This is significant because based on the pain-adaptation model (Lund et al., 1991), gait kinematics (Arendt-Nielsen et al., 1996), and neuromuscular (MacDonald et al., 2009) differences are not limited to the painful joint/structure. If this is the case with plantar heel pain, successful treatment/rehabilitation may not only involve addressing the differences within the foot but also in the proximal lower extremity joints. Indeed, Harutaichun et al. (2021) did report dysfunction in the proximal joints during gait. However, the study only enrolled young active military recruits with plantar heel pain, therefore, it is not clear if the same differences would be present in less active middle-aged adults with plantar heel pain.

Effect of Plantar Heel Pain on Lower Extremity Neuromuscular Function

The research investigating lower extremity neuromuscular function in patients with plantar heel pain has also been limited. To date, only a single study has investigated the impact of plantar heel pain on electromyography (EMG) activity during walking gait (Moyne-Bressand et al., 2018). Although no EMG differences were found between the plantar heel pain and healthy group during the stance phase, there were

differences in the reflex max/muscle max and reflex wave/muscle wave reflex ratios. Plantar heel pain patients had higher reflex max/muscle max and reflex wave/muscle wave ratios (Moyne-Bressand et al., 2018). Further, the differences persisted despite a reported decrease in pain level following treatment for the pain. The researchers concluded that the persistence of the reflex differences may indicate neurological adaptations to chronic pain even after treatment that successfully decreased the pain associated with plantar heel pain. They further hypothesized that the neurological adaptations may contribute to the long-term persistence/recurrence of pain that is common in patients with plantar heel pain (Moyne-Bressand et al., 2018). These findings corroborate the assertions made by the pain adaptation model which are that the body initiates protective neurological and physical adaptations to pain that ease the perception of pain, but may ultimately contribute to further dysfunction and pain in the affected area (Arendt-Nielsen, 2009; Lund et al., 1991). Another functional tool for measuring neuromuscular function during gait is net joint power analysis (Winter and Eng, 1995), which has been utilized to investigate chronic pain conditions and injuries but has yet to be applied to plantar heel pain research.

Additional study of the neuromuscular difference in patients with plantar heel pain is clearly warranted. In addition to the need for lower extremity net joint power analysis, investigation of potential differences in lower extremity muscle activity within the stance subphases, versus over the entire stance phase, may also be important.

Intrinsic and Extrinsic Risk Factors of Plantar Heel Pain

Numerous studies aimed at identifying extrinsic and intrinsic plantar heel pain risk factors have been conducted. However, only a small subset of the variables

investigated have been consistently identified as significant risk factors. The common assumption of investigated risk factors is that they cause/contribute to mechanical overload of the plantar aponeurosis, leading to its degeneration and the development of plantar heel pain. Plantar heel pain affects both physically active (Landorf and Menz, 2008), and sedentary (Davis et al., 1994; Williams, 1987) individuals, making both excessive and inadequate activity levels plausible extrinsic risk factors. Overload injury due to excessive physical activity may begin due to abnormal loading of a normal tissue (Leach et al., 1986; Snider et al., 1983; Tountas and Fornasier, 1996). If, like other musculoskeletal tissues, the plantar aponeurosis weakens in the absence of regular loading, then overload due to inactivity and sedentary lifestyles may begin as the result of a normal load on an abnormal tissue. The other extrinsic risk factors strongly associated with plantar heel pain are prolonged standing and/or working on a hard surface (Riddle et al., 2003; Werner et al., 2010).

The intrinsic risk factors most strongly associated with plantar heel pain are obesity (Irving et al., 2007; Rano et al., 2001; Riddle et al., 2003; Sullivan et al., 2015b; Thomas et al., 2019), inadequate vascularity and blood flow (Berlin et al., 1990; Chen et al., 2013, 2012; van Leeuwen et al., 2016; McNally and Shetty, 2010; Walther et al., 2004), hamstring tightness (Bolívar et al., 2013; Labovitz et al., 2011; Lee et al., 2020; Thummar et al., 2020), reduced ankle dorsiflexion ROM (Bolívar et al., 2013; Riddle et al., 2003; Sullivan et al., 2015b; Yildiz et al., 2018), and reduced ankle evtor and toe flexor muscle strength (Allen and Gross, 2003; McClinton et al., 2016; Sullivan et al., 2015b; Yildiz et al., 2018). Other commonly investigated intrinsic factors including sex (Taunton et al., 2002; Thomas et al., 2019) and foot posture (Aranda and Munuera,

2014; Headlee et al., 2008; Huang et al., 2004; Irving et al., 2007; Werner et al., 2010) have not been consistently shown to be associated with plantar heel pain.

While many studies have investigated risk factors associated with plantar heel pain, the majority have investigated differences using ANOVA, t-tests, ANCOVA, or non-parametric equivalents. Although these analyses identify differences in the risk factors between plantar heel pain and uninjured groups, they didn't specifically investigate the association of the variables with plantar heel pain. Work investigating associations of risk factors with plantar heel pain using regression models have only included a subset of the most common intrinsic risk factors (Irving et al., 2007; Labovitz et al., 2011; Riddle et al., 2003). Importantly, none of the studies have included kinematic or neuromuscular gait variables that have been identified as significantly different between plantar heel pain and uninjured groups. There is, therefore, a critical need to identify the association between the gait difference and risk factors and plantar heel pain in middle-aged adults. Without such information, treatment and prevention programs will remain largely ineffective, and the prevalence, economic, and personal costs associated with plantar heel pain will remain a significant public health problem.

Statement of the Purpose of the Study

The long-term goal of this line of research is to contribute to the development of more effective prevention and intervention strategies that decrease the prevalence of plantar heel pain and improve the health and treatment outcomes of plantar heel pain patients. The overall objectives for this dissertation were to identify the: kinematic and lower-extremity neuromuscular gait difference in middle-aged plantar heel pain patients;

and to determine the association between the gait difference, extrinsic and intrinsic risk factors of plantar heel pain, and plantar heel pain in middle-aged adults.

The central hypothesis was that plantar heel pain patients would demonstrate gait differences consistent with insufficient plantar aponeurosis tension caused by degeneration of the structure, and that the identified mechanical variables will significantly improve the ability to predict plantar heel pain in middle-aged adults. The hypothesis was formulated based on the function of the plantar aponeurosis during gait, the pathophysiology of plantar heel pain, and models of overuse injury and neuromuscular adaptations to chronic pain. The rationale for this exploratory project was that identification and characterization of the kinematic and neuromuscular difference within the foot and lower extremity during gait may provide modifiable factors that can be used in the development of more effective plantar heel pain treatment programs.

Specific Aims and Hypotheses of the Study

Aim #1. Identify the Kinematic Gait Differences in Middle-aged Patients with Plantar Heel Pain

Working Hypothesis. Based on the previous multi-segment foot model studies of patients with plantar heel pain (Bovonsunthonchai et al., 2019; Chang et al., 2014; Harutaichun et al., 2021), the pathophysiology of plantar heel pain (Leach et al., 1986; Snider et al., 1983; Tountas and Fornasier, 1996), a dynamic model plantar aponeurosis tension during gait (Caravaggi et al., 2009), the auto-supportive mechanisms of the plantar aponeurosis during gait (Bojsen-Moller, 1979; Dananberg, 1993; Hicks, 1954), and the pain-adaptation model (Arendt-Nielsen and Falla, 2009;

Lund et al., 1991), our working hypothesis was that plantar heel pain patients would demonstrate foot and lower extremity differences during the early, mid and late stance subphases of walking gait. Given that the plantar aponeurosis functions to control foot pronation and assist foot supination, we anticipated foot kinematic difference would be exhibited as an increased ROM in the directions associated with foot pronation. In the rearfoot and the lateral and medial midfoot, we anticipated increased dorsiflexion, eversion, and abduction. Based on the pronation twist concept of the forefoot (Hicks, 1953), we hypothesized patients with plantar heel pain would exhibit increased medial forefoot dorsiflexion and inversion and increased lateral forefoot plantar flexion and inversion. In the proximal joints we postulated there would be increased flexion during early stance to decrease pain associated with initial ground impact and then increased extension during the propulsive portions of stance to compensate for decreased foot stability.

Aim #2. Identify the Neuromuscular Gait Differences in Middle-aged Patients with Plantar Heel Pain

Working Hypothesis. The working hypothesis was based on the pathophysiology of plantar heel pain (Leach et al., 1986; Snider et al., 1983; Tountas and Fornasier, 1996) and the pain-adaptation model (Arendt-Nielsen and Falla, 2009; Lund et al., 1991). During the loading response subphase, we hypothesized patients with plantar heel pain would demonstrate increased: sagittal and frontal plane hip eccentric power; sagittal plane knee, eccentric power; and knee extensor muscular activity to decrease impact load on calcaneus. During the terminal/push-off subphase, we postulated plantar heel pain patients would exhibit decreased muscular activity and

concentric ankle joint power in the ankle plantar flexors, and compensatory increased knee extensor muscular activity and knee and hip joint sagittal plane concentric power.

Aim #3. Determine the Association Between the Risk Factors, Gait Difference, and Plantar Heel Pain in Middle-aged Adults

Working Hypothesis. Based on previous research investigating extrinsic and intrinsic risk factors associated with plantar heel pain, and the widely accepted belief that mechanical overload is the primary mechanism of plantar heel pain, we postulated that inclusion of gait variables associated with mechanical overload of the plantar aponeurosis identified in aim #1 with the modifiable extrinsic and intrinsic risk factors would significantly improve the ability to predict plantar heel pain in middle-aged adults.

Delimitations of the Study

1. Participants were middle-aged adults ranging from 45-64 years old, therefore, the findings of this study may not be generalizable to other age groups.
2. Physical activity was assessed via a questionnaire. As physical activity will not be directly assessed, some participants may overestimate their physical activity (Haskell et al., 2007; Shephard, 2003).
3. Participants were barefoot during the gait assessment; therefore, the results may not be generalizable to gait patterns during other footwear conditions.
4. The multi-segment foot model defines six-foot segments and a shank segment that are used to identify six functional foot articulations (rear foot, medial midfoot, lateral midfoot, medial forefoot, lateral forefoot, first metatarsophalangeal). Other than the lateral midfoot, the functional foot articulations do not represent true

anatomical joints, therefore, the results may not be generalizable to all the anatomical joints of the foot.

Assumptions of the Study

1. The kinematics of each lower extremity joint and foot functional articulation were accurately represented by the movement of surface markers located on each segment. The retroreflective skin surface markers were a non-invasive method of measuring underlying bone movement of different segments (kinematic analysis). However, since the markers were placed on the skin versus directly on the bones, some measurement error due to soft tissue movement will be present. These adverse effects of the soft tissue movement were minimized by placing markers in areas where there is less soft tissue motion and using a reconstruction optimization procedure.
2. Participants walked at their natural and preferred stride length and rate.
3. Participants truthfully answered questions regarding their injury history and physical activity levels.
4. EMG can be adversely affected by excess adipose tissue. To remediate this issue, we followed current recommendations for skin preparation and electrode placement to obtain the best possible signal.

Significance of the Study

After completion of the proposed research, the expected outcomes were to have elucidated the foot and lower extremity kinematic and neuromuscular gait difference in middle-aged plantar heel pain patients. We expected to also demonstrate the association between gait difference and plantar heel pain in middle-aged adults. These

exploratory results were predicted to have an important positive impact because they would provide strong evidence-based proof of the difference in plantar heel pain that may contribute to, or be the result of, the mechanical overload of the plantar aponeurosis during gait. The results were also expected to contribute to the development of novel interventions to prevent and treat plantar heel pain.

CHAPTER TWO: THE INFLUENCE OF PLANTAR HEEL PAIN ON FOOT AND LOWER EXTREMITY WALKING GAIT KINEMATICS IN MIDDLE-AGED ADULTS

Introduction

A recent large-scale study investigating the population prevalence of plantar heel pain (PHP) in the United States estimated that 1.1% of adults over the age of 18 were diagnosed with plantar fasciitis in the previous year and that the prevalence was greatest in those between the ages of 45 and 64 (Nahin, 2018). Despite intervention, PHP often persists with symptom duration ranging from 6 to 96 months (Davis et al., 1994), and 44% of individuals reporting ongoing symptoms up to 15 years post-diagnosis (Hansen et al., 2018). The prevalence and persistence of PHP imposes a substantial, long-term burden, marked by impaired mobility (Nahin, 2018; Riddle and Schappert, 2004), reduced physical activity and participation (Thomas et al., 2019), and diminished health-related quality of life (HRQOL) (Fernandez-Lao et al., 2016). Further, each year, approximately one million patients seek medical care for PHP (Riddle and Schappert, 2004), which carries an estimated annual treatment cost of \$284 million (Tong and Furia, 2010).

The general clinical belief is that mechanical overload of the plantar aponeurosis during loading activities such as gait causes repetitive microtrauma and subsequent degeneration of the plantar aponeurosis, which eventually leads to the signs and symptoms associated with PHP (Leach et al., 1986; Snider et al., 1983; Tountas and Fornasier, 1996). Although mechanical overload of the plantar aponeurosis during loading activities is believed to lead to PHP, the pathomechanics of PHP during gait remain poorly understood. This lack of knowledge is a critical barrier to the development of effective preventive and therapeutic interventions.

To date, only three studies have investigated the effect of PHP on foot ROM during walking gait (Bovonsunthonchai et al., 2019; Chang et al., 2014; Harutaichun et al., 2021). At the rearfoot complex, Chang et al. (2014) reported increased rearfoot eversion ROM between the initial contact position and peak eversion in patients with PHP. When calculating total gait cycle ROM (maximum position – minimum position), Bovonsunthonchai et al. (2019), identified reduced rearfoot frontal plane ROM in patients with PHP. Finally, when calculating ROM within stance subphases, Harutaichun et al. (2021) did not report frontal plane ROM between individuals with and without PHP, but did report increased transverse plane ROM in the early subphase in patients with PHP. At the medial forefoot, Chang et al. (2014) reported increased dorsiflexion ROM in patients with PHP. However, Bovonsunthonchai et al. (2019) reported decreased sagittal plane gait cycle ROM in patients with PHP and Harutaichun et al. (2021) reported decreased dorsiflexion ROM during early stance and increased eversion ROM during midstance. The only study that included a midfoot segment reported decreased dorsiflexion ROM during midstance in patients with PHP (Harutaichun et al., 2021).

While the previous studies have advanced the understanding of gait alterations in PHP, several important considerations require further investigation. First, of the three studies, only Harutaichun et al. (2021) partitioned stance into subphases, which may be important due to the varying functional demands that must be accomplished by the foot during gait. Second, only one of the studies included a midfoot functional articulation (Harutaichun et al., 2021), and two of the three studies defined the forefoot as a single rigid segment (Bovonsunthonchai et al., 2019; Harutaichun et al., 2021). This may be

important given the motion between the rearfoot and midfoot, and the relative functional independence of medial and lateral forefoot regions (Wolf et al., 2008). Finally, only one study assessed joints proximal to the ankle (Harutaichun et al., 2021). This may be significant based on the pain-adaptation model (Lund et al., 1991), and previous gait kinematics studies of patients with chronic pain (Arendt-Nielsen et al., 1996), indicating that compensatory changes may extend beyond the site of pain. While Harutaichun et al. (2021) did report differences in the hip and knee joints during gait, the study only enrolled young active military recruits with PHP, and therefore, it is not clear if the same differences would be present in less active middle-aged adults with PHP.

The purpose of this study was to identify the foot and lower-extremity kinematic gait difference in middle-aged PHP patients. We hypothesized that PHP patients would demonstrate foot and lower extremity differences during the loading response, mid/terminal-stance, and push-off phases of gait. Given that the plantar aponeurosis functions to control foot pronation and assist foot supination, we anticipated that the foot kinematic difference would be exhibited as increased ROM in the directions associated with foot pronation. In the rearfoot and the lateral and medial midfoot, we anticipated increased dorsiflexion, eversion, and abduction. Based on the pronation twist concept of the forefoot (Hicks, 1953), we hypothesized patients with PHP would exhibit increased medial forefoot dorsiflexion and inversion as well as increased lateral forefoot plantar flexion and inversion. In the proximal joints, we postulated there would be increased flexion during early stance to decrease pain associated with initial ground impact and then increased extension during the propulsive portions of stance to compensate for decreased foot stability.

Methods

Participants

Sixty middle-aged adults (age range: 45 - 64 yrs.) with PHP (n = 30) and without PHP (n = 30) participated in the study. The sample size for was determined using G*Power (version #3.1.9.4) with data from several previous PHP studies that utilized multi-segment foot models (Bovonsunthonchai et al., 2019; Chang et al., 2014; Harutaichun et al., 2021). The power analyses were performed for a one-way ANCOVA fixed effects, main effects, and interactions: [$\alpha = 0.05$, $\beta = 0.20$; degrees of freedom = 1, large effect size (Cohen's $f = 0.40$)] indicated minimum group sizes ranging from 20-26 participants per group. A one-way ANCOVA with repeated measures was chosen to allow a more precise evaluation of group effects and to assess differences between groups on a dependent variable, while controlling for the influence of sex and Body Mass Index (BMI) as covariates.

PHP participants had: a history of an insidious onset of PHP lasting for at least the past three months (Irving et al., 2008); point tenderness at the proximal attachment of the plantar aponeurosis (medial calcaneal tubercle); and a complaint of pain with the initial steps in the morning, following periods of prolonged inactivity, or during prolonged weight-bearing activity (Bovonsunthonchai et al., 2019; Riddle et al., 2003; Sullivan et al., 2015a). The uninjured (CON) group were age (± 5 y), sex, and limb matched with the participants in the PHP group.

Exclusion criteria for PHP participants included PHP that could not be reproduced during clinical exams, previous surgical treatment for PHP (e.g., plantar aponeurosis release) and/or recent (within the previous six months) non-surgical PHP

treatment from an allied health professional (e.g., physical therapy, custom-molded foot orthoses, corticosteroid injection). Exclusion criteria for both groups included: significant lower limb edema; current/history of (previous 3 months) low back, lower extremity, or foot pain (except PHP for the PHP group); a history of major lower extremity injury or surgery; or other medical conditions that may result in plantar foot pain (e.g., diabetes, arthritis, neuromuscular or vascular disease); current use of medications that may cause dizziness or impair the ability to walk; or implanted electronic devices of any kind (e.g., cardiac pace-makers). Pregnancy was also an exclusion criterion for females due to ligament/aponeurosis laxity that occurs with pregnancy.

Procedures

Following a clinical screening exam to confirm the plantar heel pain in PHP participants was due to pathology of the plantar aponeurosis and to rule out other common sources of heel pain, the equipment and procedures were explained, and participants provided informed consent approved by the University's Institutional Review Board. Participants then completed a series of questionnaires that assessed their lower limb pain and injury history, their general health [36-Item Short Form Survey (SF-36) (Ware and Sherbourne, 1992)], physical activity [International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003)], foot and ankle function [Foot and Ankle Function Ability Measure (FAAM) (Martin et al., 2005)], and foot pain/disability [Manchester Foot Pain and Disability Index (MFPDI) (Garrow et al., 2000)].

Following completion of the questionnaires, each participant's height, weight, and lower extremity ROM and strength were assessed. Ankle dorsiflexion (Bennell et al., 1998) and knee extension (Berryman Reese and Bandy, 2010) ROM were assessed

using a goniometer and inclinometer. The strength of nine lower extremity muscles was assessed using a handheld dynamometer [JTech Commander Echo Dynamometer (JTECH Medical, Midvale, UT) or microFET ²™ (Hoggan Scientific, LLC., Salt Lake City, UT)] and appropriate manual muscle testing procedures (Bazett-Jones et al., 2011; Hébert et al., 2011; Katoh and Yamasaki, 2009; Quinlan et al., 2021; Spink et al., 2010). The muscles tested included the: gluteus medius, gluteus maximus, quadriceps, hamstrings, tibialis anterior, fibularis longus/brevis, gastrocnemius, intrinsic flexors of the 2nd – 5th toes, and intrinsic hallux flexors. Participants completed three maximal isometric tests for each muscle and the maximum trial was used for subsequent data analysis (Katoh et al., 2019). Only PHP participants' involved limb and the matched limb of CON participants were tested. If a PHP participant had bilateral heel pain, the involved limb was defined as the more painful of the two.

To assess foot and lower extremity walking gait kinematics, 50 retroreflective markers (6.4 –10 mm) were placed either directly on the skin or on custom-built wands to define the pelvis, thigh, shank, and six-foot segments of interest (Table 2.1, Figure 2.1) of the involved limb for PHP participants and the matched limb for CON participants. An additional 11 anatomical landmarks on the foot were identified using a pointer device during a static calibration procedure (Table 2.1, Figure 2.1) (Cobb et al., 2016). The six foot segments and the shank segment were used to identify six functional foot articulations (rearfoot complex, medial midfoot, lateral midfoot, medial forefoot, lateral forefoot, and first metatarsophalangeal) (Cobb et al., 2016).

Following application of the markers, a static calibration procedure with the participant barefoot in seated and standing positions was performed. The seated trial

was used to capture the time-invariant positions of the foot anatomical markers and landmarks and the positions of the foot functional articulations without compensatory movements that may occur with abnormal foot postures during weightbearing. The standing trial was used to capture the time invariant positions of the other lower extremity anatomical landmarks. A 14-camera motion capture system (Raptor 4, Motion Analysis Inc, Santa Rosa, Ca) sampling at 200 Hz was used to record positions of the retroreflective markers during the static calibration and walking gait trials.

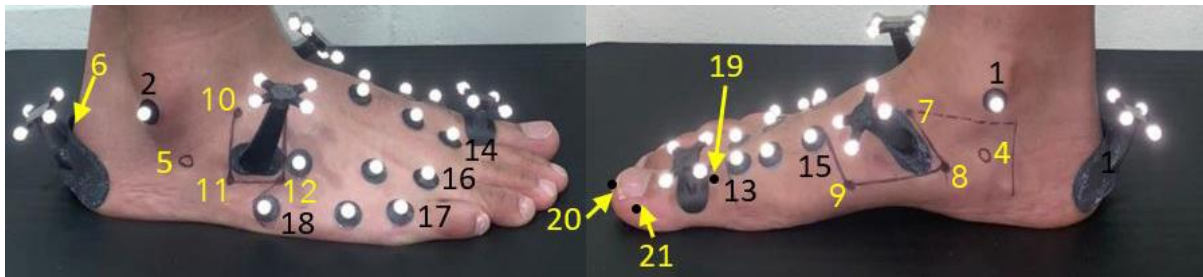


Figure 2.1. Anatomical Markers (Black Font) and Landmarks (Yellow Font): Shank [medial malleolus (1), lateral malleolus (2), tibial tuberosity (3, not pictured)]; Calcaneus [sustentaculum tali (4), peroneal tubercle (5), dorsal proximal (6)]; Navicular [dorsal proximal (7), plantar proximal (8), plantar distal medial cuneiform (9)]; Cuboid [dorsal proximal (10), plantar proximal (11), plantar distal (12)]; Medial rays [1st metatarsal head (13), 2nd metatarsal head (14), 1st metatarsal base (15)]; Lateral rays [4th metatarsal head (16), 5th metatarsal head (17), 5th styloid process (18)]; Hallux [proximal phalanx base (19), distal phalanx head (20), medial aspect (21)].

Table 2.1. Foot & Lower Extremity Technical Marker Clusters, Pelvis, and Thigh Anatomical Markers.

Segment	Location and Describe
Pelvis	Right & Left ASIS ^{A,T} , Right & Left PSIS ^{A,T}
Thigh	Right & Left Greater trochanters ^A , Medial femoral epicondyle ^A , Lateral femoral epicondyle ^A Rigid cluster of 4 markers ^T
Shank	Tibial tuberosity ^A , Medial malleolus ^A , Lateral malleolus ^A Cluster of 4 surface markers ^T
Calcaneus	Rigid cluster of 4 markers ^T
Navicular	Rigid cluster of 4 markers ^T
Cuboid	Rigid cluster of 4 markers ^T
Medial rays	Cluster of 4 surface markers ^T
Lateral rays	Cluster of 4 surface markers ^T
Hallux	Rigid cluster of 4 markers ^{A,T}
Metatarsals	1 st Metatarsal base ^{A,T} , 1 st Metatarsal head ^A , 2 nd Metatarsal head ^A , 4 th Metatarsal head ^A , 5 th Metatarsal base ^{A,T} , 5 th Metatarsal head ^A
Opposite limb	1 st Metatarsal head ^{A,T} , 5 th Metatarsal head ^{A,T} , Calcaneus ^{A,T}

^AAnatomical marker

^TTechnical marker

After the calibration procedure, all anatomical markers except for those on the bases of the first and fifth metatarsals were removed. Then, following practice trials to familiarize participants with the procedures, and establish preferred walking speeds, all participants completed 10 successful barefoot walking trials at a self-selected speed, and 10 successful barefoot trials at a fixed speed of 1.3 m/s along a 15 m walkway. The fixed speed trials, were within the normal range for adults between the ages of 50 and 64 (Whittle et al., 2012). Gait speed was monitored using an optoelectronic timing device and three force plates (AMTI, Watertown, MA, USA) embedded in the middle portion of the walkway and collecting at 2000 Hz were used to identify stance phase events. A successful trial was defined as a trial in which the involved and opposite limb events occur on the appropriate force plate and the participant's gait speed is within $\pm 10\%$ of the appropriate speed (preferred, fixed).

Data Processing

Following completion of the gait trials, three-dimensional positions of the markers collected during the static calibration and gait trials were tracked using Cortex software (version 8.0, Motion Analysis Inc, Santa Rosa, CA). The tracked position data and the synchronized GRF data were exported for subsequent data processing.

Custom-written MATLAB programs (R2024b, MathWorks, Natick, MA, USA) were used to calculate the foot and lower extremity kinematics. The position and force plate data were filtered using a fourth order zero-lag Butterworth low-pass filter with cut-off frequencies of 6 Hz and 30 Hz, respectively. The cut-off frequencies were determined by performing residual analysis of pilot data (Winter, 2009). Three-dimensional rigid body transformation procedures were performed using the calibrated

anatomical system technique (Cappozzo, 1984), local joint coordinate systems were defined within each segment, and three-dimensional joint angles were calculated using the joint coordinate system technique (Grood and Suntay, 1983). Three-dimensional joint angles were calculated for the hip and knee joints and the six functional foot articulations. All rotations were defined as rotation of the distal segment on the proximal segment. For the foot functional articulations, positive sagittal, frontal, and transverse plane joint angles were defined as dorsiflexion/extension, inversion, and adduction, respectively. For the hip and knee, positive sagittal and frontal plane rotations were defined as flexion and adduction, respectively. The data from the first five successful trials in which there were no obvious erroneous marker displacements were used for subsequent data analysis.

The vertical GRF data was then used to identify the initial contact and toe-off stance events (20 N threshold) and the stance subphases. The events identified included involved limb initial contact, opposite limb toe-off, opposite limb initial contact, and involved limb toe-off. The events were used to identify loading response (involved limb initial contact to opposite limb toe-off), midstance-terminal stance (opposite limb toe-off to opposite limb initial contact), and push-off (opposite limb initial contact to involved limb toe-off) stance subphases. ROM (maximum position – minimum position) of the hip and knee joints and the six functional foot articulations were calculated within each stance subphase. Finally, the stance phase of each gait trial was time-normalized to 100% stance (101 points) and exported to generate time-series figures.

Statistical Analysis

Prior to performing the statistical analyses of the descriptive data (age, height, BMI, gait speed, SF-36, IPAQ, FAAM, MFPDI, lower extremity ROM, lower extremity strength), the normality of the data was assessed using the Kolmogorov-Smirnov test. For normally distributed variables, independent t-tests were run to test for significance between group differences (mean $\pm$ SD). Mann-Whitney U tests were performed for non-normally distributed variables.

For each joint/functional foot articulation, the stance subphase ROM of interest from the five gait trials were averaged for each participant (Table 2.2). Prior to performing the statistical analyses, the Kolmogorov-Smirnov was performed to assess the normality of the data. For normally distributed variables, one-way ANCOVAs were performed to investigate group differences. For non-normally distributed variables, Rank-Based ANCOVA tests were performed. Because the influence of sex on foot function, and as a risk factor for PHP, have not been definitively determined, sex was used as a covariate. BMI, which has been identified as a potential risk factor for PHP, was also used as a covariate. Separate ANCOVAs were performed for each dependent variable of interest during each stance subphase. The independent variable in each one-way ANCOVA was group (PHP, CON). All statistical analyses were performed using SPSS (SPSS, version 28), and the significance for the statistical tests was set at $\alpha = 0.05$. SPSS interpolated the effect sizes through partial eta squared [small (0.01), medium (0.06), and large (0.14)], quantifying the magnitude of between-group effects, and offering a standardized metric to enhance the interpretability and clinical relevance of the findings.

Table 2.2. Joint/Functional Articulation Planes of Interest.

Joint/ Functional Articulation	Movement Plane
1. Hip	Sagittal and Frontal
2. Knee	Sagittal
3. Ankle (Rearfoot (RC))	Sagittal, frontal, and transverse
4. Medial midfoot (MMF)	Sagittal, frontal, and transverse
5. Lateral midfoot (LMF)	Sagittal, frontal, and transverse
6. Medial forefoot (MFF)	Sagittal and frontal
7. Lateral forefoot (LFF)	Sagittal and frontal
8. First Metatarsophalangeal (1MTP)	Sagittal

Results

Descriptive Data

Participants' descriptive data results are presented in Table 2.3. Results for the physical characteristics revealed significantly increased body mass in the PHP group, but no significant age, height, or BMI group differences. With respect to the questionnaires, the PHP group had poorer scores on all the forms. The ROM and strength variable results revealed significantly decreased ankle dorsiflexion ROM, and decreased hamstrings, ankle dorsiflexor, ankle evtor, hip extensor, and intrinsic hallux flexor strength in the PHP group. Lastly, a statistically significant group difference was found for preferred walking speed, with the PHP group exhibiting a slower walking speed. Because gait speed can significantly affect gait kinematics, the fixed speed walking trial data were used for subsequent data kinematics analysis.

Table 2.3. Descriptive Data Mean (SD).

Results	Groups		p-value
	CON	PHP	
Physical Characteristics			
Sex (sample size of participant): Female Male	24 participants 6 participants	24 participants 6 participants	
Age (years)	54.53 (5.69)	54.33 (4.42)	
Height (cm)	166.46 (7.54)	169.61 (7.38)	0.11
Mass (kg)	76.18 (18.22)	85.82 (15.84)	0.03*
BMI (kg/m ²)	27.37 (5.94)	29.86 (5.40)	0.10
Questionnaire Forms			
SF-36 (points)	105.03 (6.72)	100.90 (7.24)	0.03*
IPAQ (MET minutes/week)	8188.26 (5252.64)	5091.04 (4087.71)	0.01*
FAAM-ADL ^a (points)	81.50 (4.21)	67.60 (10.80)	0.00**
FAAM-Sport ^a (points)	23.60 (6.70)	16.00 (6.58)	0.00**
MFPDI ^a (%)	4.82 (11.31)	38.38 (16.44)	0.00**
Lower Extremity Range of Motion (degrees)			
Ankle Dorsiflexion ^a	47.64 (5.93)	43.41 (5.89)	0.01*
Knee Extension (Hamstring Length)	169.03 (8.83)	168.96 (6.86)	0.97
Lower Extremity Muscles Strength (kg)			
Hip abductor	24.72 (7.70)	22.53 (3.75)	0.17
Hip extensor	22.12 (6.80)	18.78 (4.77)	0.03*
Knee extensor	27.98 (7.49)	25.75 (5.09)	0.18
Knee flexor	15.55 (3.97)	13.51 (2.68)	0.02*
Ankle dorsiflexor	15.37 (4.80)	12.79 (3.30)	0.02*
Foot evertor	9.63 (2.02)	8.62 (1.41)	0.03*
Ankle plantar flexor	31.87 (8.58)	28.50 (7.47)	0.11
Intrinsic 2 nd – 5 th Toe Flexors	11.17 (3.36)	9.80 (2.35)	0.07
Intrinsic Hallux Flexors	10.60 (2.60)	8.68 (3.31)	0.02*
Gait Speed (m/s)			
Preferred Walking Speed	1.30 (0.08)	1.24 (0.11)	0.01*
Fixed Walking Speed ^a	1.32 (0.06)	1.29 (0.06)	0.13
MET = multiples of the resting metabolic rate			
^a Data did not follow a normal distribution.			
* Significant between group difference – Independent t-tests			
** Significant between group difference – Mann-Whitney U tests			

Gait Kinematics

Kinematics data results are presented in Table 2.4. After statistically controlling for the effects of sex and BMI as covariates, patients with PHP demonstrated significant kinematic differences compared to the CON group during the loading response and mid/terminal stance phases of gait. During loading response, the PHP group demonstrated decreased rearfoot complex lateral rotation [$F(1,56) = 5.52, p = 0.02$, partial eta squared = 0.09], decreased medial midfoot dorsiflexion [$F(1,56) = 4.02, p =$

0.05, partial eta squared = 0.07], and increased medial forefoot dorsiflexion [$F(1,56) = 4.92$, $p = 0.03$, partial eta squared = 0.08] ROM compared to the CON group (Table 2.4, Figures 2.2, 2.3, and 2.4). During mid/terminal-stance the PHP group demonstrated decreased rearfoot complex dorsiflexion ROM [$F(1,56) = 6.44$, $p = 0.01$, partial eta squared = 0.10] (Table 2.4, Figure 2.5). The time-series for the non-significant joints/functional articulations investigated are presented in Appendix K.

Table 2.4. Mean (SD) Joint/Functional Articulation Stance Subphase ROM (°).

Joint-Plane	Loading Response			Mid/terminal			Push-Off		
	CON	PHP	η^2	CON	PHP	η^2	CON	PHP	η^2
Hip-Sag	-3.82 (2.42)	-4.71 (2.76)	0.01 ^a	-44.57 (3.91)	-44.70 (5.67)	0.00	10.68 (1.97)	11.49 (2.09)	0.02
Hip-Fron	5.62 (2.44)	5.68 (1.74)	0.00	1.51 (4.96)	1.56 (3.98)	0.00	-5.75 (1.58)	-5.97 (1.74)	0.01
Knee-Sag	-15.15 (2.81)	-14.87 (2.53)	0.00	20.34 (3.92)	21.72 (5.75)	0.01	-32.35 (4.23)	-33.33 (4.50)	0.00
RC-Sag	-6.49 (3.37)	-4.85 (4.91)	0.05 ^a	14.93 (2.92)	12.76 (2.75)	0.10*	-19.20 (4.44)	-18.46 (4.58)	0.02 ^a
RC-Fron	-3.46 (2.22)	-3.55 (2.17)	0.00	4.36 (3.06)	4.11 (3.52)	0.00 ^a	3.56 (2.08)	4.07 (2.61)	0.00
RC-Tran	-6.11 (2.02)	-5.20 (1.58)	0.09*	7.07 (3.05)	6.04 (3.11)	0.02	4.06 (2.27)	4.26 (2.64)	0.00
MMF-Sag	3.00 (1.01)	2.34 (1.80)	0.07*	-2.59 (1.99)	-2.53 (1.85)	0.00	-1.34 (2.58)	-1.27 (2.85)	0.00
MMF-Fron	-1.95 (1.72)	-1.74 (1.81)	0.01	-4.17 (2.64)	-4.76 (1.97)	0.01	2.30 (2.36)	3.30 (2.05)	0.03
MMF-Tran	-0.50 (1.80)	-0.86 (1.78)	0.00	-2.26 (2.96)	-2.15 (3.09)	0.00	1.77 (2.18)	1.93 (3.08)	0.00
LMF-Sag	2.59 (1.44)	2.91 (1.50)	0.01	0.44 (2.44)	0.49 (2.20)	0.00	-4.74 (2.18)	-5.91 (2.28)	0.04
LMF-Fron	-3.34 (1.54)	-3.28 (3.11)	0.01	4.31 (2.12)	3.57 (2.52)	0.03	0.99 (2.53)	1.89 (3.44)	0.02
LMF-Tran	-2.22 (1.87)	-2.82 (1.62)	0.02 ^a	-1.04 (3.26)	-0.20 (2.26)	0.03	4.79 (2.15)	5.02 (2.21)	0.00
MFF-Sag	3.38 (2.51)	4.26 (2.18)	0.08*	6.00 (3.07)	5.96 (4.05)	0.01 ^a	-17.44 (4.60)	-19.12 (4.60)	0.02
MFF-Fron	0.22 (1.95)	-0.13 (2.08)	0.00 ^a	3.78 (2.84)	3.32 (3.15)	0.02 ^a	-7.69 (3.36)	-8.51 (3.21)	0.00
LFF-Sag	2.26 (1.05)	2.09 (1.24)	0.00	-0.54 (2.21)	0.37 (2.29)	0.01 ^a	-6.22 (2.45)	-6.35 (2.05)	0.00
LFF-Fron	-4.13 (2.82)	-4.04 (3.01)	0.00	2.77 (4.50)	3.38 (3.83)	0.01 ^a	1.59 (2.67)	0.15 (3.56)	0.04 ^a
MTP-Sag	-12.91 (6.93)	-14.27 (4.61)	0.01	11.85 (10.19)	14.52 (6.78)	0.06 ^a	27.49 (7.22)	26.40 (5.66)	0.03

Sag = Sagittal plane, Fron = Frontal plane, Tran = Transverse plane.
^a Data did not follow a normal distribution.
* Significant between group difference – Independent t-tests

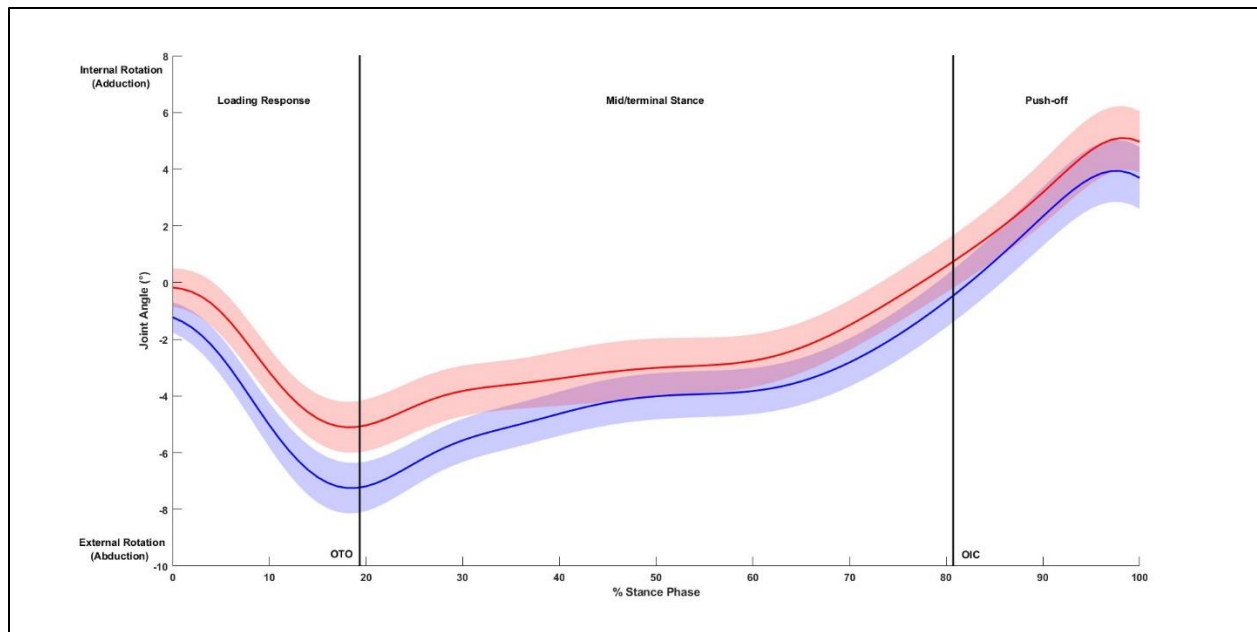


Figure 2.2. Rearfoot Complex Transverse Plane CON (blue) and PHP (red) Group Time-Series (Mean $\pm$ 1 SD). OTO = Opposite Toe-off and OIC = Opposite Initial Contact.

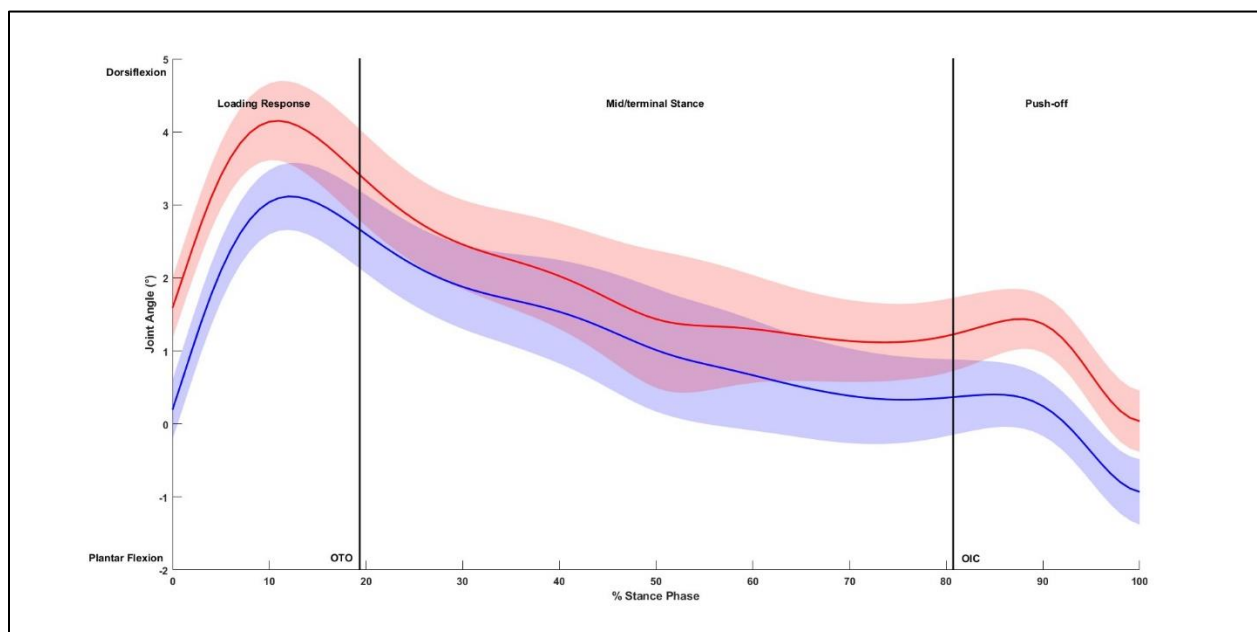


Figure 2.3. Medial Midfoot Sagittal Plane CON (blue) and PHP (red) Group Time-Series (Mean $\pm$ 1 SD). OTO = Opposite Toe-off and OIC = Opposite Initial Contact.

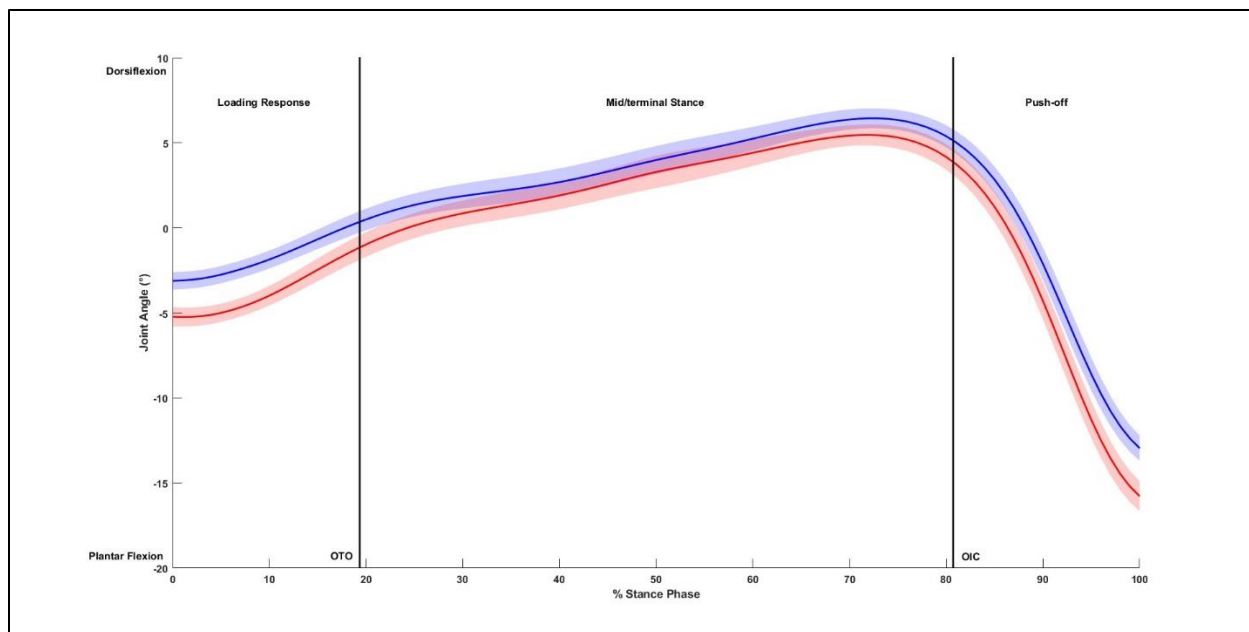


Figure 2.4. Medial Forefoot Sagittal Plane CON (blue) and PHP (red) Group Time-Series (Mean $\pm$ 1 SD). OTO = Opposite Toe Off and OIC = Opposite Initial Contact.

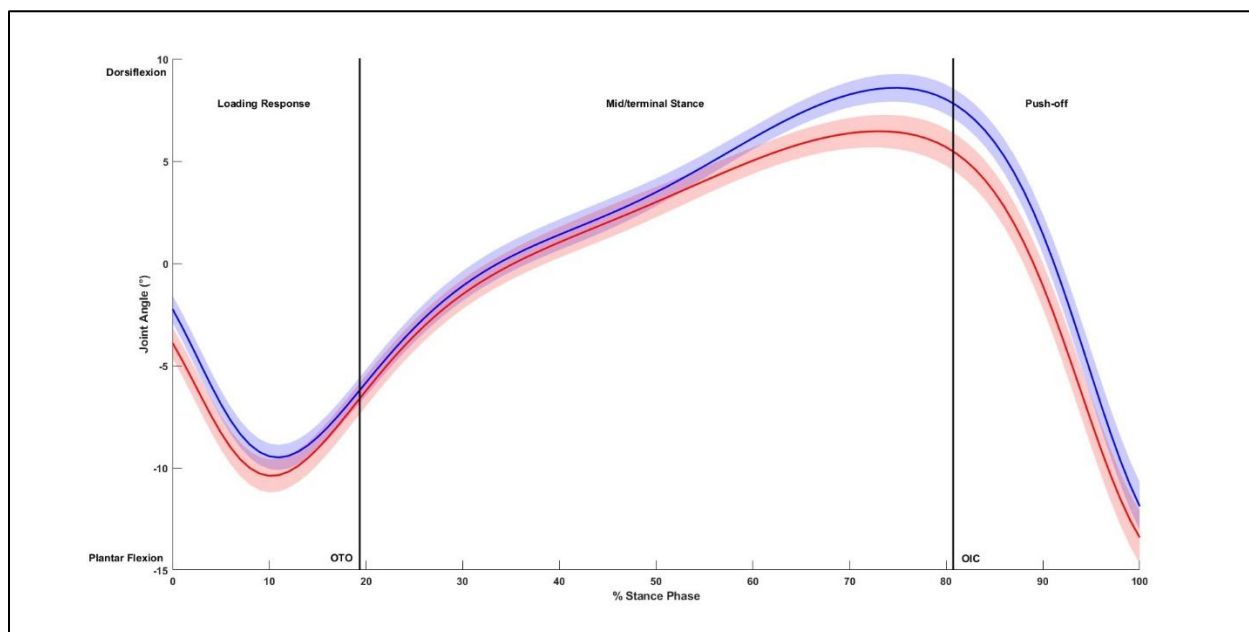


Figure 2.5. Rearfoot Complex Sagittal Plane CON (blue) and PHP (red) Group Time-Series (Mean $\pm$ 1 SD). OTO = Opposite Toe-off and OIC = Opposite Initial Contact.

Discussion

The purpose of this study was to investigate the kinematic differences in foot and lower-extremity gait patterns among middle-aged individuals with PHP. We hypothesized that, due to degeneration of the plantar aponeurosis associated with PHP, individuals with PHP would exhibit increased pronation during early stance and decreased supination during late stance.

Descriptive Data

The significantly increased body mass in the PHP group is consistent with previous studies that investigated risk factors associated with PHP (Irving et al., 2007; Sullivan et al., 2015b). However, the lack of significant difference between the PHP and CON group BMIs is not consistent with previous studies that investigated risk factors associated with PHP (Irving et al., 2007; Rano et al., 2001; Riddle et al., 2003; Sullivan et al., 2015b; Thomas et al., 2019). It may be important for future studies to investigate if body mass or BMI is more strongly associated with, or a better predictor of, PHP.

The present study identified significant impairments across the HRQOL (SF-36), physical activity (IPAQ), and foot function (FAAM, MFDPI) assessed domains in individuals with PHP that were consistent with previous studies. The diminished HRQOL in the PHP group supports evidence linking chronic pain to reduced overall health (Irving et al., 2007) and the significantly lower IPAQ scores align with prior research indicating that pain-induced mobility restrictions contribute to decreased physical activity (Tountas and Fornasier, 1996) and an overall sedentary lifestyle (Riddle et al., 2004). Additionally, significantly lower FAAM and significantly higher MFPDI scores in the PHP

group confirm the condition is associated with substantial foot pain and disability (Thomas et al., 2019).

With respect passive joint ROM, the reduced ankle dorsiflexion ROM in individuals with PHP is consistent with previous studies suggesting that gastrocnemius and soleus tightness may contribute to increasing strain on the plantar aponeurosis (Cornwall and McPoil, 1999; DeMaio et al., 1993; Molund et al., 2018; Patel and DiGiovanni, 2011; Riddle et al., 2003). The lack of significantly decreased knee extension ROM (hamstring tightness) between the groups was not consistent with previous studies (Bolívar et al., 2013; Labovitz et al., 2011). Two factors may have contributed to the inconsistency. First, the current study consisted of primarily female participants (24/30 in each group) versus the previous studies that included more male subjects. This may be relevant as some studies have reported greater prevalence of hamstring tightness in males versus females (Marshall and Siegler, 2014; Youdas et al., 2005). Second, the Bolivar et al. (2013) study excluded participants that had received hamstring stretching exercises as part of their PHP treatment. A history of hamstring stretching was not an exclusion criteria for PHP patients in the current study.

With respect to lower extremity muscle strength, patients with PHP demonstrated significantly decreased hip extensor, knee flexor, ankle dorsiflexor, foot evtor, and intrinsic hallux flexor strength compared to the CON group. The decreased hip extensor, knee flexor, and ankle dorsiflexor strength in the PHP group are consistent with proximal joint strength changes anticipated by the pain-adaptation model (Lund et al., 1991). However, it is also possible the weakness was due to decreased activity in the PHP group. The decreased foot evtor and intrinsic hallux flexor strength are

consistent with previous studies (Allen and Gross, 2003; McClinton et al., 2016; Sullivan et al., 2015b; Yildiz et al., 2018), and may be particularly important due their role as dynamic stabilizers to control pronation during loading response and facilitate supination during late stance. Weakness in the muscles may compromise these functions resulting in increased strain on the plantar aponeurosis that could lead to the development and/or persistence of PHP.

Finally, patients with PHP walked at a significantly slower self-selected walking speed compared to the uninjured individuals. Patients with PHP may decrease their preferred walking speed to decrease pain associated with the impact of initial foot contact in early stance and/or push-off in late stance.

Gait Kinematics

The original hypothesis was that, due to degeneration of the plantar aponeurosis associated with PHP, patients with PHP would demonstrate increased pronation during early stance and insufficient supination during late stance. The changes would reflect a decreased ability of the plantar aponeurosis to control pronation in early stance and to facilitate supination in late stance. However, the decreased rearfoot complex lateral rotation and medial midfoot dorsiflexion ROM during loading response and decreased rearfoot complex dorsiflexion ROM during mid/terminal stance were not consistent with this hypothesis. These inconsistencies may have been due to the decreased passive dorsiflexion ROM and/or a pain-avoidant gait adaptation in the patients with PHP.

Limited passive dorsiflexion ROM could potentially restrict the amount of rearfoot pronation in early stance and again as the rearfoot is transitioning from dorsiflexion to plantar flexion in mid-late stance. However, given that PHP patients had an average of

43.4° of passive dorsiflexion ROM and that the peak dorsiflexion positions in early stance and mid-late stance were not likely near the end-range, limited passive dorsiflexion ROM restricting pronation may not have been the primary factor. Another possibility is that the patients with PHP were limiting the amount of pronation to avoid pain caused by strain on the plantar aponeurosis in early and mid-late stance. This may be supported by a previous walking gait study of injured participants that suggested the plantar aponeurosis is preloaded prior to initial contact, tension is maintained until approximately 30% of stance, and then increases to a peak at approximately 80% of stance (Caravaggi et al., 2009). Further, following initial contact and during push-off, 90% (27/30) of the PHP patients in the current study self-reported having pain during walking gait; during walking trials, 80% (24/30) of the PHP patients reported experiencing heel pain, and their pain increased after walking. It should also be noted that although the limited passive dorsiflexion ROM may not have restricted pronation, it may have been associated with earlier/increased plantar aponeurosis strain and pain as the rearfoot complex dorsiflexed.

The increased medial forefoot dorsiflexion ROM during the loading response in patients with, which is associated with increased pronation (Hicks, 1953), was consistent with our original hypothesis. The reason for the anticipated change at the medial forefoot, but not the rearfoot and medial midfoot may be related to when the differences occurred within loading response. Inspection of the stance phase time-series of the rearfoot complex (Figure 2.2) and medial midfoot (Figure 2.3), which both include the calcaneus segment, suggest that the difference between the groups occurred primarily in the early-mid loading response period just after initial contact when

patients with PHP may be experiencing an acute increase in heel pain. Inspection of the medial forefoot time-series (Figure 2.4), which does not include the calcaneus segment, suggests the difference between the groups occurred primarily during mid-late loading response. The loading of the medial forefoot would not begin to increase dramatically until after foot flat (approximately 10% stance) and after the acute increase in pain associated with initial contact.

Comparison of the current study results with the three previous multi-segment foot models is difficult due to the differences in the foot models used, the study inclusion/exclusion criteria, and the calculation of the variables of interest (Bovonsunthonchai et al., 2019; Chang et al., 2014; Harutaichun et al., 2021). The current study results cannot be compared with those of Bovonsunthonchai et al. (2019) due that study calculating ROM as the difference between maximum and minimum positions over the entire gait cycle versus just stance phase.

Chang et al. (2014), which included rearfoot complex and medial forefoot functional articulations, reported increased rearfoot complex eversion and medial forefoot dorsiflexion stance phase ROM (maximum stance phase position minus initial contact position) in patients with PHP. Although patients with PHP in the present study did demonstrate increased rearfoot complex eversion ROM during the loading response subphase, the difference was not statistically significant. The significantly increased medial forefoot dorsiflexion ROM in patients with PHP in the present study is consistent with Chang et al. (2014), however, the differences in the calculation of the ROM (loading response versus entire stance phase) should be noted.

The Harutaichun et al. (2021) study was the most similar to the current study in terms of the foot functional articulations defined (rearfoot, midfoot, forefoot) and the calculation of the variables of interest within stance subphases. While both the Harutaichun et al. (2021) and the present study reported significant rearfoot complex and forefoot ROM differences in patient with PHP during loading response, the differences in the two studies were opposite. Patients with PHP in the Harutaichun et al. (2021) demonstrated increased rearfoot complex medial rotation and decreased forefoot dorsiflexion ROM. Both studies also reported significantly decreased midfoot dorsiflexion ROM in patients with PHP, however, the subphase in which the differences occurred were different. In the present study, the difference occurred during loading response, while the difference in the Harutaichun et al. (2021) study occurred during terminal stance. There were also several other differences that were not consistent between the two studies. During mid/terminal stance patients with PHP in the Harutaichun et al. (2021) demonstrated increased forefoot eversion, decreased hip extension, and decreased knee extension ROM. During same subphase, patients with PHP in the present study exhibited decreased rearfoot complex ROM (Figure 2.5). Finally, during push-off, hip abduction ROM was significantly increased patients with PHP in the Harutaichun et al. (2021) study. The differences between the studies may have been related to the inclusion/exclusion criteria and/or the foot models used. With respect the inclusion/exclusion criteria, participants in the Harutaichun et al. (2021) were male military recruits, and potential PHP participants were excluded if they had pain during the walking gait trials. This contrasts to the participants in the present study that were middle-aged, mostly female, less physically active, and were experiencing heel

pain during the gait trials. It is possible that patients with PHP exhibit different gait patterns during periods of time when they are symptomatic versus asymptomatic. With respect to the foot models, while both studies included midfoot and forefoot functional articulations, the Harutaichun et al. (2021) study defined a single midfoot functional articulation and a single forefoot functional articulation whereas the present study defined medial and lateral midfoot and medial and lateral forefoot functional articulations.

Before drawing conclusions regarding this study, several limitations should be considered. First, the present study only investigated middle-aged individuals with PHP, therefore the results may not be generalizable to younger or older adult PHP patients. Second, to allow placement of the markers associated with the multi-segment foot model, walking gait was performed barefoot, therefore the results may not be applicable to shod walking gait. Third, because the patients with PHP walked at a slower preferred walking speed, and speed can influence joint kinematics, only the fixed gait speed trials were assessed. While the decision removed the potential for joint kinematic differences to be due to walking speed and not PHP, some individuals may have altered their gait if the fixed speed was faster or slower than their preferred speed. Fourth, because this was a retrospective study, it is not possible to determine if the differences in the patients with PHP were the cause or effect of PHP.

Conclusion

This is the first study to investigate lower extremity and foot function in middle-aged adults with PHP, the portion of the population most affected by the condition. Our results suggest that in addition to decreased foot evor and intrinsic foot flexor

strength and decreased passive ankle dorsiflexion ROM that could contribute to increase plantar aponeurosis strain, middle-aged patients with PHP also have decreased strength in the proximal lower extremity joints. These results emphasize the importance for PHP treatment/rehabilitation programs to assess the entire lower extremity, not just the foot. The results of the walking gait assessment suggest PHP affects the function of the entire foot, and that patients with symptomatic PHP may adopt a gait strategy to avoid/limit pain caused by strain on the plantar aponeurosis in early and mid-late stance. Future prospective studies are needed to determine if the differences identified in the current study are the cause or effect of PHP. Future retrospective studies of patients with recurring PHP are also warranted to determine if patients adopt different gait patterns when symptomatic versus asymptomatic.

CHAPTER THREE: THE INFLUENCE OF PLANTAR HEEL PAIN ON FOOT AND LOWER EXTREMITY WALKING GAIT NEUROMUSCULAR FUNCTION IN MIDDLE-AGED ADULTS

Introduction

A recent cross-sectional study of data from the National Health and Nutrition Examination Survey (NHANES) reported that 11.1% adults aged ≥ 20 years experienced PHP, with the highest overall prevalence (14.5%) in individuals aged 50–65 (Liu et al., 2024). Further, the condition often proves persistent, with symptom duration ranging from 6 to 96 months (Davis et al., 1994), and 44% of individuals reporting ongoing symptoms up to 15 years post-diagnosis (Hansen et al., 2018). Despite intervention, the prevalence and persistence of PHP also imposes a substantial, long-term burden, marked by impaired mobility (Nahin, 2018; Riddle and Schappert, 2004), reduced physical activity and participation (Thomas et al., 2019), and diminished health-related quality of life (HRQOL) (Fernandez-Lao et al., 2016).

The limited efficacy of current PHP interventions is underscored by the absence of a standardized treatment protocol (Klein et al., 2012). A critical barrier to advancing management strategies is the insufficient understanding of neuromuscular difference gait alterations in individuals with PHP. Without this knowledge, the development of effective preventive and therapeutic interventions remains constrained. Although the clinical belief is that degeneration of the plantar aponeurosis leading to the development of PHP (Leach et al., 1986; Snider et al., 1983; Tountas and Fornasier, 1996) is the result of mechanical overload of the plantar aponeurosis during activities such as gait, the effect of PHP on lower extremity neuromuscular function during gait remains poorly understood.

To date, only one study has examined lower extremity electromyographic (EMG) activity during gait in this population (Moyne-Bressand et al., 2018). While no differences in EMG amplitude of the lower extremity muscles were observed during stance, patients with PHP demonstrated elevated soleus muscle reflex max/muscle max and reflex wave/muscle wave ratios, suggesting altered reflexive neuromuscular control. Notably, these abnormalities persisted even after pain reduction, indicating potential long-term neuroplastic adaptations to chronic pain (Moyne-Bressand et al., 2018).

In addition to EMG analysis, net joint power analysis is an established method for assessing neuromuscular function during gait (Winter and Eng, 1995). Despite its utility in chronic ankle/foot injury research (Chimenti et al., 2016; Kim et al., 2019), it has yet to be applied to the study of PHP.

The purpose of this study was to identify the lower-extremity neuromuscular gait difference in middle-aged PHP patients. We hypothesized that PHP patients would demonstrate lower extremity neuromuscular difference during the early and late stance phases of gait. During early stance, we hypothesized patients with PHP would demonstrate increased concentric hip extensor power, increased eccentric hip abductor frontal plane power, increased sagittal plane knee eccentric power, and increased knee extensor muscular activity to decrease impact load on the calcaneus. During the late stance, we postulated PHP patients would exhibit decreased muscular activity and decreased concentric ankle joint plantar flexor power along with compensatory increased knee extensor muscular activity and increased knee and hip joint sagittal plane concentric power.

Method

Participants

A total of 60 middle-aged adults (aged 45–64 yrs), comprising individuals with PHP symptomatic (PHP; $n = 30$) and asymptomatic (CON; $n = 30$), were recruited for this investigation. The sample size was determined a priori using G*Power (version 3.1.9.4), informed by data from previous study employing neuromuscular function (Moyne-Bressand et al., 2018) during gait. Power analysis was conducted for a one-way ANCOVA with fixed effects, examining main effects and interactions. The parameters for the power analysis included: [$\alpha = 0.05$, $\beta = 0.20$; degrees of freedom = 1, large effect size (Cohen's $f = 0.40$)]. The analysis indicated that a minimum of 20 to 26 participants per group was required to achieve adequate statistical power. A one-way repeated-measures ANCOVA was employed to evaluate intergroup differences, while statistically controlling for the confounding influences of sex and Body Mass Index (BMI).

PHP participants had: a history of an insidious onset of PHP lasting for at least the past three months (Irving et al., 2008); point tenderness at the proximal attachment of the plantar aponeurosis (medial calcaneal tubercle); and a complaint of pain with the initial steps in the morning, following periods of prolonged inactivity, or during prolonged weight-bearing activity (Bovonsunthonchai et al., 2019; Riddle et al., 2003; Sullivan et al., 2015a). The uninjured (CON) group were age (± 5 y), sex, and limb matched with the participants in the PHP group.

Exclusion criteria for PHP participants included PHP that could not be reproduced during a screening clinical exam, previous surgical treatment for PHP (e.g., plantar aponeurosis release) and/or recent (within the previous six months) non-surgical

PHP treatment from an allied health professional (e.g., physical therapy, custom-molded foot orthoses, corticosteroid injection). Exclusion criteria for both groups included: significant lower limb edema; current/history of (previous 3 months) low back, lower extremity, or foot pain (except PHP for the PHP group); a history of major lower extremity injury or surgery; or other medical conditions that may result in plantar foot pain (e.g., diabetes, arthritis, neuromuscular or vascular disease) (Moyne-Bressand et al., 2018); current use of medications that may cause dizziness or impair the ability to walk; or implanted electronic devices of any kind (e.g., cardiac pace-makers). Pregnancy was also an exclusion criterion for females due to ligament/aponeurosis laxity that occurs with pregnancy.

Procedures

Before participating in the study, potential PHP patients received a brief clinical screening examination: to confirm that the PHP symptoms could be reproduced and were attributable to pathology of the plantar aponeurosis; and to exclude alternative etiologies of heel pain. Next, the study procedures were explained and all qualified participants provided informed consent in accordance with protocols approved by the University's Institutional Review Board.

The lower extremity muscle activity of the involved limb of PHP patients and the matched limb of CON participants during the gait trials were assessed by bipolar surface electrodes (Trigno, Delsys, 35 Natick, MA) sampling at 2000 Hz. Following skin preparation, surface electrodes were placed on the tibialis anterior, fibularis longus, medial gastrocnemius, quadriceps, biceps femoris, following SENIAM guidelines (Hermens et al., 1999) and the revisions to the guidelines proposed by Sacco et al.

(2009). Appropriate muscle testing was performed for each muscle to confirm correct EMG placement before data collection. Participants then completed three MVIC trials for each muscle. The peak EMG activity of the three maximal isometric trials for each muscle was used to normalize muscle activity during the gait trials.

All participants completed 10 successful barefoot walking trials at a self-selected pace, as well as 10 additional trials at a standardized walking speed of 1.3 m/s along a 15-meter walkway. The fixed-speed condition was within the normative gait velocity range for adults aged 50 to 64 years (Whittle et al., 2012). Gait speed was monitored using an optoelectronic timing system. Additionally, three force plates (AMTI, Watertown, MA, USA), embedded in the middle of the walkway and sampling at 2000 Hz, were utilized to capture ground reaction forces and identify stance phase events. The vertical GRF data was then used to identify the initial contact and toe-off stance events (20 N threshold) and the stance subphases. The events identified included involved limb initial contact, opposite limb toe-off, opposite limb initial contact, and involved limb toe-off. The events were used to identify loading response (involved limb initial contact to opposite limb toe-off), midstance-terminal stance (opposite limb toe-off to opposite limb initial contact), and push-off (opposite limb initial contact to involved limb toe-off) stance subphases. A trial was considered successful if foot contact for both the involved and contralateral limbs occurred entirely within the designated force plates, and the participant's walking velocity remained within $\pm 10\%$ of the prescribed speed condition (preferred or fixed).

Data Processing

Following completion of the gait trials, three-dimensional positions of the markers collected during the static calibration and gait trials were tracked using Cortex software (version 8.0, Motion Analysis Inc, Santa Rosa, CA). To assess lower extremity EMG activity, the synchronized force plate and EMG data were exported for subsequent data processing in MATLAB (R2024b, MathWorks, Natick, MA, USA). The EMG data during the isometric testing and gait trials were filtered using a 4th order zero-lag Butterworth bandpass filter (10 Hz – 350 Hz), fully rectified, and smoothed (30 ms moving window). The mean EMG of each muscle within each stance subphase during the gait trials was normalized to the muscle's peak activity during the isometric testing.

To assess lower extremity net joint power during gait, the synchronized marker position and force plate data were exported for subsequent data processing in Visual3D (C-Motion, Inc., Germantown, MD). The position and GRF data were low-pass filtered using a fourth-order zero-lag Butterworth filter with a cut-off frequency of 6 Hz (Bruggemann et al., 2008; Massaad et al., 2007). The hip joint center was calculated using the Bell et al. (1990) regression equations. Joint centers of the knee and ankle were calculated as the midpoint between the medial and lateral femoral epicondyles and malleoli, respectively. Body segment parameters were defined using the regression equations proposed by Dempster (1955). Sagittal plane joint hip, knee, and ankle joint net joint moments were expressed as internal moments in the proximal segment coordinate system (positive internal moments: extension/plantar flexion) and normalized to participant's body mass. Finally, sagittal plane net joint hip, knee, and ankle power during each trial were calculated as the product of the normalized net joint moments,

and the joint angular velocities. Positive power was associated with concentric muscle actions.

Statistical Analysis

For all the statistical analyses, the variables of interest from each of the five gait trials were averaged for each participant. Prior to performing the statistical analysis, the normality of all data was assessed using the Kolmogorov-Smirnov test. For normally distributed variables, one-way ANCOVAs were performed to investigate group differences. The Rank-Based ANCOVA tests were performed for non-normally distributed variables. Because the influence of sex on foot function, and as a risk factor for PHP, have not been definitively determined, sex was used as a covariate. BMI, which has been identified as a potential risk factor for PHP, was also used as a covariate. All statistical analyses were performed using SPSS (SPSS, version 28), and the significance for the statistical tests was set at $\alpha = 0.05$. Partial eta squared [small (0.01), medium (0.06), and large (0.14)] effect sizes were calculated to enhance interpretation of the clinical relevance of the results.

Lower Extremity EMG Activity. The normalized mean EMG of each muscle (tibialis anterior, fibularis longus, medial gastrocnemius, rectus femoris, biceps femoris) within the three stance subphases were the dependent variables of interest. Separate ANCOVAs were performed for each dependent variable of interest during each stance subphase. The independent variable in each one-way ANCOVA was group (PHP, CON).

Lower Extremity Net Joint Power. The dependent joint power variables of interest were the peak positive and negative sagittal plane net joint hip, knee, and ankle

joint powers during stance. For the ankle, this included an eccentric peak (A1) and a concentric peak (A2) (Figure 3.1). For the knee, this included two eccentric peaks (K1, K3) and a concentric peak (K2) (Figure 3.2). For the hip sagittal plane, this included two concentric peaks (H1, H3), and an eccentric peak (H2) (Figure 3.3) (Winter and Eng, 1995). For the hip frontal plane, this included one eccentric peak (H1) and two concentric peaks (H2, H3) (Sadeghi et al., 1997). Separate ANCOVAs were performed for each dependent variable of interest. The independent variable in each one-way ANCOVA was group (PHP, CON).

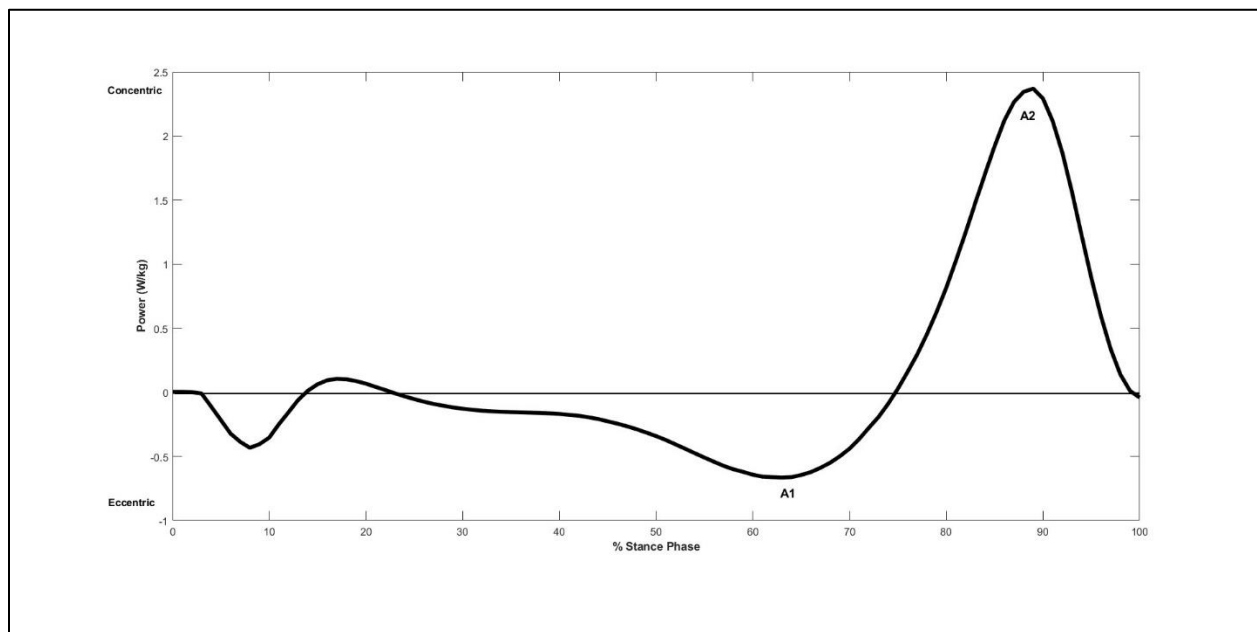


Figure 3.1. Representative Sagittal Plane Ankle Net Joint Power Stance Phase Time-series. A1 = Eccentric Plantar Flexor Peak and A2 = Concentric Plantar Flexor Peak.

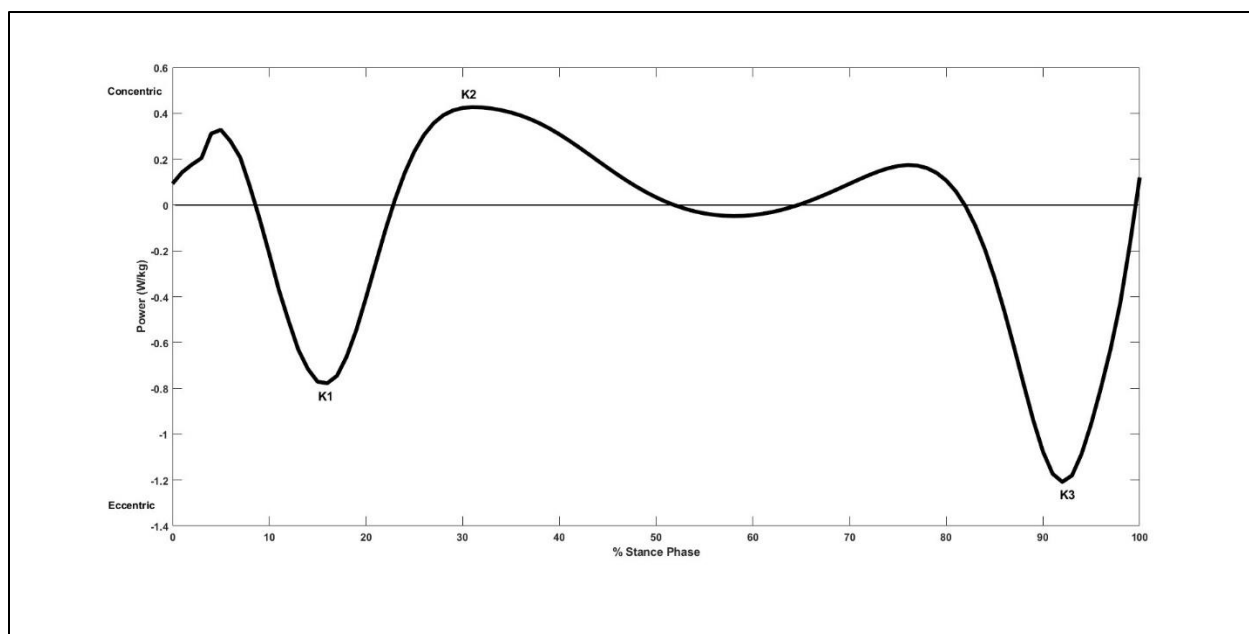


Figure 3.2. Representative Sagittal Plane Knee Net Joint Power Stance Phase time-series. K1 = Eccentric Knee Extensor Peak, K2 = Concentric Knee Extensor Peak, and K3 = Eccentric Knee Extensor Peak.

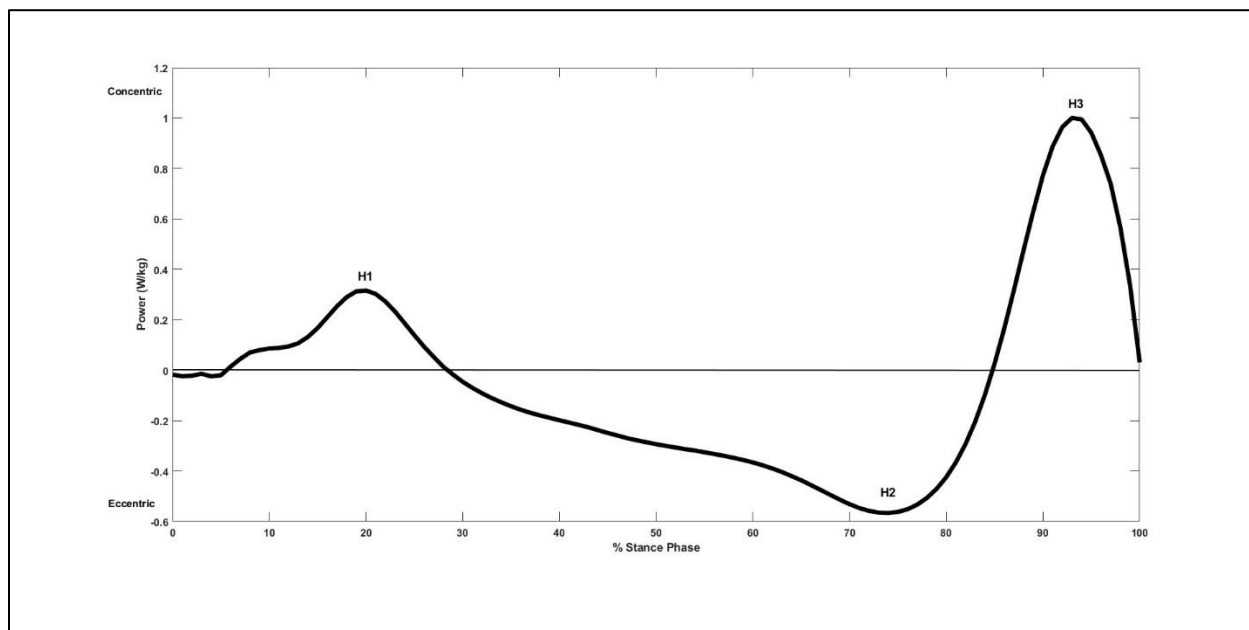


Figure 3.3. Representative Sagittal Plane Hip Net Joint Power Stance Phase time-series H1 = Concentric Extensor Peak, H2 = Eccentric Flexor peak, and H3 = Concentric Flexor Peak.

Results

Descriptive Data

Participants' descriptive data and the statistical analyses of the descriptive data are reported in Chapter 2.

Lower Extremity Muscle EMG Activity. Results of the lower extremity muscle EMG activity are presented in Table 3.1. After statistically controlling for the effects of sex and BMI as covariates, there were no statistically significant group differences for any of the muscle activity variables of interest.

Lower Extremity Net Joint Power. Results of the lower extremity net joint power analyses are presented in Table 3.2. After statistically controlling for the effects of sex and BMI as covariates, patients with PHP demonstrated lower sagittal peak joint power of the ankle during the eccentric peak (A1) [$F(1,56) = 5.45$, $p = 0.02$, partial eta squared = 0.09] compared to the CON group (Table 3.2 and Figure 3.4). The peak joint power time-series for the non-significant joint power variables investigated are presented in Appendix L.

Table 3.1. Mean (SD) EMG Muscle Activity (% MVIC).

Muscles	Loading Response			Mid/terminal			Push-Off		
	CON	PHP	η^2	CON	PHP	η^2	CON	PHP	η^2
Quadriceps	20.36 (17.30)	20.16 (13.25)	0.01 ^a	9.32 (8.26)	10.46 (6.95)	0.00 ^a	35.41 (18.66)	60.98 (87.87)	0.02 ^a
Hamstrings	10.58 (7.91)	13.19 (13.36)	0.00 ^a	57.65 (33.15)	47.34 (20.41)	0.06	35.10 (18.70)	39.76 (50.54)	0.00 ^a
Tibialis Anterior	10.09 (7.03)	12.33 (10.98)	0.00 ^a	10.74 (7.20)	11.88 (10.68)	0.00 ^a	23.51 (20.82)	38.64 (32.03)	0.04 ^a
Fibularis Longus	42.64 (33.92)	37.00 (26.97)	0.02 ^a	4.17 (2.42)	6.70 (10.76)	0.01 ^a	52.68 (23.56)	56.72 (28.33)	0.00 ^a
Gastrocnemius	13.74 (9.41)	13.98 (11.22)	0.00 ^a	33.65 (17.50)	42.39 (47.33)	0.00 ^a	17.37 (13.54)	21.74 (26.73)	0.00 ^a

^a Data did not follow a normal distribution.

Table 3.2. Mean (SD) Peak Joint Power (W/kg).

Group	CON	PHP	η^2
Net Joint Power			
Hip-Fron (H1)	- 0.62 (0.25)	- 0.61 (0.26)	0.01
Hip-Fron (H2)	0.23 (0.21)	0.20 (0.18)	0.00
Hip-Fron (H3)	0.57 (0.17)	0.55 (0.16)	0.01
Hip-Sag (H1) ^a	0.38 (0.28)	0.39 (0.28)	0.01
Hip-Sag (H2)	- 0.61 (0.23)	- 0.55 (0.22)	0.00
Hip-Sag (H3)	1.04 (0.27)	1.00 (0.25)	0.00
Knee-Sag (K1)	- 0.87 (0.31)	- 0.85 (0.32)	0.00
Knee-Sag (K2) ^a	0.48 (0.24)	0.49 (0.29)	0.00
Knee-Sag (K3)	-1.27 (0.38)	-1.26 (0.31)	0.00
Ankle-Sag (A1) ^a	- 0.78 (0.29)	- 0.59 (0.21)	0.09*
Ankle-Sag (A2)	2.42 (0.43)	2.21 (0.51)	0.03

Sag = Sagittal plane, Fron = Frontal plane.
 Positive values are associated with concentric muscle actions
 Negative values are associated with eccentric muscle actions
^a Data did not follow a normal distribution.
 *Significant between group difference – Mann-Whitney U tests

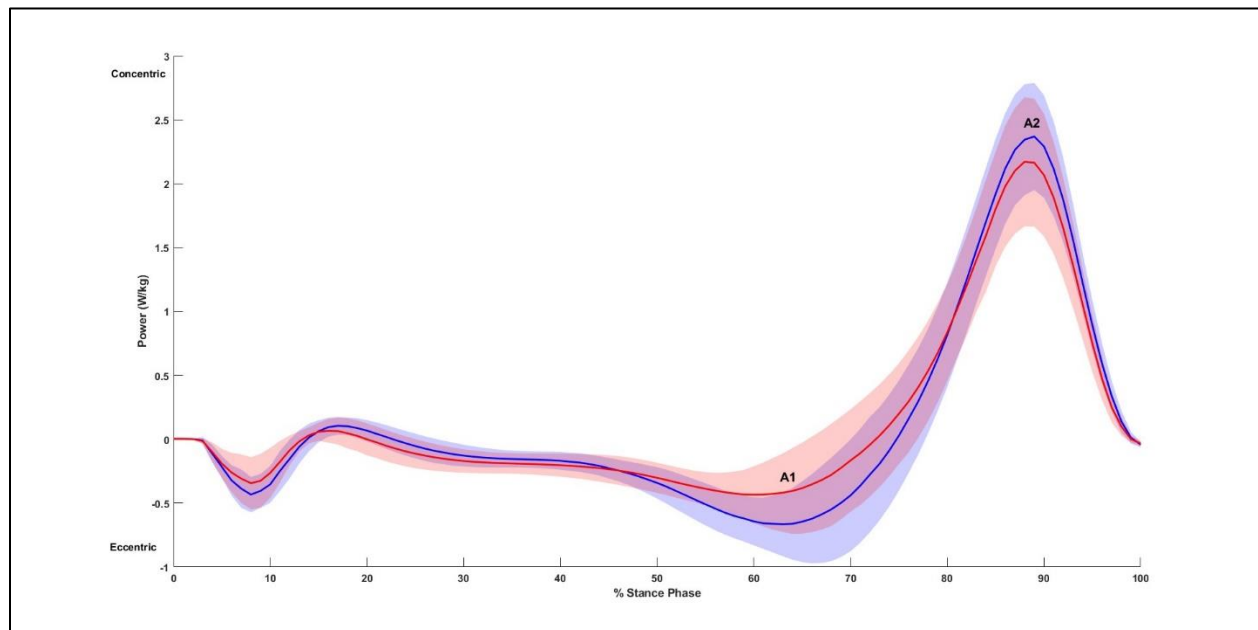


Figure 3.4. Sagittal Plane Ankle Net Joint Power Time-Series (Mean $\pm$ 1 SD) for the CON (blue) and PHP (red) Groups. A1 = Eccentric Plantar Flexor Peak and A2 = Concentric Plantar Flexor Peak.

Discussion

The objective of this study was to identify lower-extremity neuromuscular gait alterations in middle-aged individuals with PHP. We hypothesized that individuals with plantar PHP would exhibit altered lower extremity neuromuscular function during both early and late stance phases of gait. During early stance, we expected greater concentric hip extensor and hip abductor frontal plane power, increased eccentric knee sagittal plane power, and elevated knee extensor muscle activity mechanisms presumed to mitigate impact loading on the calcaneus. In late stance, we anticipated reduced ankle plantar flexor muscle activity and diminished concentric ankle power, accompanied by compensatory increases in knee extensor activation and elevated concentric knee and hip sagittal plane power.

Lower Extremity EMG Activity

The findings of this study did not support the initial hypotheses regarding lower extremity neuromuscular differences in individuals with PHP. Contrary to expectations, no statistically significant differences in muscle activity were observed between the PHP and control groups during either early or late stance phases of gait. The results are consistent with the only previous study to examine mean EMG activity during walking gait in patients with PHP (Moyne-Bressand et al., 2018). Although the Moyne-Bressand et al. (2018) study did not find significant differences in EMG activity during the walking gait stance phase, the study did report significant differences in soleus muscle reflex ratios during voluntary muscle contraction even after pain reduction associated with foot orthosis intervention. These adaptations were hypothesized to contribute to the persistence or recurrence of pain, even after pain reduction. Thus, future studies

investigating the muscle reflex ratio of other lower extremity muscles and/or during gait are warranted.

Lower Extremity Net Joint Power

The original hypotheses regarding the lower extremity net joint powers were not supported. Although there was a significant net joint power difference at the ankle, it was a difference in the A1 peak (eccentric plantar flexor power) versus the hypothesized A2 peak (concentric plantar flexor power). We originally hypothesized that PHP patients would exhibit decreased concentric ankle plantar flexor power (A2) during the propulsion phase as a pain-avoidant strategy to reduce loading through the forefoot and plantar aponeurosis. However, the results revealed a significantly lower eccentric plantar flexor power in late mid-terminal stance (A1). The decreased eccentric plantar flexor power in the PHP group may be associated with the decreased ankle dorsiflexion passive ROM (Table 2.3) and/or a pain-avoidant strategy to decrease plantar aponeurosis strain as the ankle transitions from dorsiflexion to plantar flexion. With respect to the decreased ankle dorsiflexion passive ROM in the PHP group, increased resistance to dorsiflexion could decrease the angular velocity of the ankle joint. If this were the case, it could result in the decreased ankle joint power (the product of the plantar flexor moment and the dorsiflexion angular velocity). Another other possibility is that the patients with PHP decreased the peak eccentric plantar flexor power to decrease plantar aponeurosis strain as the ankle transitions from dorsiflexion to plantar flexion.

Before drawing conclusions regarding this study, several limitations should be considered. First, the present study only investigated middle-aged individuals with PHP,

therefore the results may not be generalizable to younger or older adults with PHP. Second, walking gait was performed in a barefoot condition, therefore the results may not be applicable to shod walking gait. Third, because the patients with PHP walked at a slower preferred walking speed, and speed can influence joint kinematics, only the fixed gait speed trials were assessed. While the decision removed the potential for joint kinematic differences to be due to walking speed and not PHP, some individuals may have altered their gait if the fixed speed was faster or slower than their preferred speed. Fourth, because this was a retrospective study, it is not possible to determine if the differences in the patients with PHP were the cause or effect of PHP.

Conclusion

This is the first study to investigate lower extremity neuromuscular in middle-aged adults with PHP, the portion of the population most affected by the condition. Our results suggest that patients with symptomatic PHP may adopt a gait strategy due to restricted ankle dorsiflexion passive ROM and/or to avoid/limit pain caused by strain on the plantar aponeurosis as the ankle transitions from dorsiflexion in late mid/terminal stance to plantar flexion in propulsion. Future prospective studies are needed to determine if the differences identified in the current study are the cause or effect of PHP. Future retrospective studies of patients with recurring PHP are also warranted to determine if patients adopt different gait patterns when symptomatic versus asymptomatic.

CHAPTER FOUR: DETERMINE THE ASSOCIATION BETWEEN THE RISK FACTORS, GAIT MECHANICS, AND PLANTAR HEEL PAIN IN MIDDLE-AGED ADULTS

Introduction

A recent study of plantar heel pain (PHP) in adults over the age of 20 from the National Health and Nutrition Examination Survey (NHANES), reported an overall prevalence rate of 11.1%, with the highest prevalence in those 30 – 50 (44.3% of the total cases) and 50–65 (38.3 % of the total cases) years of age (Liu et al., 2024). In addition to the prevalence, the symptoms of PHP are often persistent. Patients in a study by Davis et al. (1994) reported symptom durations ranging from 6 to 96 months, while those in a study by Hansen et al. (2018) reported symptoms up to 15 years post-diagnosis. Not surprisingly, PHP is associated with impaired mobility (Nahin, 2018; Riddle and Schappert, 2004), reduced physical activity and participation (Thomas et al., 2019), and diminished health related quality of life (HRQOL) (Fernandez-Lao et al., 2016).

Numerous studies have sought to identify intrinsic and extrinsic risk factors associated with PHP, however, only a limited number of the investigated factors have been consistently identified as significant. A prevailing assumption across this body of research is that the intrinsic and extrinsic risk factors contribute to mechanical overload of the plantar aponeurosis, leading to tissue degeneration and symptom onset.

Extrinsic Risk Factors

PHP is observed in both physically active (Landorf and Menz, 2008) and sedentary individuals (Davis et al., 1994; Williams, 1987), suggesting that both excessive and insufficient activity may be extrinsic risk factors. In active individuals, overload may result from abnormal loading of otherwise healthy tissue (Leach et al., 1986; Snider et

al., 1983; Tountas and Fornasier, 1996), while in sedentary individuals, disuse related tissue weakening may lead to overload from normal loading conditions. The only other extrinsic factors that have been consistently associated with PHP are prolonged standing and/or occupational exposure to hard surfaces (Riddle et al., 2003; Werner et al., 2010).

Intrinsic Risk Factors

Among intrinsic risk factors, the most consistently associated with PHP have been obesity (Irving et al., 2007; Rano et al., 2001; Riddle et al., 2003; Sullivan et al., 2015b; Thomas et al., 2019), impaired vascular perfusion (Berlin et al., 1990; Chen et al., 2013, 2012; van Leeuwen et al., 2016; McNally and Shetty, 2010; Walther et al., 2004), hamstring tightness (Bolívar et al., 2013; Labovitz et al., 2011; Lee et al., 2020; Thummar et al., 2020), restricted ankle dorsiflexion range of motion (ROM) (Bolívar et al., 2013; Riddle et al., 2003; Sullivan et al., 2015b; Yildiz et al., 2018), and diminished strength in the ankle evertors and toe flexors (Allen and Gross, 2003; McClinton et al., 2016; Sullivan et al., 2015b; Yildiz et al., 2018). Other frequently examined factors such as sex (Taunton et al., 2002; Thomas et al., 2019) and foot posture (Aranda and Munuera, 2014; Headlee et al., 2008; Huang et al., 2004; Irving et al., 2007; Werner et al., 2010) have yielded inconsistent associations with PHP.

Although numerous studies have examined risk factors associated with PHP, most have employed group comparison methods such as t-tests, ANOVAs, ANCOVAs, or their non-parametric equivalents. While these approaches detect between group differences, they do not quantify the strength between specific variables and PHP. Regression-based analyses are capable of identifying such associations, but their

application has been limited and the studies conducted have only addressed a narrow subset of intrinsic risk factors (Irving et al., 2007; Labovitz et al., 2011; Riddle et al., 2003). Further, none of the previous regression-based studies have incorporated kinematic or neuromuscular gait variables that may contribute to the mechanical overload of the plantar aponeurosis.

The purpose of this study was to determine the association between the extrinsic and intrinsic risk factors, gait mechanics, and PHP in middle-aged adults. To obtain this objective, we hypothesized that the inclusion of gait variables associated with mechanical overload of the plantar aponeurosis with the consistently identified intrinsic and extrinsic risk factors would improve the ability to predict PHP in middle-aged adults.

Methods

Participants

A convenience sample of 60 middle-aged adults (aged 45–64 yrs.) with ($n = 30$) and without ($n = 30$) PHP participated in the study. The sample size for this study was determined a priori using G*Power (version 3.1.9.4), using data from previous investigations that employed multi-segment foot models (Bovonsunthonchai et al., 2019; Chang et al., 2014; Harutaichun et al., 2021), examined neuromuscular function (Moyne-Bressand et al., 2018) during gait, and studies that analyzed the association between the risk factors and PHP (Allen and Gross, 2003; Bolívar et al., 2013; McClinton et al., 2016; Ozdemir et al., 2005). Power analyses were conducted for a Logistic Multiple Regression Fixed model, single regression coefficient: [$\alpha = 0.05$, $\beta = 0.20$; degrees of freedom = 1, large effect size (Cohen's $f = 0.40$)]. These parameters

indicated a required minimum group size of 20 to 26 participants, yielding an estimated total sample size of approximately 46 participants.

Participants in the PHP group had common clinical symptoms of PHP associated with pathology of the plantar aponeurosis. The clinical symptoms included an insidious symptom onset persisting for at least three months (Irving et al., 2008), point tenderness at the medial calcaneal tubercle indicative of proximal plantar aponeurosis involvement, and characteristic pain during initial morning steps, after prolonged non-weight-bearing, or during extended weight-bearing activities (Buchanan and Kushner, 2021; Thomas et al., 2010). Control (CON) participants had no history of plantar heel pain and were matched with PHP participants by age (± 5 years), sex, and tested limb.

Exclusion criteria for participants in the PHP group included cases in which symptoms could not be reproduced during a clinical examination, a history of surgical intervention for PHP (e.g., plantar aponeurosis release), or treatment from an allied health professional within the preceding six months. Treatments included, but were not limited to, physical therapy, custom-molded foot orthoses, corticosteroid injections, botulinum toxin, or platelet-rich plasma therapy (Moyne-Bressand et al., 2018).

Exclusion criteria for both the PHP and CON groups were: the presence of significant lower extremity edema; current or recent (within the past three months) history of low back, lower limb, or foot pain excluding PHP in the symptomatic group; a prior history of major lower extremity trauma or surgical intervention; or systemic and musculoskeletal conditions known to contribute to plantar foot pain, including diabetes mellitus, arthritis, neuromuscular disorders, and vascular disease (Bovonsunthonchai et al., 2019; Chang et al., 2014; Harutaichun et al., 2021; Irving et al., 2008; Moyne-

Bressand et al., 2018; Riskowski et al., 2015). Additional exclusion criteria included current use of medications known to cause dizziness or impair gait, the presence of any implanted electronic medical devices (e.g., cardiac pacemakers, electronic infusion pumps, or neural stimulators). Female participants who were pregnant were also excluded due to pregnancy-associated ligamentous and aponeurotic laxity.

Procedures

Following a clinical screening examination to verify that PHP symptoms were attributable to pathology of the plantar aponeurosis and to exclude alternative sources of heel pain, the study procedures were explained and participants provided written informed consent in accordance with ethical standards approved by the University's Institutional Review Board.

Participants then completed a the International Physical Activity Questionnaire (IPAQ) to quantify their self-reported physical activity (Craig et al., 2003). Following completion of the IPAQ, participants underwent a series of anthropometric and physical assessments, including measurements of height, weight, lower extremity strength, and joint ROM. Isometric muscle strength was evaluated for nine lower limb muscle groups using a handheld dynamometer either the JTech Commander Echo (JTECH Medical, Midvale, UT) or the microFET2™ (Hoggan Scientific, LLC, Salt Lake City, UT) in accordance with established manual muscle testing protocols (Bazett-Jones et al., 2011; Hébert et al., 2011; Katoh and Yamasaki, 2009; Quinlan et al., 2021; Spink et al., 2010). The muscle groups assessed included the gluteus medius, gluteus maximus, quadriceps, hamstrings, tibialis anterior, fibularis longus/brevis, gastrocnemius, intrinsic flexors of the 2nd–5th toes, and intrinsic hallux flexors. For each muscle group,

participants performed three maximal voluntary isometric contractions, with the highest recorded peak force used for subsequent analysis (Kato et al., 2019). Strength testing was conducted on the symptomatic limb of PHP participants and the matched limb of control participants. In cases of bilateral PHP, the limb with greater symptom severity was designated as the involved side. Joint ROM assessments included passive knee extension (Berryman Reese and Bandy, 2010) and ankle dorsiflexion (Bennell et al., 1998), measured using a standard goniometer and digital inclinometer to ensure accuracy and reliability.

To evaluate foot and lower extremity kinematics during walking gait, 50 retroreflective markers (6.4–10 mm in diameter) were affixed either directly to the skin or mounted on custom-built rigid wands to define anatomical segments of the pelvis, thigh, shank, and six distinct foot segments (Table 2.1, Figure 2.1). Marker placement was conducted on the involved limb of participants in the PHP group and the corresponding (matched) limb of CON participants. Additionally, 11 anatomical landmarks on the foot were identified using a pointer device during a static calibration trial (Table 2.1, Figure 2.1) (Cobb et al., 2016). The marker model identified pelvis, thigh, shank, and six foot segments (calcaneus, navicular, cuboid, medial rays, lateral rays, and hallux). The segments defined hip and knee joints and six functional foot articulations (rearfoot complex, medial midfoot, lateral midfoot, medial forefoot, lateral forefoot, and 1MTP joint) (Figure 2.1; Appendices I and J) (Cobb et al., 2016).

Following marker placement, a static calibration procedure was conducted with participants barefoot in both seated and standing positions. The seated trial was employed to capture the time invariant positions of foot anatomical markers and

landmarks, as well as the relative positions of the functional foot articulations in a non-weightbearing condition, thereby minimizing the influence of compensatory movements or structural deviations associated with pathological foot postures. The standing trial was used to record the anatomical landmarks associated with the pelvis, thigh, and shank. A 14-camera optical motion capture system (Raptor 4; Motion Analysis Corporation, Santa Rosa, CA), operating at a sampling frequency of 200 Hz, was utilized to track the three-dimensional trajectories of all retroreflective markers during both static calibration and dynamic walking trials.

Following completion of the static calibration procedure, all anatomical markers were removed except those affixed to the bases of the first and fifth metatarsals, which were retained to aid in foot segment tracking during gait trials. Participants then completed practice walking trials to familiarize themselves with the experimental protocol. Each participant subsequently completed 10 successful barefoot walking trials at a fixed pace, standardized to a walking speed of 1.3 m/s along a 15-meter walkway, corresponding to normative gait velocities reported for adults aged 50 to 64 years (Whittle et al., 2012). Gait speed was monitored using an optoelectronic timing system. Ground reaction forces were recorded via three embedded force plates (AMTI, Watertown, MA, USA), located within the central region of the walkway and sampled at 2000 Hz. These force platforms were used to identify stance phase events and served as inputs for inverse dynamics analyses to calculate lower extremity net joint powers. A walking trial was deemed successful if full foot contact of both the involved and contralateral limbs occurred entirely within the boundaries of the respective force plates, and the participant's walking speed remained within $\pm 10\%$ of the target velocity.

Data Processing

Upon completion of the gait trials, the three-dimensional trajectories of retroreflective markers captured during both the static calibration and dynamic walking trials were processed using Cortex software (version 8.0; Motion Analysis Corporation, Santa Rosa, CA). Synchronized marker trajectory and ground reaction force (GRF) data were subsequently exported for subsequent processing.

Kinematics. Stance phase lower extremity and foot kinematics were computed using custom-developed scripts in MATLAB (R2024b; MathWorks, Natick, MA, USA). Marker position and GRF data were low-pass filtered using a fourth-order, zero-lag Butterworth filter with cut-off frequencies of 6 Hz and 30 Hz, respectively. These cut-off values were empirically determined through residual analysis of pilot data (Winter, 2009). Rigid body transformations were performed using the Calibrated Anatomical Systems Technique (CAST) (Cappozzo, 1984) and local joint coordinate systems were defined for each anatomical segment. Three-dimensional joint angles were then computed using the joint coordinate system method (Grood and Suntay, 1983). Joint kinematics were derived for the hip, knee, and six functional articulations of the foot. All joint angles were expressed as the rotation of the distal segment relative to the proximal segment. For foot articulations, positive sagittal, frontal, and transverse plane rotations were defined as dorsiflexion/extension, inversion, and adduction, respectively. For the hip and knee joints, positive sagittal and frontal plane rotations corresponded to flexion and adduction, respectively. The first five successful walking trials that had no obvious marker displacement errors were used for subsequent analysis.

The vertical GRF data were utilized to identify stance subphase events. A threshold of 20 N was applied to the vertical GRF signal to detect initial contact and toe-off events. Specifically, the following temporal events were identified: initial contact of the involved limb, toe-off of the contralateral limb, initial contact of the contralateral limb, and toe-off of the involved limb. These discrete time points were subsequently used to define three functional subphases of stance: (1) loading response: initial contact of the involved limb to toe-off of the contralateral limb; (2) midstance/terminal stance: contralateral toe-off to contralateral initial contact; and (3) push-off: contralateral initial contact to toe-off of the involved limb. Range of motion (ROM) for the hip, knee, and each of the six functional foot articulations was computed for each subphase as the difference between maximum and minimum joint angles.

Net Joint Power. Synchronized three-dimensional marker trajectories and GRF data were exported in .c3d format and processed using Visual3D software (C-Motion, Inc., Germantown, MD, USA). Both kinematic and kinetic data were low-pass filtered using a fourth-order zero-lag Butterworth filter with a cut-off frequency of 6 Hz, in accordance with established gait analysis protocols (Bruggemann et al., 2008; Massaad et al., 2007).

Joint center estimations were derived using anatomical and regression-based approaches. The hip joint center was calculated via the regression equations proposed by Bell et al. (1990), while the knee and ankle joint centers were defined as the midpoint between the medial and lateral femoral epicondyles and malleoli, respectively. Body segment inertial parameters were assigned based on regression equations provided by Dempster (1955). Net joint moments for the hip, knee, and ankle in the sagittal plane

were computed and expressed as internal moments within the coordinate system of the proximal segment. These moments were normalized to each participant's body mass and defined such that positive values reflected extension and plantar flexion moments. Sagittal plane joint powers were calculated as the product of normalized net joint moments and corresponding joint angular velocities. Positive joint power values were interpreted as indicative of concentric muscular contractions, reflecting active energy generation across the respective joints during gait.

Statistical Analysis

For the statistical analyses, the variables of interest from each of the five gait trials were averaged for each participant. Logistic multiple regressions were performed to investigate the association between PHP and the significant kinematic and/or neuromuscular function variables identified in studies one and two, as well as the extrinsic/intrinsic risk factors of interest (Table 4.1). This technique allows blocks of variables to be entered in a predetermined order. The blocks were: 1. kinematic variables, 2. neuromuscular variables, 3. lower extremity ROM, 4. lower extremity strength, 5. physical activity, and 6. BMI (Table 4.1). Before performing the logistic multiple regression analyses, preliminary analyses to investigate the assumptions of normality, linearity, homoscedasticity, and presence of multicollinearity were conducted. Based on the statistical analyses conducted in the first and second study, the significant kinematic and/or neuromuscular function variables identified in studies one and two, as well as the associations of extrinsic and intrinsic risk factors with PHP, are comprehensively summarized and presented in Table 4.1. Significance for the logistic regression analysis was set at $\alpha = 0.05$, (SPSS, version 28).

Table 4.1. Logistical Regression Analysis Variables Entered to Predict PHP.

Blocks	Predictor Variable
1. Gait Kinematics	Significant kinematic variables from study one: 1. Loading response rearfoot complex transverse plane ROM 2. Loading response medial midfoot sagittal plane ROM 3. Loading response medial forefoot sagittal plane ROM 4. Mid/terminal stance rearfoot complex sagittal plane ROM
2. Gait Neuromuscular Function	Significant neuromuscular variables from study two: 1. Peak eccentric ankle plantar flexor joint power (A1)
3. Lower Extremity ROM	1. Ankle dorsiflexion passive ROM
4. Lower Extremity Strength	1. Hip extensor 2. Knee flexor 3. Ankle dorsiflexor 4. Ankle evertor 5. Intrinsic hallux flexors
5. Physical Activity	1. International physical activity questionnaire (IPAQ)
6. Body Mass Index	1. Body mass index (BMI)

Results

Descriptive Data

Participants' descriptive data and the statistical analyses of the descriptive data are reported in Chapter 2. Statistically significant differences were identified across various blocks in Table 4.1. Through logistic regression analysis, it was found that four of the predictor variables had a strong correlation with PHP (Table 4.2). During mid/terminal stance, the PHP group demonstrated decreased rearfoot complex sagittal plane ROM. A decrease in rearfoot complex dorsiflexion ROM was associated with a 4.69% increase in the odds of injury related to PHP (OR = 0.78). The PHP group also demonstrated lesser peak eccentric ankle plantar flexor joint power (A1). A decrease in peak sagittal plane eccentric ankle plantar flexor joint power (A1) was associated with a 6.49% increase in the odds of injury related to PHP (OR = 0.04). Reduced ankle dorsiflexion passive ROM was significantly associated with PHP. A decrease in ankle dorsiflexion passive ROM was associated with a 6.24% increase in the odds of injury related to PHP (OR = 0.88). There was no change in odds for IPAQ scores, but the

factor remained significant. A lower IPAQ was associated with a 5.40% increase in the odds of injury related to PHP (OR = 1.00).

Table 4.2. Results of Logistical Regression Analysis of Variables Entered to Predict PHP.

Predictor Variable	B	S.E	Wald	Sig	Exp(B)
Loading response rearfoot complex Tran ROM	0.19	0.17	1.21	0.27	1.21
Loading response medial midfoot Sag ROM	-0.15	0.22	0.47	0.50	0.86
Loading response medial forefoot Sag ROM	0.00	0.14	0.00	0.98	1.00
Mid/terminal stance rearfoot complex Sag ROM	-0.25	0.11	4.96	0.03*	0.78
Peak sagittal plane eccentric ankle plantar flexor joint power (A1)	-3.16	1.24	6.49	0.01*	0.04
Ankle dorsiflexion ROM	-0.13	0.05	6.24	0.01*	0.88
Hip extensor strength	-0.03	0.07	0.16	0.69	0.97
Knee flexor strength	-0.06	0.11	0.37	0.54	0.94
Ankle dorsiflexor strength	-0.07	0.09	0.69	0.41	0.93
Ankle evertor strength	-0.10	0.21	0.22	0.64	0.90
Intrinsic hallux flexors strength	-0.10	0.11	0.83	0.36	0.90
IPAQ	0.00	0.00	5.40	0.02*	1.00
BMI	0.08	0.05	2.66	0.10	1.09
Sag = Sagittal plane, Tran = Transverse plane. * Significant predictor variable associated with PHP, ($p \leq 0.05$) – Logistical Regression					

Discussion

This study aimed to examine the association between intrinsic and extrinsic risk factors, kinematic and neuromuscular function gait differences, and the PHP in middle-aged adults. We hypothesized that integrating gait-related variables, with commonly identified extrinsic and intrinsic risk factors would significantly enhance the predictive capacity for PHP in this population.

Our results demonstrated significant relationships between several key variables, namely those that are consistent with our hypothesis, specific kinematic parameters, neuromuscular function variables, ankle dorsiflexion ROM, and physical activity levels with the presence of PHP. These findings contribute to a growing body of literature exploring the multifactorial nature of PHP and provide important insights into the interrelations among gait differences and the commonly assessed extrinsic and intrinsic risk factors.

A binary logistic regression was conducted to examine the effects of four predictor variables loading response rearfoot complex transverse plane ROM, loading response medial midfoot sagittal plane ROM, loading response medial forefoot sagittal plane ROM, and mid/terminal stance rearfoot complex sagittal plane ROM on the likelihood of the outcome variable. The overall model was statistically significant [$\chi^2 (4) = 11.09, p = 0.03$], indicating that the model was able to distinguish between participants based on the predictors included. Among the individual predictors, mid/terminal stance rearfoot complex sagittal plane ROM was found to be a significant contributor to the model ($B = -0.25, SE = 0.11, Wald = 4.96, p = 0.03$). The odds ratio [$\text{Exp}(B)$] for this variable was 0.78 (95% confidence interval: 0.63–0.97), indicating that a one-unit increase in mid/terminal stance rearfoot complex sagittal plane ROM is associated with a 21.9% decrease in the odds of the outcome occurring, holding all other variables constant. The other variables loading response rearfoot complex transverse plane ROM ($p = 0.27$), loading response medial midfoot sagittal plane ROM ($p = 0.50$), and loading response medial forefoot sagittal plane ROM ($p = 0.98$) did not reach statistical significance, suggesting that they were not meaningful predictors in the current model.

The effect of peak sagittal plane eccentric ankle plantar flexor joint power (A1) on the likelihood of the outcome variable PHP was assessed through a binary logistic regression. The overall model was statistically significant [$\chi^2 (1) = 8.14, p = 0.00$], indicating that the predictor variable reliably distinguished between groups. The regression coefficient for peak sagittal plane eccentric ankle plantar flexor joint power (A1) was significant ($B = -3.16, SE = 1.24, Wald \chi^2 = 6.49, p = 0.01$). The odds ratio was

0.04, suggesting that for each one-unit decrease in peak sagittal plane eccentric ankle plantar flexor joint power (A1), the odds of occurrence for the outcome increased by a factor of approximately 0.04. The 95% confidence interval for the odds ratio range (0.00 to 0.48) indicated a high degree of uncertainty, reinforcing the variable's significance.

To evaluate the effect of ankle dorsiflexion passive ROM on the likelihood of the outcome variable, another logistic regression was conducted. The overall model was statistically significant [$\chi^2 (1) = 7.48, p = 0.01$], indicating that the predictor variable significantly contributed to the model. The regression coefficient for ankle dorsiflexion ROM was significant ($B = -0.13, SE = 0.05, \text{Wald } \chi^2 = 6.24, p = 0.01$). The odds ratio was 0.88, suggesting that for each one-unit increase in dorsiflexion ROM, the odds of the outcome occurring decreased by approximately 12%. The 95% confidence interval for the odds ratio range (0.80 to 0.97), which did not include 1, indicates a statistically significant effect.

The results of the omnibus tests for model coefficient IPAQ indicated that the model is statistically significant, with a Chi-square value of 6.40 ($df = 1, p = 0.01$), suggesting that the variable entered into the model significantly contributed to the prediction. Regarding the variables in the equation, IPAQ had a coefficient (B) of 0.00, with a standard error (S.E.) of 0.00, and was statistically significant ($\text{Wald} = 5.40, df = 1, p = 0.02$). The $\text{Exp}(B)$ for IPAQ was 1.00, with its 95% confidence interval range (1.00 to 1.00) indicating no change in the odds for IPAQ. The association between higher physical activity levels, as measured by IPAQ, and PHP, though statistically significant, yielded an odds ratio of 1.00, suggesting a negligible effect size despite reaching

significance. A higher IPAQ was associated with a 5.40% decrease in the odds of injury related to PHP.

The omnibus test of model coefficient BMI (kg/cm^2) showed that the overall model was not statistically significant, with a Chi-square value of 2.94 ($df = 1$, $p = 0.09$). This indicates that this predictor variable did not significantly improve the model over a model with no predictors. In the analysis of individual predictors, BMI had a coefficient (B) of 0.08, with a standard error (S.E.) of 0.05. The Wald statistic was 2.66 ($df = 1$, $p = 0.10$), indicating that BMI was not a statistically significant predictor. The odds ratio was 1.09, with a 95% confidence interval range (0.98 to 1.20) suggesting a slight increase in odds with higher BMI, though it is not statistically significant.

A somewhat unexpected finding of our study was the lack of a direct, strong association between muscle strength and PHP, despite several studies identifying reduced muscle strength in the lower extremities as a key intrinsic risk factor for PHP (Allen and Gross, 2003; McClinton et al., 2016; Sullivan et al., 2015b; Yildiz et al., 2018).

Before drawing conclusions regarding this study, several limitations should be considered. First, the present study only investigated middle-aged individuals with PHP, therefore the results may not be generalizable to younger or older adults with PHP. Second, walking gait was performed in a barefoot condition, therefore the results may not be applicable to shod walking gait. Third, because the patients with PHP walked at a slower preferred walking speed, and speed can influence joint kinematics, only the fixed gait speed trials were assessed. While the decision removed the potential for joint kinematic differences to be due to walking speed and not PHP, some individuals may

have altered their gait if the fixed speed was faster or slower than their preferred speed. Fourth, because this was a retrospective study, it is not possible to determine if the differences in the patients with PHP were the cause or effect of PHP.

Conclusion

This is the first study to investigate the association between lower extremity kinematics and neuromuscular gait function, commonly identified intrinsic and extrinsic PHP risk factors, and PHP in middle-aged adults with PHP. Our results suggest that, in addition to decreased dorsiflexion passive ROM and decreased physical activity, decreased rearfoot complex dorsiflexion ROM during mid/terminal stance and decreased peak eccentric ankle joint power are significant predictors of PHP. Future prospective studies are needed to determine if the significant predictors identified in the current study are the cause or effect of PHP.

CHAPTER FIVE: SUMMARY AND CONCLUSIONS

Objectives and Hypothesis

The purposes of this exploratory study were to: identify the kinematic (Chapter 2) and neuromuscular (Chapter 3) gait differences within the foot and lower extremity in middle-aged PHP patients; and determine the association between the gait mechanics, PHP risk factors, and PHP in middle-aged adults (Chapter 4). We hypothesized that patients with PHP would demonstrate: (1) foot and lower extremity differences during loading response, mid/terminal-stance, and push-off phases of gait, (2) lower extremity neuromuscular difference during the early and late stance phases of gait, and (3) the inclusion of gait variables associated with mechanical overload of the plantar aponeurosis with the primary risk factors would improve the ability to predict PHP in middle-aged adults.

Summary of Methods

A convenience sample of 60 middle-aged adults (aged 45–64 years), comprising individuals with symptomatic plantar heel pain (PHP; $n = 30$) and asymptomatic controls (CON; $n = 30$), participated in this study. Descriptive data were obtained through validated health and activity questionnaires (SF-36, IPAQ, FAAM, and MFPDI). Lower extremity strength and range of motion were assessed using handheld dynamometry and goniometric measurements. Barefoot walking trials were conducted at both self-selected and standardized speeds, with gait events identified via embedded force plates. Three-dimensional kinematic data were processed to calculate joint angles for the hip, knee, and foot segments. To evaluate neuromuscular function, bipolar surface electrodes were applied to key lower limb muscles (tibialis anterior, fibularis longus,

gastrocnemius, quadriceps, and biceps femoris) to record EMG activity, and inverse dynamics were performed with the synchronized motion and force data to calculate net joint powers. Independent t-tests were performed for descriptive data comparisons. To identify the kinematic (Chapter 2) and neuromuscular (Chapter 3) gait differences within the foot and lower extremity, one-way ANCOVAs with sex and BMI treated as covariates were performed. Logistic multiple regression was performed to determine the association between the gait mechanics, PHP risk factors, and PHP in middle-aged adults (Chapter 4).

General Conclusions

In addition to decreased foot evor and intrinsic foot flexor strength and decreased ankle dorsiflexion passive ROM that could contribute to increase plantar aponeurosis strain, middle-aged patients with PHP also have decreased strength in the proximal lower extremity joints. These results emphasize the importance for PHP treatment/rehabilitation programs to assess the entire lower extremity, not just the foot.

Except for increased medial forefoot dorsiflexion ROM during loading response in patients with PHP, most of the significant foot kinematic and lower extremity neuromuscular function differences in patients with symptomatic PHP may have been more related to a pain avoidant strategy to avoid/limit pain caused by strain on the plantar aponeurosis than the result of decreased ability of the plantar aponeurosis to control pronation in early stance and to facilitate supination in late stance. Finally, the results of the logistical regression analyses suggest that, in addition to decreased dorsiflexion passive ROM and decreased physical activity, decreased rearfoot complex

dorsiflexion ROM during mid/terminal stance and decreased peak eccentric ankle joint power are significant predictors of PHP.

Future prospective studies are needed to determine if the differences identified in the current study are the cause or effect of PHP. Future retrospective studies of patients with recurring PHP are also warranted to determine if patients adopt different gait patterns when symptomatic versus asymptomatic.

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APPENDICES

Appendix A: Review of Literature

Introduction

Plantar heel pain, also known as plantar fasciitis and plantar fasciosis (Lemont et al., 2003; Riel et al., 2017), is the most common cause of hind/heel foot pain in adults (Tahririan et al., 2012; Thompson et al., 2014). In fact, it affects approximately 10 percent of people during their lifetime (Pfeffer et al., 1999; Singh et al., 1997; Tahririan et al., 2012) and accounts for over one million complaints of musculoskeletal issues in annual outpatient visits (Riddle and Schappert, 2004). Most cases are seen in individuals between the ages of 40-60 years (Healey and Chen, 2010). In patients receiving treatment/rehabilitation, the prevalence and persistence of plantar heel pain is also associated with significant and long-term personal burdens, including pain-related interference with normal work- and walking-related activities (Nahin, 2018; Riddle and Schappert, 2004), low physical activity and participation (Thomas et al., 2019), and decreased health related quality of life (HRQOL) (Fernandez-Lao et al., 2016). Additionally, greater levels of depression, anxiety (Cotchett et al., 2016; Thomas et al., 2019), and stress (Cotchett et al., 2016) have also been reported.

The functions of the plantar aponeurosis are well understood, though the intrinsic and extrinsic factors associated with plantar heel pain remain unclear (Sarrafian, 1987; Taunton et al., 1982; Wearing et al., 2006). Although the etiology and pathophysiology of plantar heel pain are not well understood, the general consensus is that increased tension on the plantar aponeurosis (mechanical overload) during loading activities such

as gait, leads to repetitive microtrauma and subsequent degeneration of the plantar aponeurosis (Leach et al., 1986; Snider et al., 1983; Tountas and Fornasier, 1996).

This review of literature will begin with an overview of the structure and function of the plantar aponeurosis and a review of the current knowledge regarding the pathophysiology of plantar heel pain. This will be followed by a review of the current knowledge regarding the risk factors associated with plantar heel pain and the effect of plantar heel pain on walking gait mechanics.

Structure of the Plantar Aponeurosis

Anatomy of the Plantar Aponeurosis

Of the 107 ligaments within the foot, the plantar aponeurosis is often considered to be one of the most functionally significant. It plays an important role in providing the primary static stability for the longitudinal arches in the feet (Thordarson et al., 1997). The plantar aponeurosis spans the sole of the foot, including the transverse tarsal, tarsometatarsal, and metatarsophalangeal joints (Nordin and Frankel, 2012; Uden et al., 2011) (Figure A.1). The broad, tendon-like structure is composed of predominantly longitudinally oriented, non-contractile, irregularly ordered inelastic collagen fibers that form a strong mechanical link between the medial calcaneal tubercle and the proximal phalanges of the toes (Mitchell et al., 1991; Nordin and Frankel, 2012; Rompe, 2009; Schwartz and Su, 2014; Wearing et al., 2006; Wright and Rennels, 1964).

Structurally, the plantar aponeurosis has been partitioned into medial, central, and lateral components, although the plantar aponeurosis is a continuous structure (Brasile and Hedrick, 1996; Chen et al., 2014; Hedrick, 1996; Lisowski, 2004; Middleton and Kolodin, 1992; Newell and Miller, 1977; Wearing et al., 2006) (Figure A.1). The

medial component forms the investing aponeurosis of the abductor hallucis muscle and acts as the fascial covering layer of the muscle. The dominant central component of the plantar aponeurosis is usually the site of pathologic disorders (Kwong et al., 1988; Ogden et al., 2001). The central segment originates on the plantar surface of the medial calcaneal tuberosity and inserts into the proximal phalanges of the toes (Mitchell et al., 1991; Nordin and Frankel, 2012; Rompe, 2009; Schwartz and Su, 2014; Wearing et al., 2006; Wright and Rennels, 1964). As it courses distally from the medial calcaneal tubercle, the central component divides into five tracts. Each of the five distal tracts within the segment has superficial and deep units (Hossain and Makwana, 2011; Kwong et al., 1988; Singh et al., 1997). The superficial units support the arches. The deeper units attach to the plantar plates of the metatarsophalangeal joints as well as to the bases of the proximal phalanges through connections to the flexor tendon sheaths (Hossain and Makwana, 2011; Kane et al., 2001; Kwong et al., 1988; Ogden et al., 2001; Sellman, 1994; Singh et al., 1997). Finally, the lateral component begins at the lateral edge of the medial tubercle of the calcaneus, reaches toward the cuboid, and attaches to the base of the fifth metatarsal (Brasile and Hedrick, 1996). This lateral band is normally more substantial than the medial band, but its thickness and development may vary (Brasile and Hedrick, 1996; Cralley et al., 1982; Hiramoto, 1983). The lateral band can be thick and fully developed, but in some individuals can be completely absent (Dylevský, 1988). In addition, females showed thinner fascial thickness than males (Shiotani et al., 2019; Taş, 2018).



Figure A.1. Medial, Central, and Lateral Bands of the Plantar Aponeurosis (Chen et al., 2014).

In addition to the bony attachments of the plantar aponeurosis, it is also attached to the superficial intrinsic foot muscles (flexor digitorum brevis, abductor hallucis, abductor digiti minimi) and several extrinsic foot and ankle muscles (flexor digitorum longus, flexor hallucis longus, tibialis anterior & posterior, fibularis longus) (Aquino and Payne, 1999; Martini et al., 2017; Stecco et al., 2013). In young adults, the plantar aponeurosis also has a continuous connection with the Achilles tendon (Rompe, 2009). However, this connection decreases with age (Rompe, 2009).

Histology of the Plantar Aponeurosis

A great deal of research has investigated the gross anatomy of the plantar aponeurosis, but investigation of the histology has been limited. The plantar aponeurosis appears as a layer of fiber bundles just a few millimeters thick and arranged longitudinally, distinct from the pattern in ligaments or tendons, and tapering off along the proximal-distal axis (Stecco et al., 2013; Wearing et al., 2006). The plantar aponeurosis is composed mostly of type I collagen fibers arranged proximo-distally, with few transverse and vertical fibers (Stecco et al., 2013; Wright and Rennels, 1964).

These fibers have a crimped, wavy appearance when unloaded (Stecco et al., 2013). They have a sensory capacity and ability to alter the composition of the extracellular matrix which is important in the functioning of the foot, and likely plays a role in the pathophysiology of plantar heel pain (Stecco et al., 2013).

The extracellular grid within the plantar aponeurosis is composed of collagenous and elastic fibers. These stretchy fibers form in longitudinal strands as well as in oscillating, collected networks. The elastic fibers are oriented in a wave-like pattern which straightens in response to weight bearing, contributing to an overall stiffening of the aponeurosis (Ogden et al., 2001; Riddle et al., 2004).

Tendons and ligaments are poorly vascularized (Benjamin and Ralphs, 1997), with varying degrees of microcirculation throughout the structure (Wearing et al., 2006). Vessels primarily near the tissue surface (Arnoczky et al., 1979; Chowdhury et al., 1991; Petersen et al., 2000), areas of attachment (Arnoczky et al., 1979; Scapinelli, 1997), and so-called critical zones within the ligament are nearly avascular (Carr and Norris, 1989; Frey et al., 1990; Petersen et al., 2002). These areas may be more prone to degenerative changes (Archambault et al., 1995). Free-nerve endings may function as “high-threshold mechanoreceptors,” which play a role in regulating blood flow in these vessels (Hogervorst and Brand, 1998; Holzer, 1988; Salo and Theriault, 1997; Wearing et al., 2006). In a study of animal tendons, the blood supply of tendons increases with exercise and during healing (Backman et al., 1991). However, there is some evidence to suggest that blood flow in ligaments decreases with tension (Dunlap et al., 1989), which would limit an inflammatory response to tissue damage (Benjamin and Ralphs, 1997).

The plantar aponeurosis is innervated with Pacinian and Ruffini corpuscles for mechanoreception, and free nerve endings act as nociceptors which respond to both inflammatory and physical stimuli (Biedert et al., 1992; Coggeshall et al., 1983; Stecco et al., 2013; Wearing et al., 2006). The mechanoreceptors also function in proprioception, thereby performing a critical role in postural stability and movement of the foot.

Function of the Plantar Aponeurosis

The primary function of the plantar aponeurosis is to provide passive stability to the multiple joints of the foot (Maffulli et al., 1999). When stationary, the foot is supported mostly by passive structures, with primary support coming from the plantar aponeurosis (Basmajian and Stecco, 1963). The plantar aponeurosis also provides passive stability during gait, which functions to control pronation and assist supination of the foot. This function is based on theories of foot function, in-vitro studies of function, and more recently several in-vivo studies of foot function.

Theories of the Plantar Aponeurosis Function During Gait

The plantar aponeurosis is theorized to provide passive stability via three auto-supportive mechanisms of the foot (Aquino and Payne, 1999). The three auto-supportive mechanisms are the calcaneocuboid joint locking mechanism (Bojsen-Moller, 1979; Dananberg, 1993), the locking wedge and truss effect (Dananberg, 1993), and the windlass mechanism (Hicks, 1954). Muscles of the feet also function in parallel with the plantar aponeurosis, contributing greatly to the support of the longitudinal arch of the foot during gait, and may have the ability to reduce the burden on the plantar aponeurosis (Fessel et al., 2014) (Figure A.2).

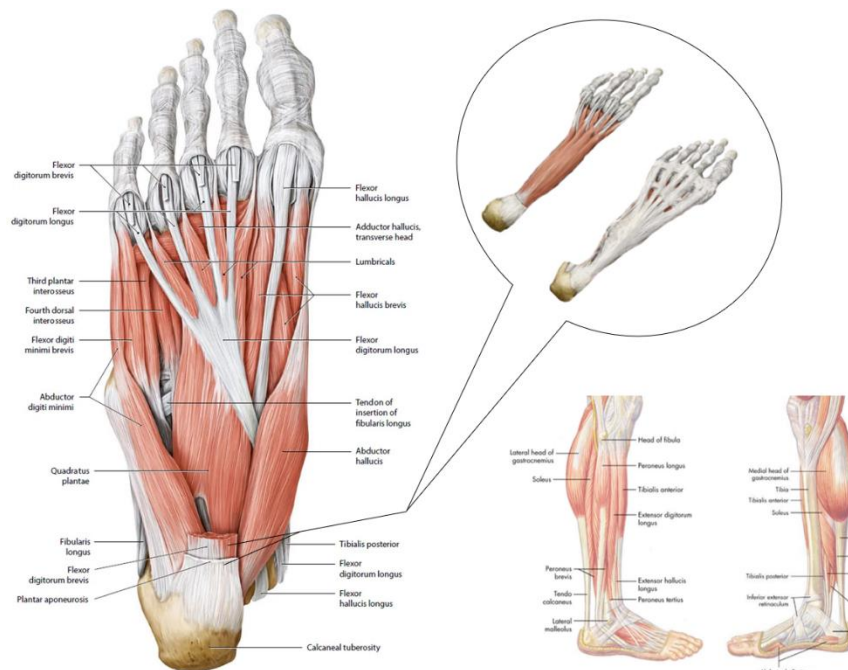


Figure A.2. Muscles that Function as Dynamic Stabilizers in Conjunction with the Plantar Aponeurosis.

The first auto-supportive mechanism, the calcaneocuboid locking mechanism, occurs in the lateral midfoot between midstance and terminal stance. The weight transfer from the lateral forefoot to the medial forefoot just before heel lift creates tension in the plantar aponeurosis, which compresses the cuboid into the calcaneus to stabilize the lateral midfoot (Bojsen-Moller, 1979; Dananberg, 1993). As weight transfer from the heel, lateral midfoot, and lateral forefoot to the medial forefoot continues, the second auto-supportive mechanism is activated. As the metatarsals begin to change orientation from horizontal to more vertical (the foot transitions from pronation to supination), compressive loading between the metatarsals and midfoot functions as a locking wedge, stabilizing the midfoot during the mid-late stance subphases (Dananberg, 1993). Tension in the plantar aponeurosis (as it functions as a tie rod between the heel and metatarsal heads) facilitates the locking wedge effect and stabilizes the midfoot in preparation for propulsion. Finally, hallux extension in late

stance causes further tension in the plantar aponeurosis, which engages the third auto-supportive mechanism, the windlass effect. This causes the medial longitudinal arch to rise, stabilizing the forefoot, midfoot, and rearfoot and allowing the foot to function as a rigid structure to allow the lower limb to be propelled into the swing phase of gait (Hicks, 1954).

In-vivo Studies

Dynamic. Early studies using force platforms and motion analysis reported peak fascial load was 2.8 times bodyweight during midstance and early push-off, but this magnitude may have overestimated the internal loading of the plantar aponeurosis by the model (Scott and Winter, 1990). To expand on these in-vivo studies, Gefen used a digital radiographic fluoroscopy imaging system to photograph the plantar aponeurosis during barefoot walking and measure its transient length during the latter half of the contact phase of the gait cycle (Gefen, 2003). The plantar aponeurosis continuously elongated during the entire stance phase. At midstance, the plantar aponeurosis rapidly elongated, and then was slower between midstance and toe-off. The stiffness of the plantar aponeurosis increased in the early period of weight acceptance, thereby contributing to the increase in arch stability during dynamic loading. The study estimated a fascial load of approximately 1.5 times body weight.

Generally, studying mechanical effects of the plantar aponeurosis requires imaging to measure arch movement. For example, imagery shows the plantar aponeurosis shortens and lengths by 6 mm through the stance phase (Kayano, 1986; Wearing et al., 2006). Surface-mounted goniometry has revealed that the arch alternates shortening and elongation during the stance phase (Yang, 1985). The

consequence is that, initially, the plantar aponeurosis lengthens with heel contact, then shortens throughout midstance, next lengthens at heel lift, and finally during the terminal stance, rapidly shortens to prepare for propulsion (Kayano, 1986; Yang, 1985).

Wearing et al. (2004) utilized in-vivo digital fluoroscopy imaging to assess the biomechanical movement of the plantar aponeurosis in patients with plantar heel pain. Researchers compared the medial longitudinal arch during sagittal movement between subjects with plantar heel pain and controls. Despite finding no significant change in arch movement, they concluded that arch mechanics likely affect the severity of plantar heel pain after onset (Wearing et al., 2004).

Pathophysiology of the Plantar Heel Pain

Plantar heel pain has been theorized to result from changes in the stiffness of the plantar aponeurosis caused by chronic inflammation (Cardinal et al., 1996; LeMelle et al., 1990). More recently, however, a review of the histological analysis of the plantar aponeurosis following fifty cases of heel spur surgery for chronic plantar heel pain did not find inflammation in patients with plantar heel pain (Lemont et al., 2003). New evidence of decreased stiffness and degeneration, with chronic inflammation as a possible secondary mechanism, contradicts the previous theories that suggest plantar heel pain results from chronic inflammation and increased stiffness (Karabay et al., 2007; Lemont et al., 2003; Taş, 2018; Wearing et al., 2007, 2006, 2004). This change of theory may be central to developing more effective treatment programs since the treatment will depend on the condition of the aponeurosis.

Further evidence for this new theory can be found in Grasel et al. (1999) study that examined magnetic resonance images of the plantar aponeurosis of plantar heel

pain patients. Inflammation was quickly eliminated as a cause of plantar heel pain because of the low prevalence and linearity of signal intensity in the aponeurosis. However, researchers did find microtears in the plantar aponeurosis. More recent studies utilizing ultrasound also revealed degeneration within the plantar aponeurosis of patients with plantar heel pain (Karabay et al., 2007). The images showed hypoechoic changes and an increase in thickness in the proximal part of the aponeurosis. The thickness of the plantar aponeurosis was greater for those suffering from plantar heel pain (> 4 mm) than for asymptomatic subjects (2–2.5 mm) (Cardinal et al., 1996). The hypoechoic appearance and thickening of the plantar aponeurosis are assumed to be associated with the underlying progression of the fiber degeneration caused by microtears (Buchanan and Kushner, 2021; Cardinal et al., 1996; Karabay et al., 2007). Recent studies provide details on the significance of microtears and microtrauma in the development of plantar heel pain (Lemont et al., 2003; Ma and Vano-Galvan, 2013; Xu and Murrell, 2008). Changes in collagen synthesis and delay in collagen repair result in tender areas of the tissue (Lemont et al., 2003; Ma and Vano-Galvan, 2013; Xu and Murrell, 2008). Cell death (apoptosis) caused by microtrauma, especially near the calcaneum, exacerbates the degeneration of the tissue (Lemont et al., 2003; Ma and Vano-Galvan, 2013; Xu and Murrell, 2008).

Wu et al. (2011) performed imaging on the plantar aponeurosis using elastography. In patients with plantar heel pain and older healthy adults, the sonoelastogram was indicative of a softening, or decreased stiffness, of the plantar aponeurosis. Since the plantar aponeurosis is vastly important in elastic energy storage,

the change in material properties of the plantar aponeurosis can lead to changes in the efficiency of energy storage (Kim and Voloshin, 1995; Wright and Rennels, 1964).

Risk Factors Associated with Plantar Heel Pain

Previous research has shown plantar heel pain is multifactorial, often a combination of intrinsic and extrinsic factors. Although numerous studies aimed at identifying plantar heel pain risk factors have been conducted, only a small subset of the variables investigated have been consistently identified as significant risk factors. This review of the risk factor literature will only focus on those intrinsic and extrinsic factors that have been consistently identified as significant risk factors. The common assumption of the risk factors investigated is that they cause and contribute to mechanical overload of the plantar aponeurosis, which then leads to degeneration and the development of plantar heel pain. The specific influences of the different factors, however, are not well understood (Arangio et al., 1998; Wearing et al., 2006).

Intrinsic Factors of the Plantar Heel Pain

Of the many intrinsic risk factors that have been investigated, only age, obesity, inadequate vascularity, blood flow, hamstring tightness, reduced dorsiflexion ROM, as well as reduced ankle evor and toe flexor muscle strength have been consistently identified as significantly associated with plantar heel pain. Other commonly investigated intrinsic factors have included abnormal foot posture (low arch and high arch) and gender. However, neither have been consistently identified as significantly associated with plantar heel pain.

Age. Age is one of the most consistently identified intrinsic factors that contribute to heel pain. Most patients in the US with plantar heel pain are middle and older aged

people (Chiew et al., 2016; Nahin, 2018). This is consistent with the histology of plantar aponeurosis degeneration, where the fascial fibers weaken with aging and do not recover as quickly as they do in young adults (Lemont et al., 2003).

Obesity. An intrinsic risk factor strongly associated with plantar heel pain is obesity (Irving et al., 2007; Rano et al., 2001; Riddle et al., 2003; Sullivan et al., 2015b; Thomas et al., 2019). In the study of Gill et al. (2016), constant foot and heel pain was shown to depend on obesity (BMI greater than 30.0 kg/m²), a trend seen in much of the literature. Several studies found that increased body weight (Chiew et al., 2016; Gill and Kiebzak, 1996; Hill and Cutting, 1989) and BMI (Harutaichun et al., 2019; Martin et al., 2014; McPoil et al., 2008; Rano et al., 2001; Riddle et al., 2003; Sullivan et al., 2015b) were significant risk factors for plantar heel pain and heel pain. When looking at non-athletes specifically, obesity impacted up to 70% of plantar heel pain patients (Tahririan et al., 2012). Additionally, the measure of disability is directly related to the BMI proportion (Riddle et al., 2004). In a study by Prichasuk (1994), 40% percent of patients with heel pain were overweight, compared to 13.5% of uninjured subjects. According to Irving et al. (2007), patients with chronic plantar heel pain were 2.9 times more likely to be obese. In Yildiz et al. study, they found the average BMI in patients who had heel pain was 29.6 kg/m² (Yildiz et al., 2018). Kanatli et al. found a significant correlation between BMI and heel pain and the resulting mean was 28.95 BMI in the heel pain group, 22.46 in the controls (Kanatli et al., 2001).

The effect of BMI may be more pronounced in the nonathletic population. A number of studies have identified a significant relationship between BMI and plantar heel pain in non-athletic individuals (Hill and Cutting, 1989; Lapidus and Guidotti, 1965;

Ozdemir et al., 2005; Prichasuk, 1994; Rano et al., 2001; Riddle et al., 2003; Rome et al., 2002, 2001). Rome's studies found that BMI was not a significant factor in heel pain in athletic populations (Rome et al., 2002, 2001).

Inadequate Vascularity and Blood Flow. Due to damage in the plantar aponeurosis of trauma, vascular and blood flow is increased in the heel (Berlin et al., 1990; van Leeuwen et al., 2016). Individuals with chronic plantar heel pain demonstrated greater incidences of vascularity and thickened fascia on their affected side than in control groups, and both these factors were associated with foot dysfunction (Chen et al., 2013). A moderate or marked increase in blood flow (hyperemia) was found in power Doppler ultrasonographic findings in the plantar aponeurosis and surrounding soft tissue on symptomatic sides, and was associated with a history of acute and high pain levels (Chen et al., 2012; Walther et al., 2004).

Hamstring Tightness. Bolivar found that the hamstring shortening in the hip can cause plantar aponeurosis dysfunction due to inadequate knee extension, which leads to prolonged forefoot loading (Bolívar et al., 2013). A strongly associated risk factor of plantar heel pain is hamstring tightness (Bolívar et al., 2013; Labovitz et al., 2011; Lee et al., 2020; Thummar et al., 2020). Harty et al. (2005) found that increased flexion at the knee joint caused an increase in forefoot pressure and decreased time spent in the contact phase with hip pain of the plantar heel pain group. Measurements of straight leg elevation, popliteal angle, ankle dorsiflexion with knee extension, and ankle dorsiflexion with knee flexion were greater in individuals with plantar heel pain group (Bolívar et al., 2013; Harty et al., 2005). Furthermore, the popliteal angle was greater in individuals with plantar heel pain (Harty et al., 2005).

Dorsiflexion ROM. A number of studies have suggested that tight gastrocnemius and soleus muscles contributes to decreased dorsiflexion ROM during gait that may lead to additional repetitive stress on the plantar aponeurosis, and contribute to the subsequent development of plantar heel pain (Cornwall and McPoil, 1999; DeMaio et al., 1993; Labovitz et al., 2011; Leach et al., 1986; Martin et al., 2014; McPoil et al., 2008; Schepsis et al., 1991; Sellman, 1994; Tisdell et al., 1999; Trojian and Tucker, 2019; Wolgin et al., 1994). DeMaio et al, reported that 88% of participants experienced deficits in lower extremity ROM. Patel and DiGiovanni (2011) found that 83% of their plantar heel pain patients specifically had limited ankle dorsiflexion. According to Molund et al. (2018), reduced dorsiflexion increases the strain on the plantar aponeurosis. Limited ankle dorsiflexion forces the forefoot to compensate with increased pronation (Riddle et al., 2003), causing more load to be placed on the plantar aponeurosis (Trojian and Tucker, 2019). Risk factor studies often report a correlation between plantar heel pain and decreased ankle dorsiflexion mobility, with less than 10° of ankle dorsiflexion leading to the greatest intrinsic risk (Bolívar et al., 2013; Cornwall and McPoil, 1999; Kibler et al., 1991; Labovitz et al., 2011; Riddle et al., 2003; Yildiz et al., 2018). Excess tension in these muscles and in the aponeurosis can limit dorsiflexion during propulsion, thereby causing collapse of the medial longitudinal arch (Amis, 2016). They also limit ankle rotation and prevent the tibia from completely rolling over the ankle (Amis, 2016).

The degree of dorsiflexion during each phase of gait is widely known. At least 4°–10° is required for the stance phase of walking gait. An angle < 10° likely results in compensation in the subtalar joint during weightbearing, which would lead to abnormal

pronation and increased stress on the plantar aponeurosis (Cornwall and McPoil, 1999). Riddle found that when the ankle joint dorsiflexion is less than or equal zero (≤ 0), the risk of plantar heel pain increased by a factor of 23 (compared to 10 degrees) (Riddle et al., 2003). Those in the patient group with plantar heel pain had 5 degrees less ankle dorsiflexion (in the calcaneal inclination angle) than healthy individuals (Yildiz et al., 2018). In comparison, Inman and colleagues found that there needed to be 10 degrees of ankle dorsiflexion with the knee extended to walk (Inman et al., 1981).

A limitation to much of the range of motion research is that data is collected during passive motion rather than dynamic motion. Much of the literature supports a negative correlation between plantar heel pain and passive ankle dorsiflexion range of motion, but how dynamic movement relates to plantar heel pain is less clear. Moreover, in subjects with unilateral plantar heel pain, studies comparing ankle dorsiflexion range of motion of the asymptomatic limb to the symptomatic limb might miss compensatory differences in the unaffected foot that results in decreased range of motion.

Conversely, one study found a positive correlation between ankle dorsiflexion and plantar heel pain. Pohl considered biomechanical factors associated with a history of plantar heel pain in female runners (Pohl et al., 2009). The runners suffering from plantar heel pain in the past showed an increase in ankle dorsiflexion. One explanation for this outcome is that the runners had a history of plantar heel pain but were undergoing physical therapy and were pain-free during the study. In fact, increasing the ankle range of motion is a common exercise for plantar heel pain therapy patients (Pohl et al., 2009).

Muscle Strength. While the plantar aponeurosis provides most of the static support in the arch during gait, other dynamic stabilizers, including the 12 extrinsic and 12 intrinsic muscles, also contribute (Martini et al., 2017; McKeon et al., 2015). The extrinsic muscles are the strongest and provide most of the active control of the foot during gait (Nordin and Frankel, 2012). Both in-vitro and in-vivo studies have assessed the contribution of the extrinsic and intrinsic muscles during gait (Basmajian and Stecko, 1963; Reeser et al., 1983; Thordarson et al., 1995). The musculature of the foot can have significant effects on stiffness and function of the longitudinal arch (Fiolkowski et al., 2003; Hashimoto and Sakuraba, 2014; Wong, 2007) and the center of pressure under both single and double leg stance loads (Kelly et al., 2012).

Further research investigated support provided by the extrinsic and intrinsic foot muscles during toe-standing (Hamel et al., 2001; Salathe and Arangio, 2002; Salathe et al., 1986; Sharkey et al., 1998; Tansey and Briggs, 2001). Toe-standing is used to simulate the propulsion phase of gait, just before toe-off. The intrinsic muscles' role is most evident as the heel is elevated from the ground during terminal stance, at which point the intrinsic muscles and plantar aponeurosis contribute equally (Hamel et al., 2001; Tansey and Briggs, 2001).

The flexor hallucis brevis is thought to be a substantial contributor to foot posture (Angin et al., 2018), as it increases medial longitudinal arch height along together with other intrinsic flexor muscles following a strengthening intervention (Hashimoto and Sakuraba, 2014). The abductor hallucis muscle has been shown to act as a dynamic elevator (Wong, 2007), a medial longitudinal arch supporter (Fiolkowski et al., 2003), and assists in maintaining medio-lateral balance in a double and single leg stance (Kelly et al., 2012). Due to the contributions of the structure of the function of the longitudinal

arch, the structure of the foot and the tissue properties may be altered in addition to the plantar aponeurosis due to changes induced by plantar heel pain.

Reduced ankle evtor and toe flexor muscle weakness have been consistently identified as risk factors strongly associated with plantar heel pain (Allen and Gross, 2003; McClinton et al., 2016; Sullivan et al., 2015b; Yildiz et al., 2018). Decreased ankle plantar flexor strength, and lower toe flexor strength have been reported in individuals with plantar heel pain, Sullivan et al. (2015b) found that participants with heel pain had reduced eversion strength, reduced great toe flexor and lesser toe flexor strength , and greater inversion/eversion strength ratio than those without plantar heel pain.

Gender. The effect of gender on plantar heel pain is unknown, mainly because studies have reported different results. Some studies have reported that the prevalence is plantar heel pain is higher in women than men (Beeson, 2014; Scher et al., 2009; Yildiz et al., 2018). For example, Yildiz et al. (2018) reported 65% of subjects with plantar heel pain were female subjects and 35% were male. Others, however, have reported in increased prevalence in males. For example, Taunton et al. (2002) found 58.8% of subjects with plantar heel pain were male and 41.2% were female. Finally, others have not identified a significant prevalence difference between females and males (Taunton et al., 2002; Thomas et al., 2019).

Extrinsic Factors of the Plantar Heel Pain

Numerous studies aimed at identifying extrinsic plantar heel pain risk factors have been conducted. Despite the common assumption that the investigated risk factors cause/contribute to mechanical overload (and thus degeneration) of the plantar

aponeurosis and subsequent plantar heel pain, only a small subset of the variables investigated have been consistently identified as significant risk factors.

The extrinsic factors that have been identified as significant risk factor for plantar heel pain are abnormal physical activity (both inadequate and excessive), occupations that require prolonged standing, and training/working on hard surfaces (Bedi and Love, 1998; Campbell-Giovaniello, 1997; Chandler and Kibler, 1993; DeMaio et al., 1993; Hill and Cutting, 1989; Kane et al., 2001; Lapidus and Guidotti, 1965; Martin et al., 2001; Riddle et al., 2003; Schepsis et al., 1991; Singh et al., 1997; Tanner et al., 1988; Tisdell et al., 1999; Wolgin et al., 1994).

Physical Activity. Plantar heel pain occurs in both athletic (physically active) individuals (Landorf and Menz, 2008), and non-athletes (sedentary) (Davis et al., 1994; Williams, 1987), making both excessive and inadequate activity levels, plausible extrinsic risk factors. Overload injury due to excessive physical activity (training errors) may begin due to abnormal loading of a normal tissue (Leach et al., 1986; Snider et al., 1983; Tountas and Fornasier, 1996). Overload due to inadequate physical activity may begin due to increased patient weight or occupational risks such as prolonged standing and walking (Tountas and Fornasier, 1996).

Occupational Risk Factors. Occupations that involve prolonged standing and or working on hard surfaces have been identified as risk factors for plantar heel pain. In a study investigating outcomes associated with nonsurgical treatment for plantar heel pain, from a manufacturing workplace, the majority with plantar heel pain (51.6%) spent most of their time on a hard floor compared to 40.5% in the control group without plantar heel pain (Gill and Kiebzak, 1996).

Multiple studies have reported that prolonged standing put individuals at increased risk of plantar heel pain (Martin et al., 2014; McPoil et al., 2008; Riddle et al., 2003). Werner et al. (2010) found that increased time spent working on a hard surface increased the risk of plantar heel pain by 30%. Increasing the time walking during work by 10% resulted in a 52% increase in the risk of developing plantar heel pain. Werner et al. (2010) also found that the prevalence of developing plantar heel pain was significantly greater in workers who had been with the company for four-to-seven years compared to new hires. Prolonged standing over the span of several years is therefore considered an important risk factor (Allam and Chang, 2020).

Effect of Plantar Heel Pain on Walking Gait Mechanics

The cause of plantar heel pain is multifactorial and likely stems from a combination of intrinsic and extrinsic factors. The balance and influence of each factor, however, is still not well understood (Arangio et al., 1998; Wearing et al., 2006). The majority of studies are retrospective, so the development of plantar heel pain cannot be observed in real-time. Moreover, intrinsic and extrinsic factors are generally assessed using static measurements and may not be directly applicable to dynamic function. A dynamic assessment of the various factors is needed to understand their impact on gait, which can ultimately lead to more effective treatment protocols for plantar heel pain patients. Several studies have utilized multi-segment foot models to investigate the effect of plantar heel pain on foot function (Bovonsunthonchai et al., 2019; Chang et al., 2021, 2014; Harutaichun et al., 2021). Patients with plantar heel pain have been known to have an increase in forefoot pronation during gait (Chang et al., 2007).

Temporal-spatial Parameters

The bulk of the gait research has focused on identifying difference in STP variables in patients with plantar heel pain. When the foot is considered as a single segment, no significant STP differences have been reported between patients with plantar heel pain and uninjured participants (Bovonsunthonchai et al., 2019; Sullivan et al., 2015a; Wearing et al., 2010, 2002).

Plantar Heel Pain vs. Uninjured-Single Foot Segment. STP variables have been assessed to quantify the general functional effects of plantar heel pain on gait. Most research has not shown any difference in the overall STP parameters between subjects with plantar heel pain and controls, especially when walking speed is matched and stance subphases other than single limb support and double limb support are not considered (Bovonsunthonchai et al., 2019). Wearing found the mean stance phase duration between subjects with plantar heel pain and controls was the same (Wearing et al., 2002). Moyne-Bressand found that the patients with plantar heel pain had a shorter stance time from initial contact to loading response compared to controls throughout the study. However, the plantar heel pain patients had a longer stance time from loading response to terminal stance to push-off in the last three weeks of the study before returning to baseline (Moyne-Bressand et al., 2018). Katoh found that the patients with plantar heel pain had a decreased toe and increased heel contact period compared to the control subjects. Also, the toe switch contact period was significantly shorter in the plantar heel pain subjects than in controls (Katoh et al., 1983b).

Plantar Heel Pain Involved vs. Uninvolved-Single Segment Foot. Liddle and Wearing found there was no change difference in total contact “stance” time between

the involved and uninvolved feet of people with heel pain, and there was no difference in mean stance phase duration between people with heel pain and controls (Liddle et al., 2000; Wearing et al., 2002). Similarly, Hsu did not report significant velocity, cadence, or step length at baseline differences between asymptomatic and symptomatic groups during stance or swing phases (Hsu et al., 2013).

Plantar Heel Pain vs. Uninjured-Multi-Segment Foot. Wearing found that the duration of digital contact-stance times was much greater in plantar heel pain patients than the controls, particularly in the region of the lateral toes (Wearing et al., 2002). Additionally, people with plantar heel pain had a longer contact time over the midfoot and medial and lateral forefoot of the affected limb (Sullivan et al., 2015a; Wearing et al., 2002). Patients with heel pain also appear to contact the ground earlier with their midfoot and forefoot, most likely in an attempt to reduce the load on the heel, though the reported level of pain did not affect the contact time (Sullivan et al., 2015a). According to Wearing, the subjects with plantar heel pain had decreased rearfoot velocity during loading phase when compared to the controls (Wearing et al., 2002).

Plantar Heel Pain Involved vs. Uninvolved-Multi-Segment Foot. Using a multi-segment model assessing the stance subphases of the hindfoot, midfoot, and forefoot segments, Wearing found that the digital contact times had a significantly greater duration in patients with plantar heel pain than in controls (Wearing et al., 2002). This study gives evidence that individuals with plantar fasciitis have altered gait patterns, mainly having reduced hindfoot and increased midfoot impulses.

Kinetics

The bulk of the gait research has focused on identifying difference in kinetic (GRF, Plantar Pressure) variables in patients with plantar heel pain. The only GRF difference assessed via force platform reported has been a decrease in the second/active peak vertical GRF in plantar heel pain patients (Chang et al., 2014). When the foot is partitioned into regions (e.g., medial and lateral heel, midfoot, medial and lateral forefoot) using plantar pressure plates or insoles, plantar heel pain patients have demonstrated decreased hindfoot and midfoot loading (Riskowski et al., 2015; Sullivan et al., 2015a). Collectively, these studies suggest that partitioning the foot into regions/segments is important in identifying the differences associated with plantar heel pain. While these studies have identified differences in and loading (GRF, plantar pressure) in patients with plantar heel pain, the variables assessed represent the outcome of the body's neuromuscular response to plantar heel pain, they do not identify the dysfunctional movement and/or neuromuscular dysfunction causing the loading differences.

GRF (Force Platform). Many studies have evaluated heel kinetics, including hindfoot impulses, contact duration, and peak pressure in individuals with symptomatic plantar heel pain using plantar pressure mats and/or insoles. All studies have concluded that these kinetics remained unchanged (Bedi and Love, 1998; Kanatli et al., 2001; Katoh et al., 1983b, 1983a; Kelly et al., 1995). The same studies, however, show different results regarding midfoot and forefoot loading. The study completed by Bedi and Love showed there to be lower midfoot impulses during gait and an increase in forefoot impulses in individuals with plantar heel pain (Bedi and Love, 1998), but a study

by Katoh et al. found the opposite (Katoh et al., 1983b). Due to the conflicting research, there is not a definitive answer as to what loading trends in symptomatic plantar heel pain individuals should look like.

Plantar Pressure. Riskowski et al. (2015) found that the subjects with rearfoot pain had lower toe and rearfoot peak pressure, but the location of the center of force did not differ between groups. However, Wearing found that in symptomatic feet, the center of pressure was located in the rear foot for significantly less time and velocity during the loading phase in plantar heel pain subjects when compared to the control group (Wearing et al., 2002). Individuals with plantar heel pain reporting greater pain had lower peak pressure in antero-medial heel and posterolateral heel regions, but their pain level did not affect the pressure time integral between the medial forefeet (Sullivan et al., 2015a). Kanatli found that there was no difference between heel pain and control groups for peak pressure at heel strike (Kanatli et al., 2001).

Studies investigating involved versus uninvolved limb in participants with plantar heel pain have reported the center of pressure to be located in the rear foot for significantly less time in the involved versus the uninvolved limb (Wearing et al., 2002). Hsu found that there is no difference in peak contact pressure in the forefoot between symptomatic as opposed to asymptomatic feet (Hsu et al., 2013).

Kinematics

The research investigating lower extremity kinematics in patients with plantar heel pain has been limited. To date, only three studies have investigated the kinematic difference associated with plantar heel pain (Bovonsunthonchai et al., 2019; Chang et al., 2014; Harutaichun et al., 2021).

A recent study suggested a coordinative defect in walking in individuals with plantar heel pain captured by reduction in rearfoot to medial-forefoot anti-phase movements and posits greater frequency of anti-phase movements to be associated with healthy foot function (Chang et al., 2021). According to the Chang, using a three-segment foot model including rearfoot, medial forefoot, and hallux, there was significantly greater total motion and maximum eversion velocities in the rearfoot of plantar heel pain subjects (Chang et al., 2014). There was significantly greater total plantar-dorsiflexion motion in patients with plantar heel pain in the medial forefoot area. In addition, the medial forefoot was more plantar flexed at initial contact in subjects with plantar heel pain. There was significantly greater maximum 1MTP dorsiflexion in late stance for subjects with plantar heel pain (Chang et al., 2014). There were no mean differences in maximum medial forefoot dorsiflexion, maximum eversion, total inversion-eversion motion, or maximum abduction angle (Chang et al., 2014). Also, there were no significant differences in positions at initial contact or at maximum eversion of stance phase of the rear foot with plantar heel pain (Chang et al., 2014).

Bovonsunthonchai et al. used a three-segment foot model assessing movement of the forefoot, rearfoot, and tibial segments. The researchers found there was significant reduction in forefoot motion with respect to hindfoot dorsiflexion, hindfoot dorsiflexion/plantarflexion, hindfoot inversion and range of hindfoot with respect to tibia inversion/eversion angles between control and plantar heel pain subjects and between plantar heel pain asymptomatic and symptomatic subjects (Bovonsunthonchai et al., 2019). With respect to other significant differences during stance phase, Bovonsunthonchai et al. found increased peak forefoot dorsiflexion and decreased

peak forefoot inversion positions in plantar heel pain patients (Bovonsunthonchai et al., 2019). Based on the figures presented in the study, the timing of peak eversion for both groups appeared to be around 60% of stance, but the timing of peak inversion in the two groups is not completely clear. Peak inversion positions at initial contact, around 50% stance, and in late stance all appear similar. Thus, it is difficult to determine if the decreased frontal plane ROM in plantar heel pain patients was due to decreased inversion or eversion ROM. With respect to the forefoot sagittal plane ROM, peak dorsiflexion in both groups appeared to be near 50% of stance, and peak plantar flexion near 60% of stance. Therefore, the decreased sagittal plane ROM in patients with plantar heel pain appeared to be decreased plantar flexion ROM between approximately 50% and 60% of stance (Bovonsunthonchai et al., 2019).

Of the studies investigating the kinematic gait difference in plantar heel pain, only Harutaichun et al. (2021) partitioned stance into subphases: shank, calcaneus, midtarsus, and metatarsus. This may be important given the different functions that must be accomplished by the foot and lower extremity within stance (e.g., mobility and load absorption in early stance, stability, and propulsion in mid and late stance). During early stance, patients with plantar heel pain demonstrated increased transverse plane and decreased sagittal plane ROM in the rearfoot and forefoot, respectively. During the middle subphases, plantar heel pain patients exhibited decreased sagittal plane ROM in the midfoot and hip joints, increased frontal plane ROM in the forefoot, and decreased sagittal and transverse plane knee joint ROM. Finally, in the late stance subphase, plantar heel pain patients demonstrated increased transverse and frontal plane ROM in the ankle and hip joints, respectively.

Although it is difficult to directly compare the results of the three studies due to differing methodologies (e.g., participant ages, multi-segment foot model utilized, discrete variables selected, and stance phase periods investigated), the common conclusion of the studies has been that most of the ROM changes in patients with plantar heel pain have been attributed to increased pronation (Chang et al., 2014; Harutaichun et al., 2021), or are consistent with inadequate supination (Bovonsunthonchai et al., 2019).

Neuromuscular Function

Electromyography. The research investigating lower extremity neuromuscular function in patients with plantar heel pain has been limited. To date, only a single study has investigated the impact of plantar heel pain on electromyography (EMG) activity during walking gait (Moyne-Bressand et al., 2018).

Moyne-Bressand et al. found the reflex max/muscle max and reflex support/muscle support ratios were higher than the muscle reflex max/muscle max in patients with plantar heel pain. Also, muscle reflex support/muscle support were lower in the healthy control participants during the reflexes and muscle activity in the knee. However, there were no change differences in EMG in the knee in participants with heel pain (Moyne-Bressand et al., 2018). The researchers concluded that the persistence of the reflex differences may indicate neurological adaptations to chronic pain even after treatment that successfully decreased the pain associated with plantar heel pain. Further, the differences persisted despite a reported decrease in pain level following treatment for the pain. They further hypothesized that the neurological adaptations may

contribute to the long-term persistence/recurrence of pain that is common in patients with plantar heel pain (Moyne-Bressand et al., 2018).

Joint Kinetics. Another functional tool for measuring neuromuscular function during gait is net joint power analysis (Winter and Eng, 1995), which has been utilized to investigate chronic pain conditions and injuries but has yet to be applied to plantar heel pain research.

Appendix B: Inclusion/exclusion Criteria Phone/Microsoft Form Screen

Participant Screening Code: SCR01
Participant Code: P01-PHP/CON
Date: 01/01/2024



IRB Protocol Number: 24.180
IRB Approval Date: 3/28/2024

PHONE/FORM SCREENING

[Section #1] General Information

1. Your Name: _____
2. Phone Number: _____
3. Email Address: _____
4. ☐ Phone ☐ Email How do you prefer to be contacted?

[Section #2] Demographic Information

5. How old are you? _____
 - If you are younger than **45** or older than **64**, you are not eligible to participate in the current study and **do not need to continue** completion of this form.
 - If you are between the ages of **45** and **64**, please **continue to question 6**.
6. What is your identified gender? ☐ Female ☐ Male ☐ Another gender identity not listed here (please specify _____)
7. ☐ Female ☐ Male When you were born, what sex was listed on your birth certificate?
8. ☐ Yes ☐ No To the best of your knowledge, are you physically intersex? That is, do you have a difference of sex development ("DSD")?
9. How tall are you? _____
10. How much do you weigh? _____
11. ☐ Yes ☐ No Are you currently an employee of UW-Milwaukee?

[Section #3] General Health History

Please check 'YES' or 'NO' to answer each question to the best of your ability.

12. ☐ Yes ☐ No Do you have significant swelling (edema) in your lower limbs that is not the result of an injury?
13. ☐ Yes ☐ No In the **last 3 months**, have you had a low back or lower extremity (hip, knee, ankle, foot) injury that caused you to decrease your normal physical activity for more than one day?

14. If you answered **'Yes'** to the question **'13'**, please briefly describe the injury(ies):

15. ☐ Yes ☐ No Have you ever had a major injury, or surgery, to your low back or lower body (Hip, knee, ankle, foot)?

16. If you answered **'Yes'** to the question **'15'**, please briefly describe the injury/surgery:

17. ☐ Yes ☐ No Do you have a **history** of arthritis (i.e., osteoarthritis, rheumatoid arthritis) in your lower back or lower extremity (hip, knee, ankle, foot)?

18. If you answered **'Yes'** to the question **'17'**, please indicate arthritis:

19. ☐ Yes ☐ No Have you been diagnosed with diabetes or a neuromuscular or vascular disease?

20. If you answered **'Yes'** to the question **'19'**, please indicate the diagnosis:

21. ☐ Yes ☐ No Are you taking any medications that may make you dizzy or impair your ability to walk?

22. If you answered **'Yes'** to the question **'21'**, please indicate the medication:

23. ☐ Yes ☐ No Do you have any skin allergies to latex?

24. ☐ Yes ☐ No Do you have any implanted electronic devices of any kind (including cardiac pace-makers or similar assistive devices, electronic infusion pumps, and implanted simulators)?

25. ☐ Yes ☐ No Do you have any allergies to Silver?

26. ☐ Yes ☐ No **For Females:** Are you pregnant or do you have reason to believe that you maybe pregnant?

[Section #4] Plantar Heel Pain

27. ☐ Yes ☐ No Do you currently have heel pain/plantar fasciitis (Pain on the bottom of your heel)?

28. ☐ Yes ☐ No Have you ever had heel pain/plantar fasciitis in the past?

If you answered **'No'** to both questions **'27and 28'**, you are **finished** with the questionnaire.
If you answered **'Yes'** to either question **'27or 28'**, please **continue** to question **29**.

29. ☐ Yes ☐ No Did your heel pain (plantar fasciitis) start as the result of a specific cause (a mechanism)?

30. If you answered **'Yes'** to the question **'29'**, please briefly describe the cause:

31. ☐ Yes ☐ No Have you had your heel pain (plantar fasciitis) for at **least 3** months?

32. ☐ Yes ☐ No When you have your heel pain, does it usually occur when you take your first few steps in the morning, after being inactive for a long period of time, and/or during prolonged standing or activity (i.e., walking)?

33. If you answered **'No'** to the question **'32'**, when does your heel pain occur?

34. ☐ Yes ☐ No Have you had surgery for your heel pain?

35. ☐ Yes ☐ No Have you received physical therapy, or other treatment from an allied health professional (i.e., injections, shock-wave therapy, custom-molded orthotics) for your plantar heel pain **in the last 6 months?**

36. If you answered **'Yes'** to the question **'35'**, please briefly describe the treatment:

Thank you for completing the questionnaire. We will follow up with you if you qualify for the study.

Appendix C: Plantar Heel Pain Screening Exam

Participant Screening Code: SCR01
Participant Code: P01-PHP/CON
Date: 01/01/2024



IRB Protocol Number: 24.180
IRB Approval Date: 3/28/2024

PHP Screening Exam

Examination of movement

- **AROM** (Note any reproduction of symptoms)
 - Ankle: Plantar flexion, dorsiflexion, inversion, eversion

- Hallux: Extension, Flexion

- **PROM** (Note any reproduction of symptoms)
 - Ankle: Plantar flexion, dorsiflexion, inversion, eversion

- Hallux: Extension, Flexion

- **Resisted Isometric movement** (Note any reproduction of symptoms)
 - Ankle: Plantar flexion, dorsiflexion, inversion, eversion

- Hallux: Extension, Flexion

Palpation (Note any reproduction of symptoms)

- Medial calcaneal tubercle

- Plantar fascia along medial longitudinal arch

Confirmation of PHP:

Appendix D: Lower Limb Pain and Injury History Questionnaire

Participant Screening Code: SCR01
Participant Code: P01-PHP/CON
Date: 01/01/2024



IRB Protocol Number: 24.180
IRB Approval Date: 3/28/2024

GENERAL HEALTH QUESTIONNAIRE

Plantar Heel Pain Group

[Section #1]

1. ☐ Yes ☐ No Are you experiencing **right foot** heel pain?
2. ☐ Yes ☐ No Are you experiencing **left foot** heel pain?
3. ☐ Right ☐ Left ☐ No difference If you are experiencing pain in **both your right and left heels**, which side causes more pain?

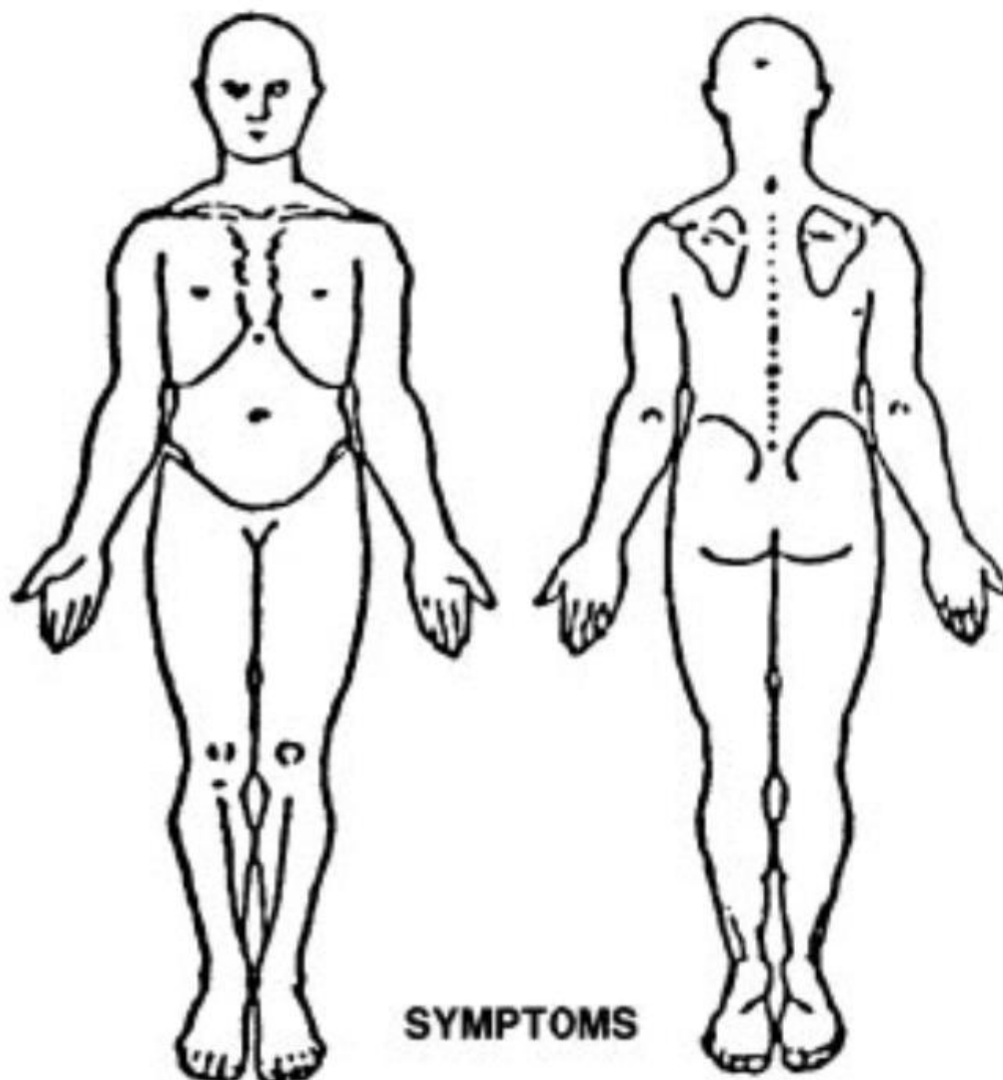
[Section #2]

*If you are experiencing **left and right foot heel pain**, please answer the following questions based on the heel that is causing more pain.*

4. ☐ Yes ☐ No Was your heel pain diagnosed by an Allied Health Professional (i.e., MD, podiatrist, physical therapist)?
5. Approximately how long have you had heel pain?
☐ 3 months
☐ 3 - 6 months
☐ 6 - 12 months
☐ More than 12 months
6. Over the **past 3 months**, approximately how often have you experienced the heel pain at **least one** time during the course of a day?
☐ Never
☐ Rarely
☐ On some days
☐ On most days
☐ Every day
7. Over the **past 3 months** has your heel pain changed?
☐ It has gotten worse.
☐ It has not changed
☐ It has improved
8. On the days that you experience heel pain, how **troublesome** would you classify it?
☐ Not at all troublesome
☐ Slightly troublesome
☐ Moderately troublesome
☐ Very troublesome
☐ Extremely troublesome

9. When you have heel pain during gait (i.e., walking), when does it occur?
- ☐ When the heel makes contact with the ground
- ☐ When pushing off with the foot
- ☐ Both when the heel contacts the ground and when pushing off
- ☐ I don't have pain during gait (i.e., walking)
- ☐ I cannot tell where it hurts during gait
10. Footwear: Please indicate the different types of footwear you commonly wear, and approximately how many hours per week you are in the footwear.
- ☐ Sneakers/athletic shoes _____ hours/week
- ☐ High Heels _____ hours/week
- ☐ Dress shoes/loafers _____ hours/week
- ☐ Sandals _____ hours/week
- ☐ Slippers _____ hours/week
- ☐ Boots _____ hours/week
- ☐ Barefoot/Socks _____ hours/week
- ☐ Other (include _____ hours/week) _____
-
11. ☐ Yes ☐ No Does your current occupation require prolonged periods of standing? If yes, please indicate the approximate number of hours per week: _____
12. ☐ Yes ☐ No Do you regularly run more than 10 miles, or 100 minutes, per week?
13. On the line below, please select the number that best represents the **least intensity** of your heel pain in the **past 3 months** on a 0-to-10 scale where 0 = No pain and 10 = Pain as intense as you can imagine.
- 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10
- No pain Pain as bad as you can imagine
14. On the line below, please select the number that best represents the **worst intensity** of your heel pain in the **past 3 months** on a 0-to-10 scale where 0 = No pain and 10 = Pain as intense as you can imagine.
- 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10
- No pain Pain as bad as you can imagine
15. On the line below, please select the number that best represents the **average intensity** of your heel pain in the **past 3 months** on a 0-to-10 scale where 0 = No pain and 10 = Pain as intense as you can imagine.
- 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10
- No pain Pain as bad as you can imagine

16. On the figures below, please indicate the location of any low back, hip, knee, ankle, and/or foot discomfort that you would describe as at least mildly bothersome on most days of the week that you have experienced over the past 3 months.



17. On the line below, please select the number that best represents the intensity of your heel pain **before beginning the gait trials** on a 0-to-10 scale where 0 = No pain and 10 = Pain as intense as you can imagine.

0 1 2 3 4 5 6 7 8 9 10

No pain Pain as bad as you can imagine

0 1 2 3 4 5 6 7 8 9 10

No pain Pain as bad as you can imagine

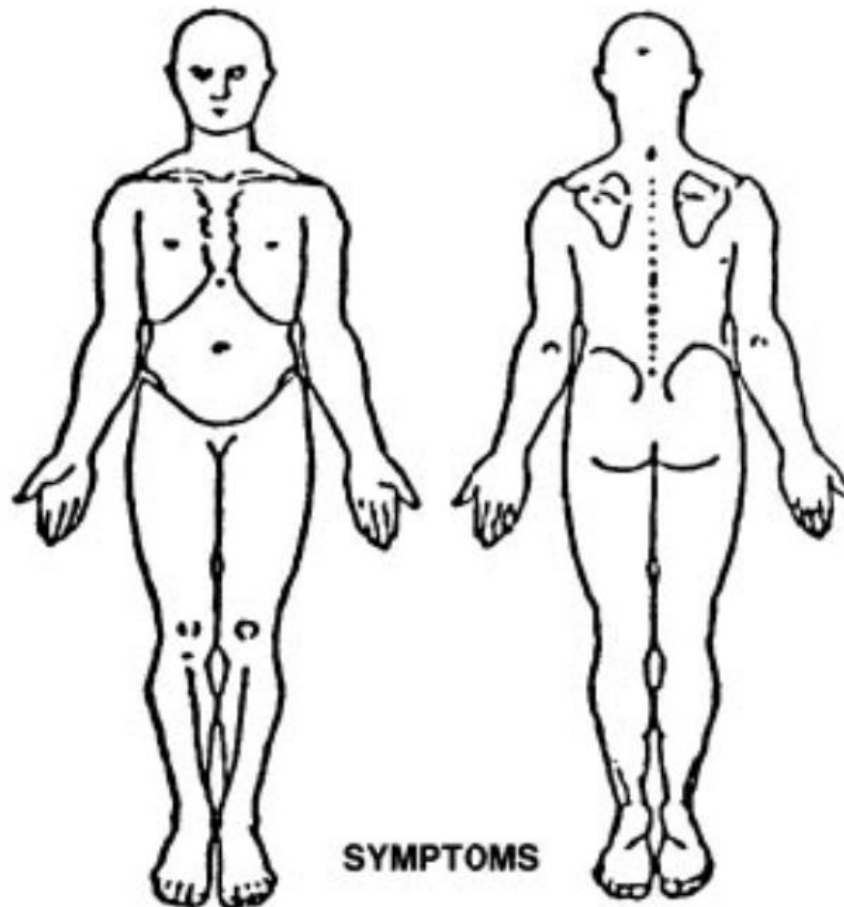
Anthropometrics	Height (cm)	Weight (kg)	BMI (kg/m²)		BMI category
ROM (°) for:	T1	T2	T3	Average	Comments
1. Ankle Dorsiflexion					
2. Knee Extension					
Muscles Testing Results (Kg)	T1	T2	T3	Peak	Comments
1. Knee extension - Rectus Femoris					
2. Knee Flexion - Hamstrings					
3. Ankle dorsiflexion - Tibialis Anterior					
4. Foot Eversion - Fibularis Longus					
5. Hip Abduction-Gluteus Medius					
6. Hip Extension-Gluteus Maximus					
7. Ankle plantar flexion - Medial Gastrocnemius					
8. Foot Flexion - Lesser Toe Flexor					
9. Foot Flexion - Hallux Flexor					

Comments:

GENERAL HEALTH QUESTIONNAIRE

Uninjured Group

1. On the figures below please indicate the location of any low back, hip, knee, ankle, and/or foot discomfort that you would describe as at least mildly bothersome on most days of the week that you have experienced **over the past 3 months**.



2. Footwear: Please indicate the different types of footwear you commonly wear, and approximately how many hours per week you are in the footwear.

- ☐ Sneakers/athletic shoes _____ hours/week
☐ High Heels _____ hours/week
☐ Dress shoes/loafers _____ hours/week
☐ Sandals _____ hours/week
☐ Slippers _____ hours/week
☐ Boots _____ hours/week
☐ Barefoot/Socks _____ hours/week
☐ Other (include hours/week) _____

3. ☐ Yes ☐ No Does your current occupation require prolonged periods of standing? If yes, please indicate the approximate number of hours per week: _____

4. ☐ Yes ☐ No Do you regularly run more than 10 miles, or 100 minutes, per week?

[Section #4] ADDITIONAL INFORMATION (For Researcher ONLY)					
Anthropometrics	Height (cm)	Weight (kg)	BMI (kg/m ²)		BMI category
ROM (°) for:	T1	T2	T3	Average	Comments
1. Ankle Dorsiflexion					
2. Knee Extension					
Muscles Testing Results (Kg)	T1	T2	T3	Peak	Comments
1. Knee extension - Rectus Femoris					
2. Knee Flexion - Hamstrings					
3. Ankle dorsiflexion - Tibialis Anterior					
4. Foot Eversion - Fibularis Longus					
5. Hip Abduction-Gluteus Medius					
6. Hip Extension-Gluteus Maximus					
7. Ankle plantar flexion - Medial Gastrocnemius					
8. Foot Flexion - Lesser Toe Flexor					
9. Foot Flexion - Hallux Flexor					
Comments:					

Appendix E: 36-Item Short Form Survey Instrument (SF-36)

Participant Screening Code: SCR01

Participant Code: P01-PHP/CON

Date: 01/01/2024



IRB Protocol Number: 24.180

IRB Approval Date: 3/28/2024

36-Item Short Form Survey Instrument (SF-36)

36-Item Health Survey 1.0 Questionnaire Items. Choose ONE option for each questionnaire item.

[Section #1]

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

- | | | | | |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| ☐ | ☐ | ☐ | ☐ | ☐ |
| 1 | 2 | 3 | 4 | 5 |
| Excellent | Very good | Good | Fair | Poor |

2. Compared to one year ago, how would you rate your health in general now?

- | | | | | |
|-----------------------------------|---------------------------------------|--------------------------------|--------------------------------------|----------------------------------|
| ☐ | ☐ | ☐ | ☐ | ☐ |
| Much better now than one year ago | Somewhat better now than one year ago | About the same as one year ago | Somewhat worse now than one year ago | Much worse now than one year ago |

[Section #2]

3. The following items are about activities you might do during a typical day. Does **your health now limit you** in these activities? If so, how much?

- | | | | |
|--|--------------------------|--------------------------|--------------------------|
| | ☐ | ☐ | ☐ |
| | 1 | 2 | 3 |
| | Yes, limited a lot | Yes, limited a little | No, not limited at all |
| a. Vigorous activities , such as running, lifting heavy objects, participating in strenuous sports | ☐ | ☐ | ☐ |
| b. Moderate activities , such as moving a table, pushing a vacuum cleaner, bowling, or playing golf | ☐ | ☐ | ☐ |
| c. Lifting or carrying groceries | ☐ | ☐ | ☐ |
| d. Climbing several flights of stairs | ☐ | ☐ | ☐ |
| e. Climbing one flight of stairs | ☐ | ☐ | ☐ |
| f. Bending, kneeling, or stooping | ☐ | ☐ | ☐ |
| g. Walking more than a mile | ☐ | ☐ | ☐ |
| h. Walking several blocks | ☐ | ☐ | ☐ |
| i. Walking one block | ☐ | ☐ | ☐ |
| j. Bathing or dressing yourself | ☐ | ☐ | ☐ |

[Section #3]

4. During the **past 4 weeks**, have you had any of the following problems with your work or other regular daily activities **as a result of your physical health**?

- | | 1
Yes | 2
No |
|--|--------------------------|--------------------------|
| a. Cut down the amount of time you spent on work or other activities | ☐ | ☐ |
| b. Accomplished less than you would like | ☐ | ☐ |
| c. Were limited in the kind of work or other activities | ☐ | ☐ |
| d. Had difficulty performing the work or other activities (for example, it took extra effort) | ☐ | ☐ |

[Section #4]

5. During the **past 4 weeks**, have you had any of the following problems with your work or other regular daily activities **as a result of any emotional problems** (such as feeling depressed or anxious)?

- | | 1
Yes | 2
No |
|---|--------------------------|--------------------------|
| a. Cut down the amount of time you spent on work or other activities | ☐ | ☐ |
| b. Accomplished less than you would like | ☐ | ☐ |
| c. Didn't do work or other activities as carefully as usual | ☐ | ☐ |

[Section #5]

- | | 1
☐
Not at all | 2
☐
Slightly | 3
☐
Moderately | 4
☐
Quite a bit | 5
☐
Extremely |
|---|---|---|---|--|--|
| 6. During the past 4 weeks , to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbors, or groups? | | | | | |

[Section #6]

- | | 1
☐
None | 2
☐
Very mild | 3
☐
Mild | 4
☐
Moderate | 5
☐
Severe | 6
☐
Very severe |
|--|---------------------------------------|--|---------------------------------------|---|---|--|
| 7. How much bodily pain have you had during the past 4 weeks ? | | | | | | |

[Section #7]

- | | 1
☐
Not at all | 2
☐
A little bit | 3
☐
Moderately | 4
☐
Quite a bit | 5
☐
Extremely |
|--|---|---|---|--|--|
| 8. During the past 4 weeks , how much did pain interfere with your normal work (including both work outside the home and housework)? | | | | | |

[Section #8]

9. These questions are about how you feel and how things have been with you **during the past 4 weeks**. For each question, please give the one answer that comes closest to the way you have been feeling.

How much of the time during the past 4 weeks :	1 All of the time	2 Most of the time	3 A good bit of the time	4 Some of the time	5 A little of the time	6 None of the time
a. Did you feel full of pep?	☐	☐	☐	☐	☐	☐
b. Have you been a very nervous person?	☐	☐	☐	☐	☐	☐
c. Have you felt so down in the dumps that nothing could cheer you up?	☐	☐	☐	☐	☐	☐
d. Have you felt calm and peaceful?	☐	☐	☐	☐	☐	☐
e. Did you have a lot of energy?	☐	☐	☐	☐	☐	☐
f. Have you felt downhearted and blue?	☐	☐	☐	☐	☐	☐
g. Did you feel worn out?	☐	☐	☐	☐	☐	☐
h. Have you been a happy person?	☐	☐	☐	☐	☐	☐
i. Did you feel tired?	☐	☐	☐	☐	☐	☐

[Section #9]

10. During the **past 4 weeks**, how much of the time has your **physical health or emotional problems** interfered with your social activities (like visiting with friends, relatives, etc.)?

1 All of the time	2 Most of the time	3 Some of the time	4 A little of the time	5 None of the time
☐	☐	☐	☐	☐

[Section #10]

11. How **TRUE** or **FALSE** is **each** of the following statements for you?

	1 Definitely true ☐	2 Mostly true ☐	3 Don't know ☐	4 Mostly false ☐	5 Definitely false ☐
a. I seem to get sick a little easier than other people	☐	☐	☐	☐	☐
b. I am as healthy as anybody I know	☐	☐	☐	☐	☐
c. I expect my health to get worse	☐	☐	☐	☐	☐
d. My health is excellent	☐	☐	☐	☐	☐

Ware, J. E., Jr, & Sherbourne, C. D. (1992). The MOS 36-item short-form health survey (SF-36). I. Conceptual framework and item selection. *Medical care*, 30(6), 473–483.

Appendix F: International Physical Activity Questionnaire (IPAQ)

Participant Screening Code: SCR01
Participant Code: P01-PHP/CON
Date: 01/01/2024



IRB Protocol Number: 24.180
IRB Approval Date: 3/28/2024

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE (October 2002)

LONG LAST 7 DAYS SELF-ADMINISTERED FORMAT

FOR USE WITH YOUNG AND MIDDLE-AGED ADULTS (15-69 years)

The International Physical Activity Questionnaires (IPAQ) comprises a set of 4 questionnaires. Long (5 activity domains asked independently) and short (4 generic items) versions for use by either telephone or self-administered methods are available. The purpose of the questionnaires is to provide common instruments that can be used to obtain internationally comparable data on health-related physical activity.

Background on IPAQ

The development of an international measure for physical activity commenced in Geneva in 1998 and was followed by extensive reliability and validity testing undertaken across 12 countries (14 sites) during 2000. The final results suggest that these measures have acceptable measurement properties for use in many settings and in different languages, and are suitable for national population-based prevalence studies of participation in physical activity.

Using IPAQ

Use of the IPAQ instruments for monitoring and research purposes is encouraged. It is recommended that no changes be made to the order or wording of the questions as this will affect the psychometric properties of the instruments.

Translation from English and Cultural Adaptation

Translation from English is encouraged to facilitate worldwide use of IPAQ. Information on the availability of IPAQ in different languages can be obtained at www.ipaq.ki.se. If a new translation is undertaken we highly recommend using the prescribed back translation methods available on the IPAQ website. If possible please consider making your translated version of IPAQ available to others by contributing it to the IPAQ website. Further details on translation and cultural adaptation can be downloaded from the website.

Further Developments of IPAQ

International collaboration on IPAQ is on-going and an **International Physical Activity Prevalence Study** is in progress. For further information see the IPAQ website.

More Information

More detailed information on the IPAQ process and the research methods used in the development of IPAQ instruments is available at www.ipaq.ki.se and Booth, M.L. (2000). *Assessment of Physical Activity: An International Perspective*. Research Quarterly for Exercise and Sport, 71 (2): s114-20. Other scientific publications and presentations on the use of IPAQ are summarized on the website.

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** and **moderate** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal.

PART 1: JOB-RELATED PHYSICAL ACTIVITY

The first section is about your work. This includes paid jobs, farming, volunteer work, course work, and any other unpaid work that you did outside your home. Do not include unpaid work you might do around your home, like housework, yard work, general maintenance, and caring for your family. These are asked in Part 3.

1. Do you currently have a job or do any unpaid work outside your home?

☐ Yes

☐ No →

Skip to PART 2: TRANSPORTATION

The next questions are about all the physical activity you did in the **last 7 days** as part of your paid or unpaid work. This does not include traveling to and from work.

2. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, heavy construction, or climbing up stairs **as part of your work**? Think about only those physical activities that you did for at least 10 minutes at a time.

_____ days per week

☐ No vigorous job-related physical activity



Skip to question 4

3. How much time did you usually spend on one of those days doing **vigorous** physical activities as part of your work?

_____ hours per day

_____ minutes per day

4. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads **as part of your work**? Please do not include walking.

_____ days per week

☐ No moderate job-related physical activity



Skip to question 6

5. How much time did you usually spend on one of those days doing moderate physical activities as part of your work?
- _____ hours per day
_____ minutes per day
6. During the last 7 days, on how many days did you walk for at least 10 minutes at a time as part of your work? Please do not count any walking you did to travel to or from work.
- _____ days per week
- ☐ No job-related walking → Skip to PART 2: TRANSPORTATION
7. How much time did you usually spend on one of those days walking as part of your work?
- _____ hours per day
_____ minutes per day

PART 2: TRANSPORTATION PHYSICAL ACTIVITY

These questions are about how you traveled from place to place, including to places like work, stores, movies, and so on.

8. During the last 7 days, on how many days did you travel in a motor vehicle like a train, bus, car, or tram?
- _____ days per week
- ☐ No traveling in a motor vehicle → Skip to question 10
9. How much time did you usually spend on one of those days traveling in a train, bus, car, tram, or other kind of motor vehicle?
- _____ hours per day
_____ minutes per day

Now think only about the bicycling and walking you might have done to travel to and from work, to do errands, or to go from place to place.

10. During the last 7 days, on how many days did you bicycle for at least 10 minutes at a time to go from place to place?
- _____ days per week
- ☐ No bicycling from place to place → Skip to question 12

11. How much time did you usually spend on one of those days to bicycle from place to place?
- _____ hours per day
_____ minutes per day
12. During the last 7 days, on how many days did you walk for at least 10 minutes at a time to go from place to place?
- _____ days per week
- ☐ No walking from place to place → *Skip to PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY*
13. How much time did you usually spend on one of those days walking from place to place?
- _____ hours per day
_____ minutes per day

PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY

This section is about some of the physical activities you might have done in the last 7 days in and around your home, like housework, gardening, yard work, general maintenance work, and caring for your family.

14. Think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do vigorous physical activities like heavy lifting, chopping wood, shoveling snow, or digging in the garden or yard?
- _____ days per week
- ☐ No vigorous activity in garden or yard → *Skip to question 16*
15. How much time did you usually spend on one of those days doing vigorous physical activities in the garden or yard?
- _____ hours per day
_____ minutes per day
16. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do moderate activities like carrying light loads, sweeping, washing windows, and raking in the garden or yard?
- _____ days per week
- ☐ No moderate activity in garden or yard → *Skip to question 18*

17. How much time did you usually spend on one of those days doing moderate physical activities in the garden or yard?
- _____ hours per day
_____ minutes per day
18. Once again, think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do moderate activities like carrying light loads, washing windows, scrubbing floors and sweeping inside your home?
- _____ days per week
- ☐ No moderate activity inside home → Skip to PART 4: RECREATION, SPORT AND LEISURE-TIME PHYSICAL ACTIVITY
19. How much time did you usually spend on one of those days doing moderate physical activities inside your home?
- _____ hours per day
_____ minutes per day

PART 4: RECREATION, SPORT, AND LEISURE-TIME PHYSICAL ACTIVITY

This section is about all the physical activities that you did in the last 7 days solely for recreation, sport, exercise or leisure. Please do not include any activities you have already mentioned.

20. Not counting any walking you have already mentioned, during the last 7 days, on how many days did you walk for at least 10 minutes at a time in your leisure time?
- _____ days per week
- ☐ No walking in leisure time → Skip to question 22
21. How much time did you usually spend on one of those days walking in your leisure time?
- _____ hours per day
_____ minutes per day
22. Think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do vigorous physical activities like aerobics, running, fast bicycling, or fast swimming in your leisure time?
- _____ days per week
- ☐ No vigorous activity in leisure time → Skip to question 24

23. How much time did you usually spend on one of those days doing vigorous physical activities in your leisure time?
- _____ hours per day
_____ minutes per day
24. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do moderate physical activities like bicycling at a regular pace, swimming at a regular pace, and doubles tennis in your leisure time?
- _____ days per week
- ☐ No moderate activity in leisure time → **Skip to PART 5: TIME SPENT SITTING**
25. How much time did you usually spend on one of those days doing moderate physical activities in your leisure time?
- _____ hours per day
_____ minutes per day

PART 5: TIME SPENT SITTING

The last questions are about the time you spend sitting while at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading or sitting or lying down to watch television. Do not include any time spent sitting in a motor vehicle that you have already told me about.

26. During the last 7 days, how much time did you usually spend sitting on a weekday?
- _____ hours per day
_____ minutes per day
27. During the last 7 days, how much time did you usually spend sitting on a weekend day?
- _____ hours per day
_____ minutes per day

This is the end of the questionnaire, thank you for participating.

Appendix G: Foot and Ankle Function Ability Measure (FAAM)

Participant Screening Code: SCR01
 Participant Code: P01-PHP/CON
 Date: 01/01/2024



IRB Protocol Number: 24.180
 IRB Approval Date: 3/28/2024

Foot and Ankle Ability Measure (FAAM) Activities of Daily Living Subscale

Please Answer **every question** with **one response** that most closely describes your condition within the past week.
 If the activity in question is limited by something other than your foot or ankle mark "Not Applicable" (N/A).

	No Difficulty	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to do	N/A
Standing	☐	☐	☐	☐	☐	☐
Walking on even Ground	☐	☐	☐	☐	☐	☐
Walking on even ground without shoes	☐	☐	☐	☐	☐	☐
Walking up hills	☐	☐	☐	☐	☐	☐
Walking down hills	☐	☐	☐	☐	☐	☐
Going up stairs	☐	☐	☐	☐	☐	☐
Going down stairs	☐	☐	☐	☐	☐	☐
Walking on uneven ground	☐	☐	☐	☐	☐	☐
Stepping up and down curbs	☐	☐	☐	☐	☐	☐
Squatting	☐	☐	☐	☐	☐	☐
Coming up on your toes	☐	☐	☐	☐	☐	☐
Walking initially	☐	☐	☐	☐	☐	☐
Walking 5 minutes or less	☐	☐	☐	☐	☐	☐
Walking approximately 10 minutes	☐	☐	☐	☐	☐	☐
Walking 15 minutes or greater	☐	☐	☐	☐	☐	☐

Foot and Ankle Ability Measure (FAAM)
Activities of Daily Living Subscale
Page 2

Because of your foot and ankle how much difficulty do you have with:

	No Difficulty at all	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to do	N/A
Home responsibilities	☐	☐	☐	☐	☐	☐
Activities of daily living	☐	☐	☐	☐	☐	☐
Personal care	☐	☐	☐	☐	☐	☐
Light to moderate work (standing, walking)	☐	☐	☐	☐	☐	☐
Heavy work (push/pulling, climbing, carrying)	☐	☐	☐	☐	☐	☐
Recreational activities	☐	☐	☐	☐	☐	☐

How would you rate your current level of function during you usual activities of daily living from 0 to 100 with 100 being your level of function prior to your foot or ankle problem and 0 being the inability to perform any of your usual daily activities.

___ . 0 %

Foot and Ankle Ability Measure (FAAM)
Sports Subscale

Because of your foot and ankle how much difficulty do you have with:

	No Difficulty at all	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to do	N/A
Running	☐	☐	☐	☐	☐	☐
Jumping	☐	☐	☐	☐	☐	☐
Landing	☐	☐	☐	☐	☐	☐
Starting and stopping quickly	☐	☐	☐	☐	☐	☐
Cutting/lateral Movements	☐	☐	☐	☐	☐	☐
Ability to perform Activity with your Normal technique	☐	☐	☐	☐	☐	☐
Ability to participate In your desired sport As long as you like	☐	☐	☐	☐	☐	☐

How would you rate your current level of function during your sports related activities from 0 to 100 with 100 being your level of function prior to your foot or ankle problem and 0 being the inability to perform any of your usual daily activities?

___ . 0%

Overall, how would you rate your current level of function?

☐ Normal ☐ Nearly Normal ☐ Abnormal ☐ Severely Abnormal

Martin, R; Irrgang, J; Burdett, R; Conti, S; VanSwearingen, J: Evidence of Validity for the Foot and Ankle Ability Measure. Foot and Ankle International. Vol.26, No.11: 968-983, 2005.

Appendix H: The Manchester Foot Pain and Disability Index (MFPDI)

Participant Screening Code: SCR01

Participant Code: P01-PHP/CON

Date: 01/01/2024



IRB Protocol Number: 24.180

IRB Approval Date: 3/28/2024

The Manchester Foot Pain and Disability Index (MFPDI)

Self-administered questionnaire on disability associated with foot pain.

Below are some statements about problems people have because of **pain in their feet**.

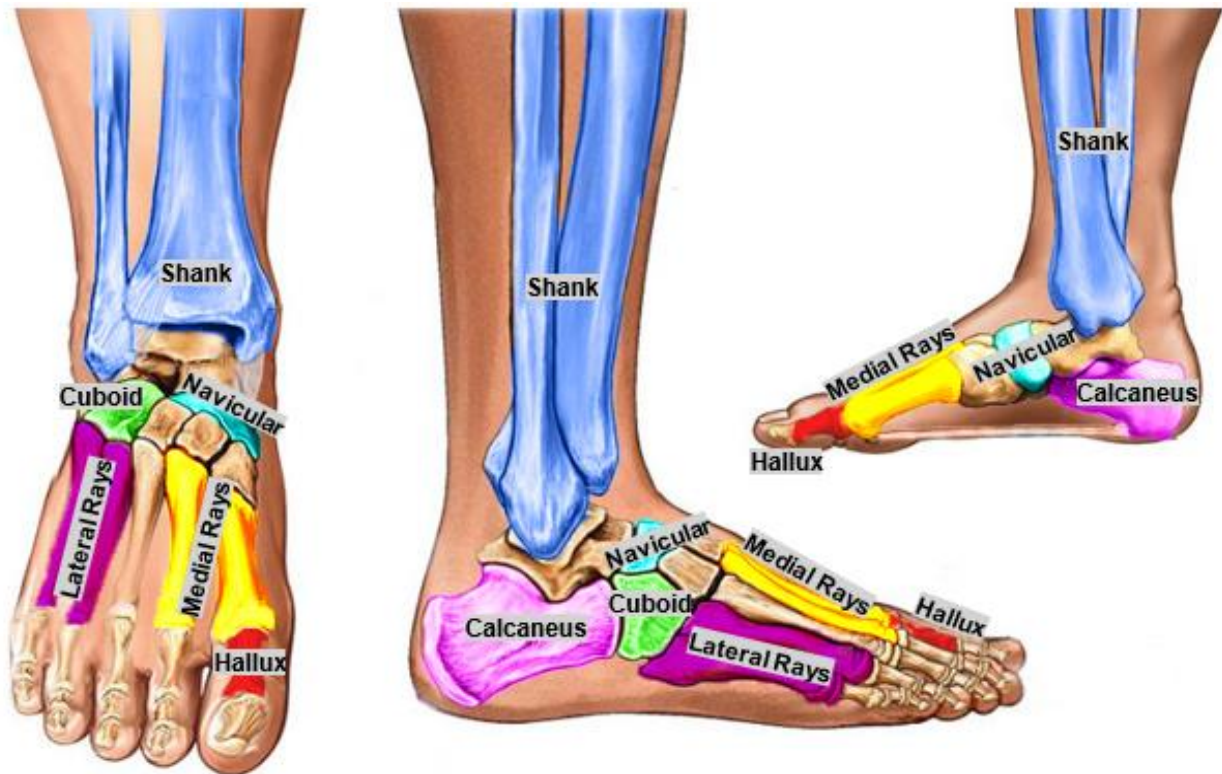
For each statement indicate if this has applied to you during the **past month**. If so, was this only on some days or on most or every day in the past month?

PLEASE TICK A BOX FOR EACH STATEMENT.

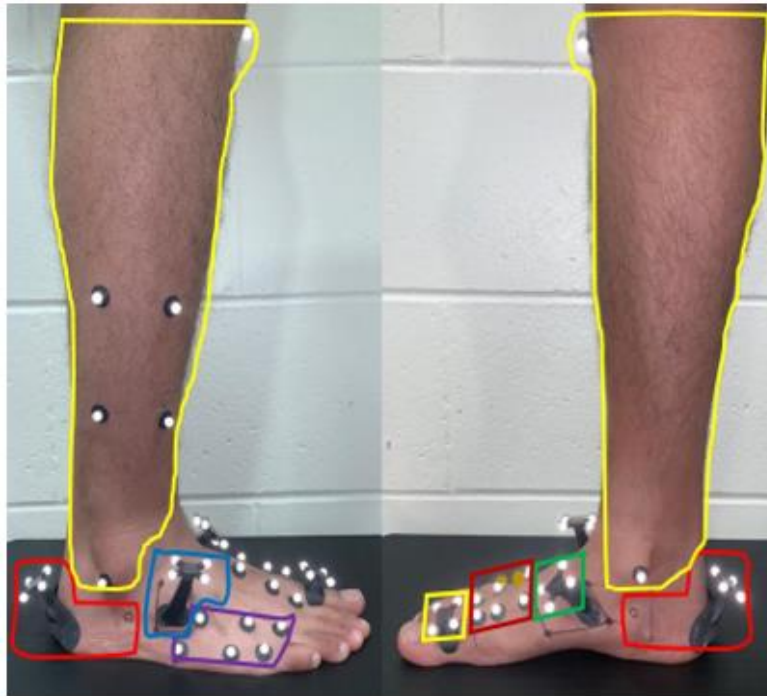
	During the past month this has applied to me			
	None of the time	On some days	On most/ every day(s)	
Because of pain in my feet:				
I avoid walking outside at all	☐	☐	☐	
I avoid walking long distances	☐	☐	☐	
I don't walk in a normal way	☐	☐	☐	
I walk slowly	☐	☐	☐	
I have to stop and rest my feet	☐	☐	☐	
I avoid hard or rough surfaces when possible	☐	☐	☐	
Because of pain in my feet:				
I avoid standing for a long time	☐	☐	☐	
I catch the bus or use the car more often	☐	☐	☐	
I need help with housework/shopping	☐	☐	☐	
I still do everything but with more pain and discomfort	☐	☐	☐	
I get irritable when my feet hurt	☐	☐	☐	
I feel self conscious about my feet	☐	☐	☐	
I feel self conscious about the shoes I have to wear	☐	☐	☐	
I have constant pain in my feet	☐	☐	☐	
My feet are worse in the morning	☐	☐	☐	
My feet are more painful in the evening	☐	☐	☐	
I get shooting pains in my feet	☐	☐	☐	
Because of pain in my feet:				
I am unable to carry out my previous work	☐	☐	☐	☐ Not applicable
I no longer do all my previous activities (sport, dancing, hill walking etc.)	☐	☐	☐	☐
TICK HERE WHEN YOU HAVE READ ALL THE STATEMENTS ON THIS PAGE				☐

Garrow, A., Papageorgiou, A., Silman, A., Thomas, E., Jayson, M., & Macfarlane, G. (2000). Development and validation of a questionnaire to assess disabling foot pain. *Pain*, 85(1-2), 107–113.

Appendix I: Seven Multi-Segment Foot Model (MSFM)



Appendix J: Functional Articulations from Six-Foot Segments

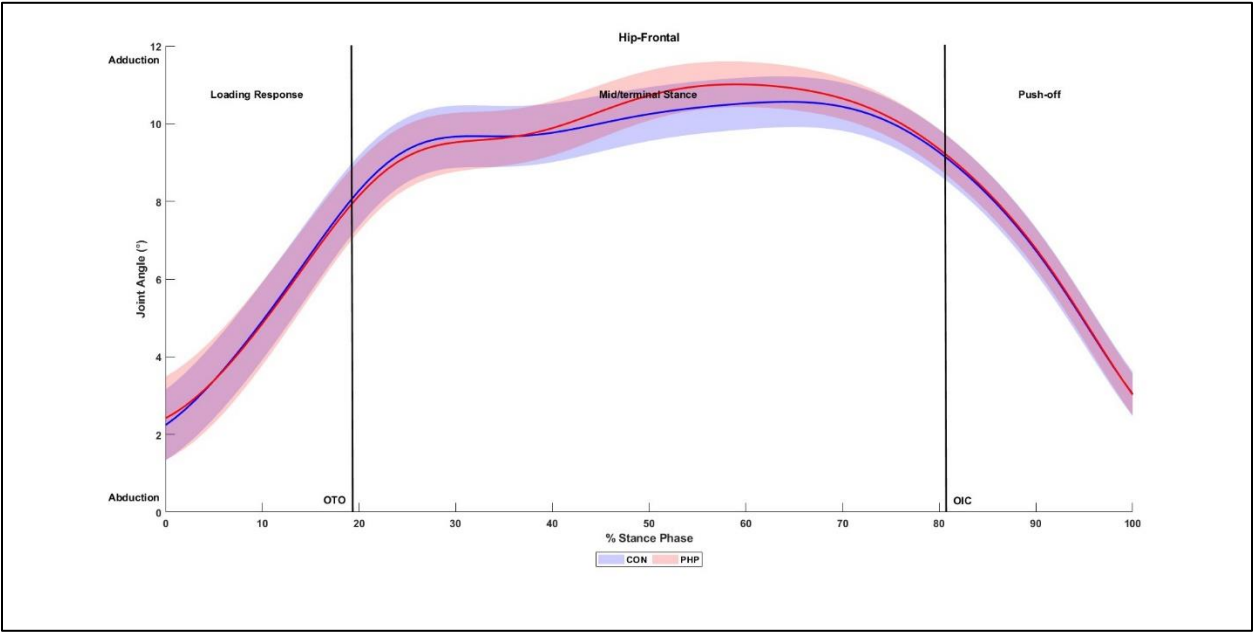
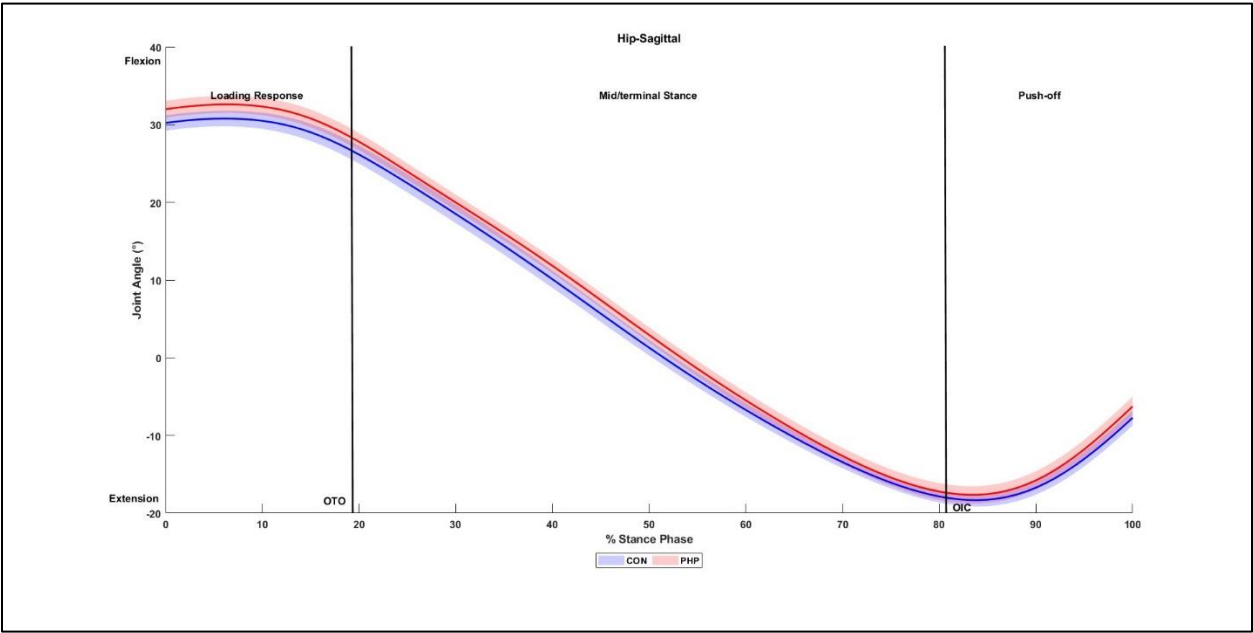


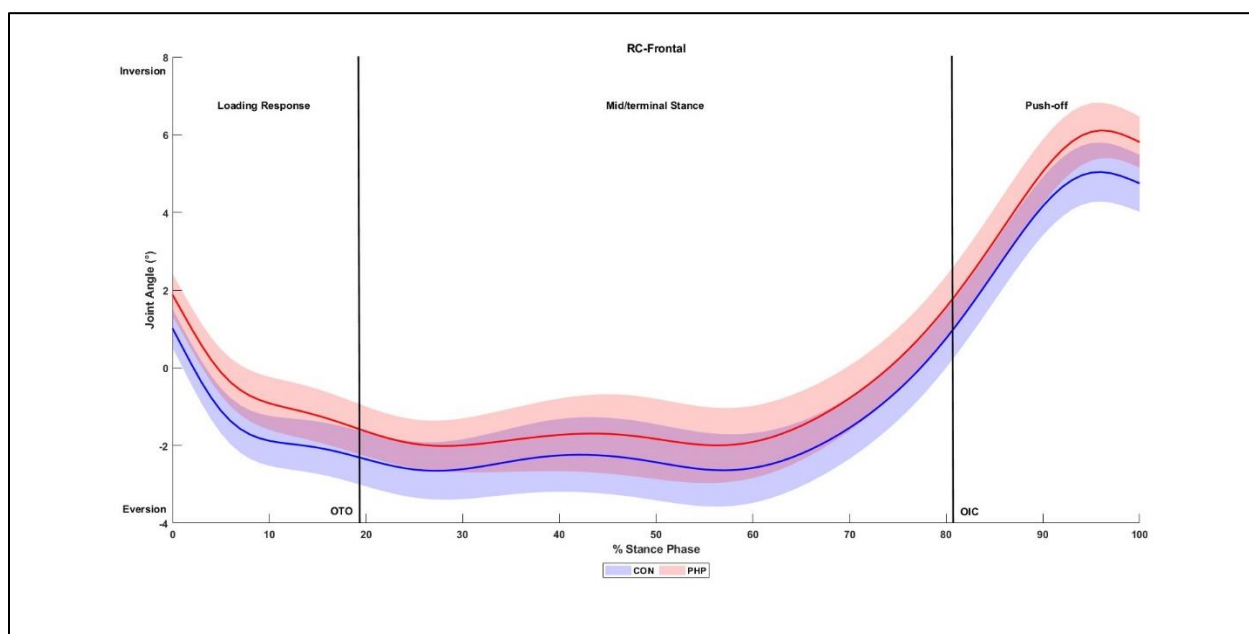
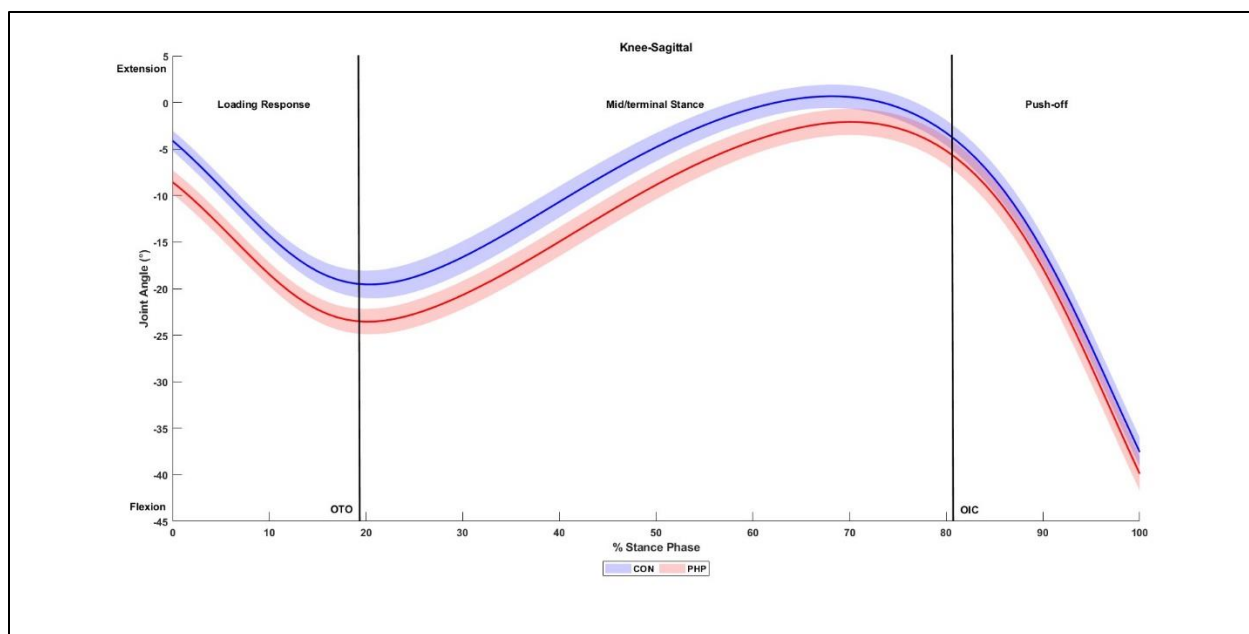
Clusters of four retroreflective technical markers (6.4 mm diameter) are placed on the right or left shank and foot to identify seven segments and six functional articulations. The seven-foot model segments that will be identified to form the following functional articulations:

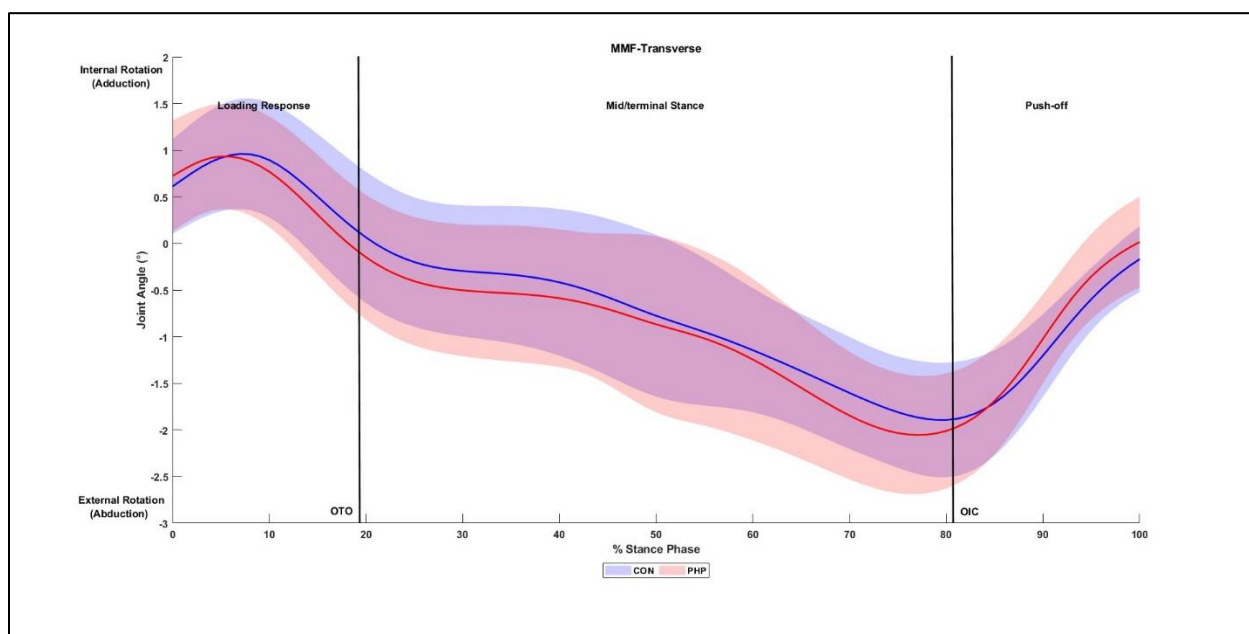
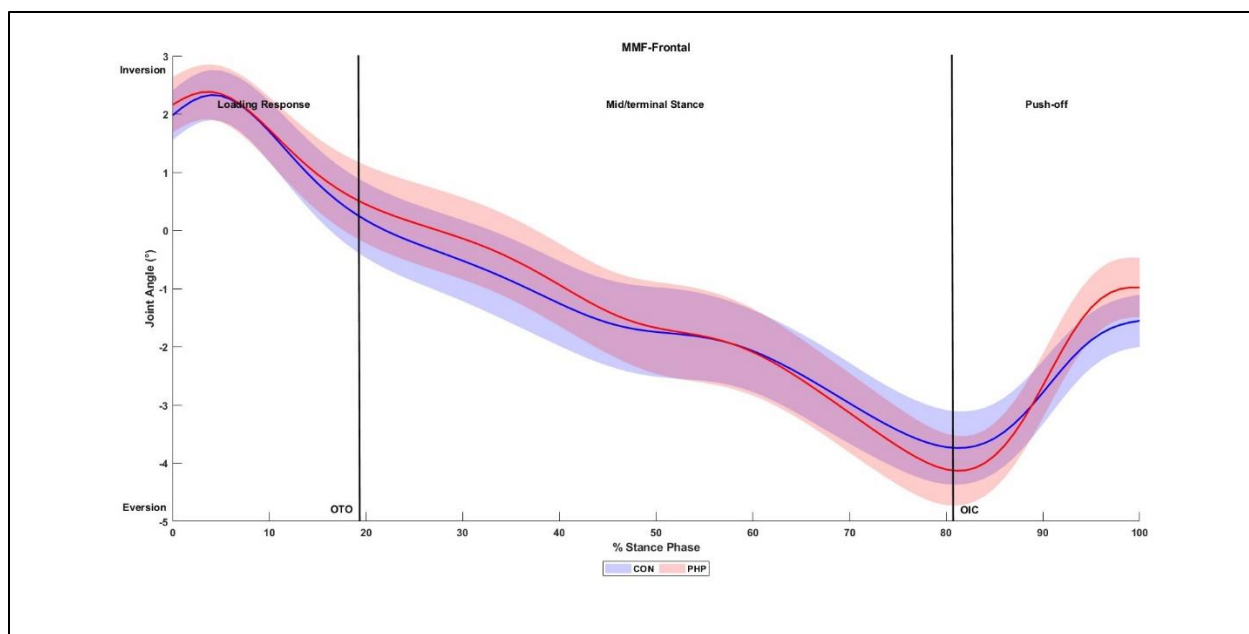
RC (Shank with CALC);
MMF (CALC with NAV);
LMF (CALC with CUB);
MFF (NAV with Medial Rays);
LFF (CUB with Lateral Rays);
1MTP (Medial Rays with HAL),
 (Cobb et al., 2016).

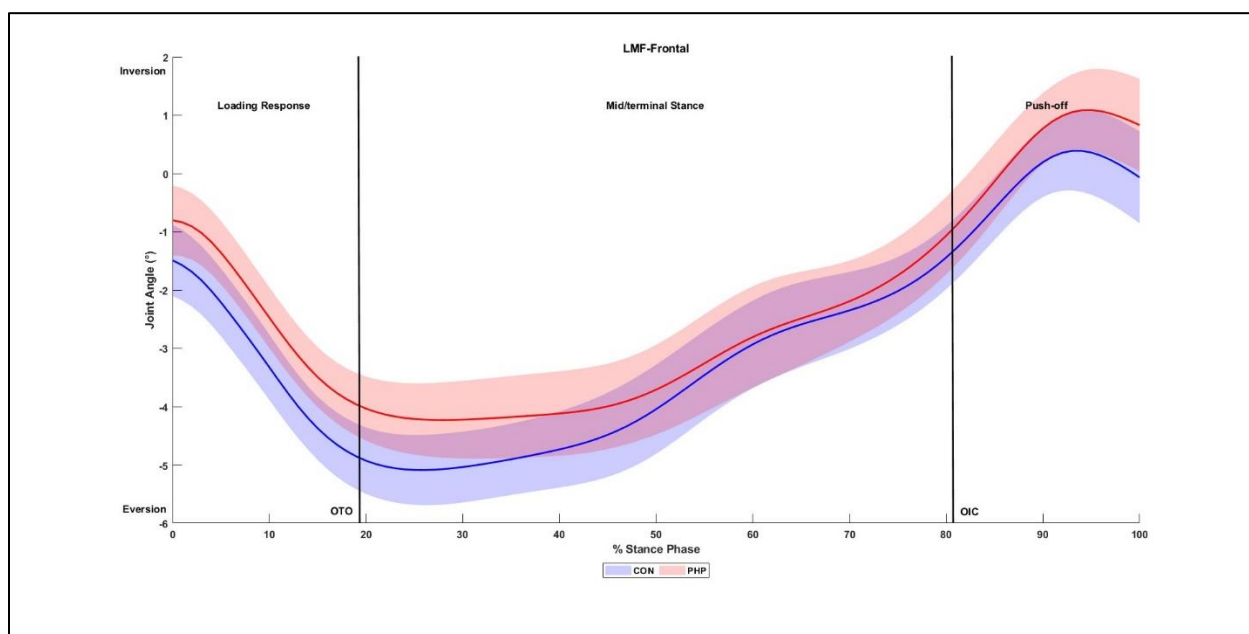
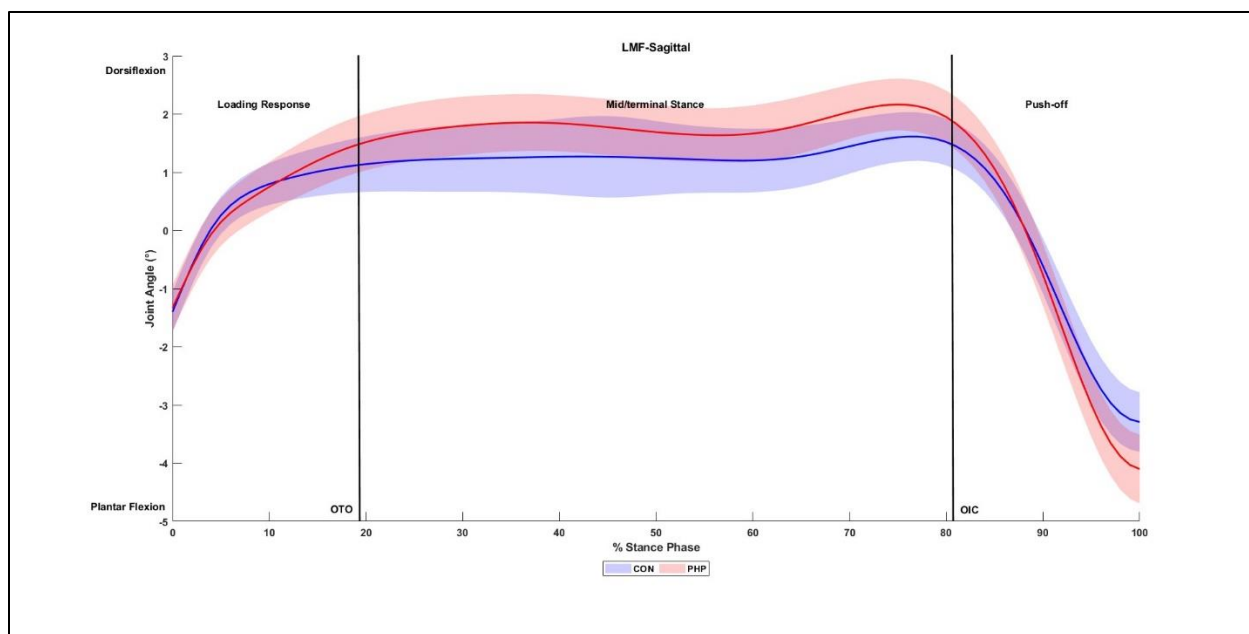
Functional Articulation	Proximal Segment	Distal Segment
Rearfoot Complex (RC)	Shank	Calcaneus
Calcaneonavicular Complex [Medial Midfoot (MMF)]	Calcaneus	Navicular
Calcaneocuboid Complex [Lateral Midfoot (LMF)]	Calcaneus	Cuboid
Medial Forefoot Complex (MFF)	Navicular	Medial rays
Lateral Forefoot Complex (LFF)	Cuboid	Lateral rays
1st Metatarsophalangeal Complex (1MTP)	Medial rays	Hallux

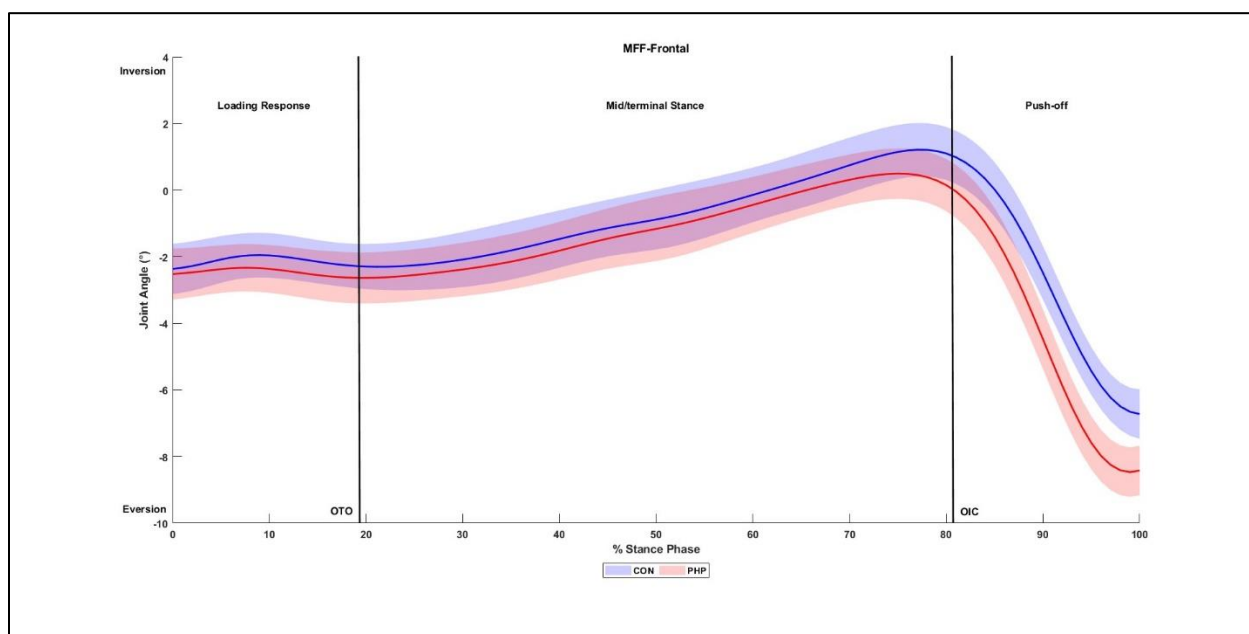
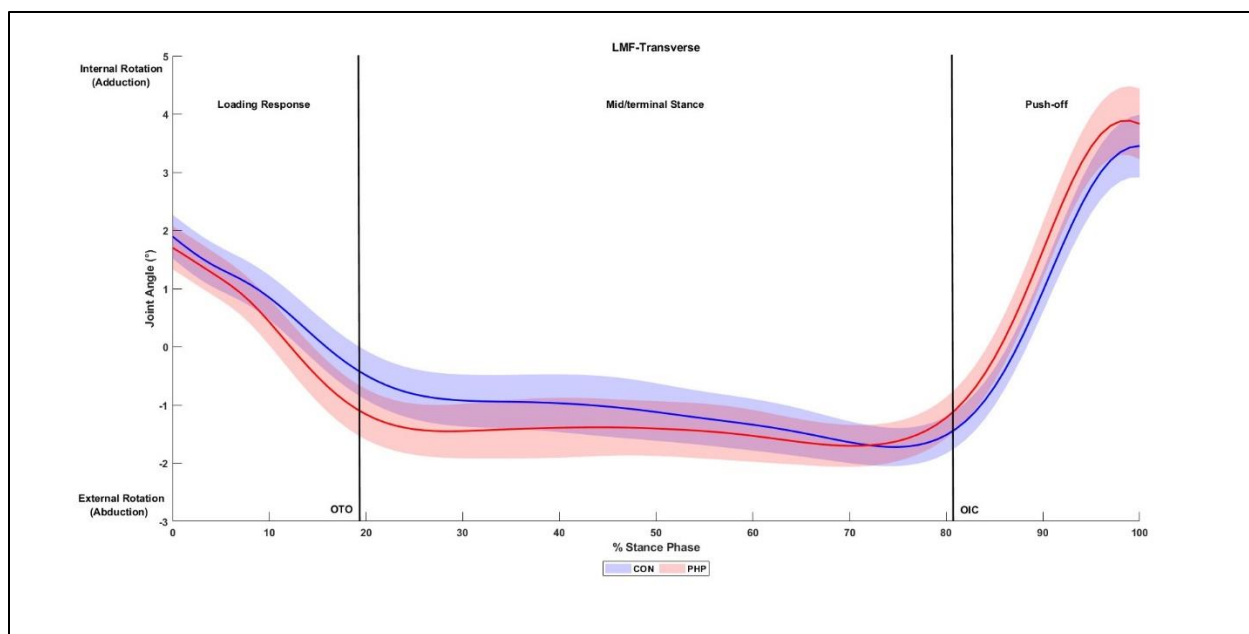
Appendix K: Time-Series for Non-Significant Joint Articulations

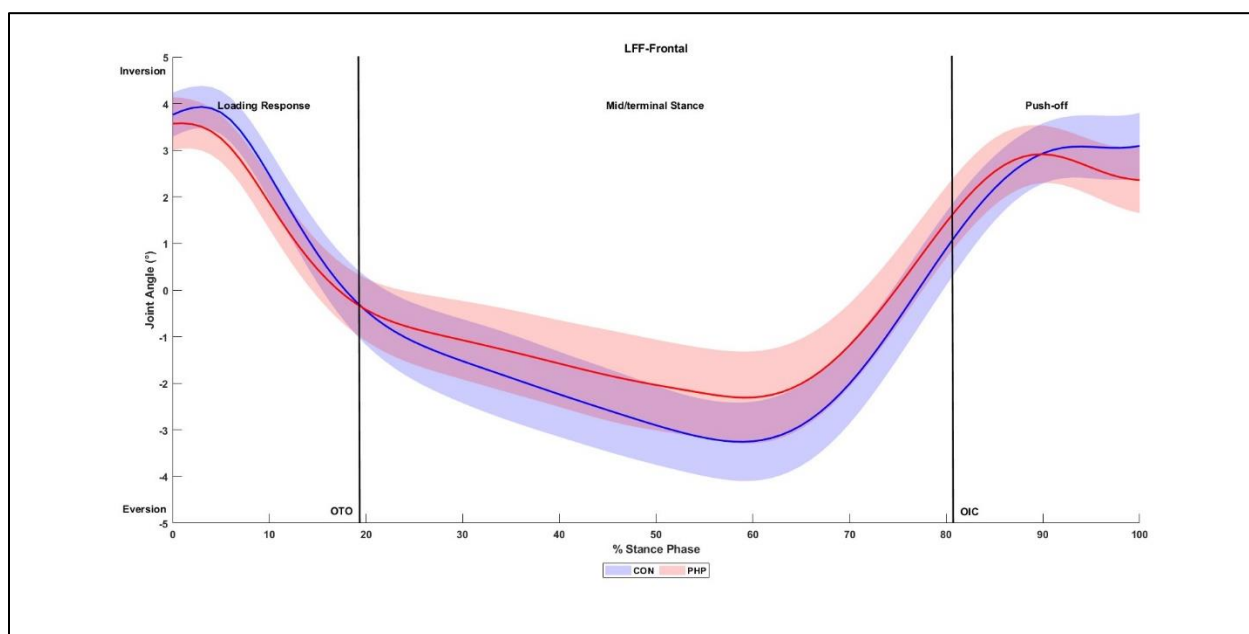
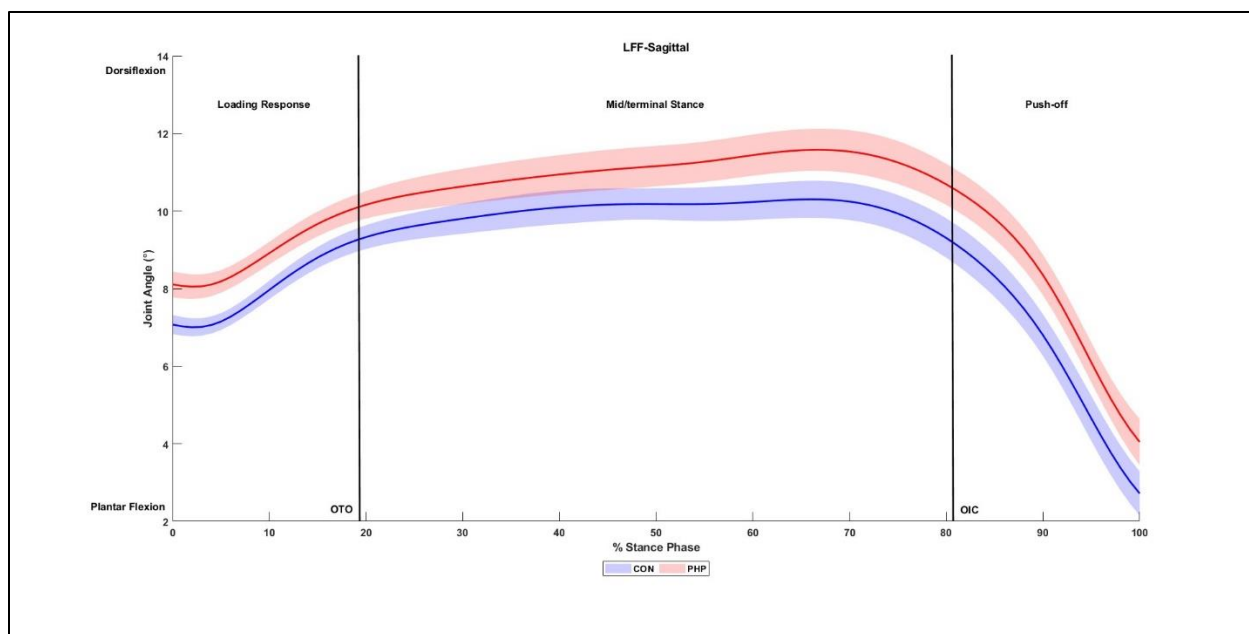


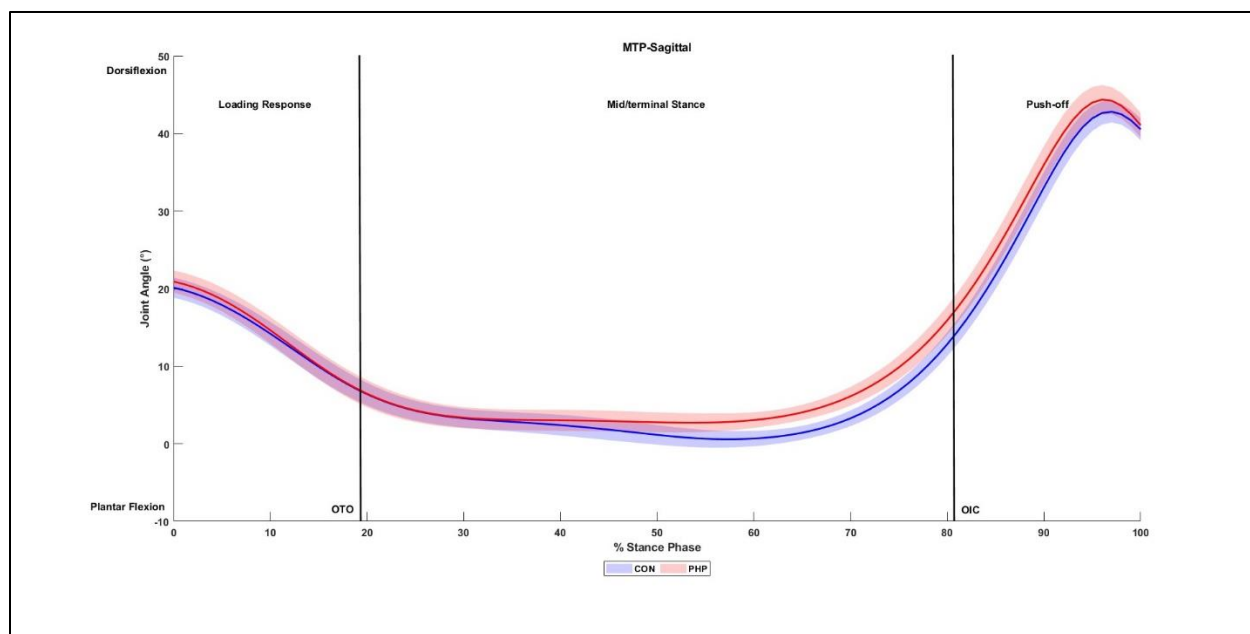












Appendix L: Net Joint Power Non-Significant Results

