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Do Different Pathologies Affect the Relationship Between the Stiffness of the Plantar Fascia and the Function of the MTP Joint?

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DO DIFFERENT PATHOLOGIES AFFECT THE RELATIONSHIP BETWEEN THE
STIFFNESS OF THE PLANTAR FASCIA AND THE FUNCTION OF THE MTP JOINT?

by

Madeline Ryan Pauley
B.S. July 2018, East Carolina University

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ABSTRACT

DO DIFFERENT PATHOLOGIES AFFECT THE RELATIONSHIP BETWEEN THE STIFFNESS OF THE PLANTAR FASCIA AND THE FUNCTION OF THE MTP JOINT?

Madeline Ryan Pauley
Old Dominion University, 2020
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Compared to healthy individuals, individuals with plantar fasciitis and diabetes experience material and structural property changes to soft tissues in the feet. The purpose of this study was to compare the relationship between material properties, power absorption, and energy storage characteristics to metatarsal power between healthy, plantar fasciitis symptomatic and asymptomatic, and diabetic participants. Investigating material change differences as well as energy storage and transfer trends in different pathology groups can lead to a better overall understanding of power transfer at the metatarsophalangeal joint (MTP). Participants were recruited for kinematic gait analysis and lower extremity shear wave elastography analysis and fell into subgroups of either having plantar fasciitis and having symptoms (PFS, n=11), plantar fasciitis without having symptoms (PFA, n=5), diabetic type 1 or 2 (DT1, n=7/DT2, n=8), or age-matched healthy controls (n=16). There was no significant difference between subgroups at either the plantar fascia (PF) proximal or distal region. PFS presented statistically significant ($p=.02$) reductions in the total range of motion consistent with prior literature. Insignificant differences in the Redistribution Ratio between subgroups, which is the ratio of total positive work performed by MTP joint musculature to the proximal joint musculature, suggests that work is performed about the MTP similarly in both eccentric and concentric motions. PFA was found to have a positive relationship between eccentric peak power and the PF proximal ($r=.897$, $p=.003$), as well as a

negative relationship between concentric peak power and the PF distal stiffness ($r=-.72$, $p=.044$).

These observations suggest that there may be an altered mechanism of moment execution in the plantarflexion propulsion movement in a PFA population.

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NOMENCLATURE

<i>PF</i>	Plantar Fascia
<i>PFA</i>	Plantar Fascia Asymptomatic
<i>PFS</i>	Plantar Fascia Symptomatic
<i>DT1</i>	Diabetes Type 1
<i>DT2</i>	Diabetes Type 2
<i>MTP</i>	Metatarsophalangeal joint
<i>TROM</i>	Total Range of Motion
<i>RR</i>	Redistribution Ratio

TABLE OF CONTENTS

	Page
LIST OF TABLES	viii
LIST OF FIGURES	ix
Chapter	
I. INTRODUCTION AND REVIEW OF LITERATURE	1
ANATOMY	1
PROPERTIES OF THE PLANTAR FASCIA	3
PLANTAR FASCIITIS	6
DIABETES PATHOLOGY AND DIAGNOSIS.....	8
II. METHODS.....	13
INCLUSION-EXCLUSION CRITERIA	13
ELASTOGRAPHY DATA COLLECTION.....	14
MOTION ANALYSIS DATA COLLECTION.....	15
DATA PROCESSING AND ANALYSIS	19
III. RESULTS	22
IV. DISCUSSION.....	39
FUTURE WORK.....	45
BIBLIOGRAPHY.....	46
APPENDICES	53
VITA.....	60

LIST OF TABLES

Table	Page
1. Foot segment directions of motion	18
2. Subject group demographics.....	22
3. Proximal (A) and distal (B) plantar fascia stiffness averages and standard deviation.....	23
4. Spatiotemporal data among subgroups	24
5. Average local maximums and minimum, TROM, and significance (A), and correlation coefficients between the subgroup TROMs versus plantar fascia proximal or distal stiffness (B)	25
6. Subgroup average maximum (concentric) power and negative (eccentric) power and standard deviation (A), Correlation coefficients and significance for MTP concentric and eccentric power vs. plantar fascia proximal and distal (B)	27
7. Correlation coefficients and significance for MTP concentric and eccentric RR vs. plantar fascia proximal and distal	30
8. Subgroup MTP inversion JRF average, standard deviation, and significance	31
9. Subgroup averages minimum MTP Moment and standard deviation	32
10. Subgroup Moment Impulse vs. PF Proximal Stiffness and PF Distal Stiffness Correlation coefficients and significance.....	33
11. Subgroup ankle Eccentric and Concentric work.....	35
12. Correlation coefficients and significance for Ankle concentric and eccentric work vs. plantar fascia proximal and distal	35
13. Correlation coefficients and significance for ankle moment impulse vs. plantar fascia proximal and distal.....	37
14. Ankle minimum, maximum, and total range of motion means	38

LIST OF FIGURES

Figure	Page
1. Complete gait cycle illustration accompanied by terminology.....	2
2. Example shear wave elastography (SWE) measurement of the proximal plantar fascia site including the 1mm circular region of interest.....	14
3. Marker placement during standing calibration	16
4. Screenshot of Visual Studio analysis.....	17
5. Marker placement and inverse dynamics of two segment foot model.....	19
6. Boxplots of proximal (A) and distal (B) plantar fascia stiffness in PFS, PFA, Control, DT2, and DT1	23
7. Total range of motion at the MTP across 100% of stance.....	24
8. Subgroup average MTP power vs. percent stance (A) and Eccentric Power Distribution (B).....	26
9. Eccentric (A) and Concentric (B) Redistribution Ratios and standard deviations in subgroups	28
10. Individual subject Eccentric Redistribution Ratio (RR) value for organized by subgroups vs. plantar fascia proximal stiffness (A), Eccentric Redistribution Ratio vs. plantar fascia distal stiffness (B), Concentric Redistribution Ratio vs. plantar fascia proximal stiffness (C), Eccentric Redistribution Ratio vs. plantar fascia distal stiffness (D)	29
11. Normalized MTP Joint Reaction Force vs. percent stance	31
12. Average Subgroup MTP Moment vs. Percent Stance (A) and Moment participant distribution (B).....	32
13. Individual Moment Impulse vs. PF Proximal Stiffness (A) and PF Distal Stiffness (B)	33
14. Ankle power vs. percent stance	34
15. Ankle Moment vs. percent stance.....	36
16. Ankle total range of motion vs. percent stance.....	37

INTRODUCTION AND REVIEW OF LITERATURE

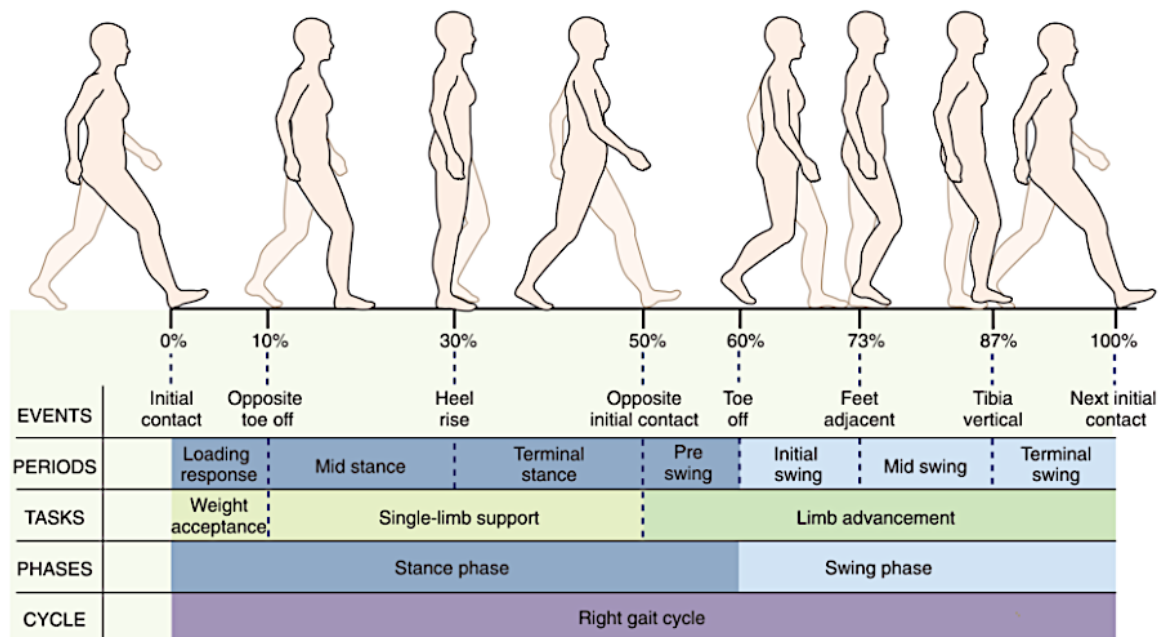
The foot is a conservational machine that allows for constant and consistent recycling of mechanical energy during locomotion. Three key events occur within a single gait cycle; during the stance phase, gravitational and kinetic energy are exchanged to conserve energy; in the swing phase, the leg transition is mainly passive, and lastly, the end foot-ground impact [1]. Energy transfers at all three of these motions are necessary to preserve smooth walking dynamics, but the focus of this study is the energy transfers during stance at the metatarsophalangeal joint (MTP).

Anatomy

The human foot is configured to optimize propulsive and locomotive efficiency [2]. Within each foot, there are five metatarsophalangeal joints located between the proximal phalanges of the toes and the metatarsal bones of the foot. They are categorized as a condyloid joint because the rounded surface of the metatarsal bones connects to the cavity made by the proximal phalanges. They act to provide a broad support area for the forefoot and assist primarily in energy absorption during the terminal stance of the gait cycle [3]. These joints can accomplish abduction, adduction, flexion, extension, and circumduction and are anchored by collateral ligaments, plantar ligaments, and deep, transverse metatarsal ligaments. Abduction is defined as a movement away from the midline. Adduction is a movement towards the midline. Flexion refers to a movement that decreases the angle between two body parts, extension refers to a movement that increases the angle between two body parts, and circumduction can be defined as a conical movement of a limb extending from the joint where the movement is controlled.

One complete gait cycle runs from one initial heel strike to the next initial contact of the same foot (Figure 1). Initial contact refers to the point at which the first foot contacts the ground and is classified as 0% stance. Heel rise refers to the heel lifting from the ground and occurs at around 30% of the gait cycle. The initial contact of the opposite foot occurs at 50% of the gait cycle, and toe-off occurs when the foot leaves contact with the ground at around 60% of the gait cycle. Throughout the gait cycle, the first metatarsal joint has plantarflexion and dorsiflexion motions that help adjust the flexibility and stability of the medial longitudinal arch. At heel contact during normal walking, the MTP is slightly extended in an overall dorsiflexion motion. From heel contact to heel-off, the MTP is then in a relatively neutral position for stability. As the foot begins the toe-off propulsive motion, the MTP again dorsiflexes, followed by a significant plantarflexion as the step motion is completed.

Figure 1 Complete gait cycle illustration accompanied by terminology



This figure was published in Kinesiology of the Musculoskeletal System, Edition 2, Donald A. Neumann, Pg. 636, Copyright Elsevier Health Sciences (2013). Reprinted with permission.

The plantar aponeurosis is a strong layer of fibrous connective tissue laterally divided into three sections that line the bottom of the foot [4]. It originates at the medial tubercle of the calcaneus and extends distally towards the toes, where it is further divided into five separate divisions that straddle the flexor tendons of each toe [4, 5].

Properties of the Plantar Fascia

The plantar fascia was first described as a 'truss'-like structure with the calcaneus, talus, navicular, three cuneiforms, and the first, second, and third metatarsals forming the medial longitudinal arch of the truss and the plantar fascia acting as the rod that ran from the phalanges to the calcaneus [6]. The structure allows for downward vertical forces to be displaced flatly onto the medial longitudinal arch and for ground reaction forces to travel upward on the calcaneus and metatarsal heads [7]. This further accentuates the flattening effect of the medial longitudinal arch when weight-bearing, yet the truss does not experience collapse due to the role of the plantar fascia. The tension of the plantar fascia while weight-bearing maintains the integrity of the truss and prevents the spreading of the calcaneus and metatarsals [8, 9]. This phenomenon is known as Windlass-Mechanism.

A windlass, by definition, is a tightening of a cable or rope about a cylinder. During dorsiflexion of the metatarsals, the plantar fascia becomes taut about the head of the metatarsal, and it is this tension that serves to shorten the distance between the calcaneus and metatarsals and, in contrast, elevate the medial longitudinal arch [8]. As such, the windlass function of the plantar fascia is extremely important during the toe-off phase of walking [6, 10, 11]. Its tension essentially transforms the midfoot joints into a firm lever that is effective in transmitting plantar flexor force during the terminal-stance phase of gait [12]. The largest support for the plantar fascia acting as a windlass comes from the nearly complete disappearance of the effect in

paralyzed feet as well as in feet that had undergone fasciotomies [6, 13]. Furthermore, several cadaveric *in vitro* studies reveal its contribution to medial longitudinal arch support in static stance as a deterioration of arch integrity is compromised by sectioning [14-16].

The Windlass-mechanism affects all of the joints in the foot but understanding the movements of the metatarsals is essential to understanding other motions within the foot caused by Windlass. During a closed kinetic chain plantarflexion movement, the toe-off motion in walking, for example, the first metatarsal moves proximally, causing the medial cuneiform, navicular, and talus proximal to it to have to move out of the way to allow for a full plantarflexion and arch raising [9]. The opposite motion of this same joint attributes to arch lowering. While motions do occur in all three planes, the largest of the Windlass mechanism motions occur in the sagittal plane, making the sagittal plane movement of the first metatarsophalangeal joint a focus of study.

The plantar fascia can store and return a portion of the strain energy during a quasi-elastic recoil, which dictates its fundamentality to medial longitudinal arch integrity; therefore, it can be theorized that the plantar fascia, along with other soft tissues, comprises a passive force mechanism that has the capability of modifying medial arch stiffness in accordance with an applied load [17, 18]. Because the plantar fascia is the largest contributor to arch maintenance, applied loads will increase the stiffness of the arch in a regulated manner to a finite deformation [18, 19]. As previously described, dorsiflexion of the toes results in a Windlass-Mechanism driven result of a shortened plantar fascia length and increased tension [6]. During an unloaded plantarflexion about the metatarsals, the plantar fascia raises the arch. However, in a loaded condition, such as static stance, a plantarflexion of the metatarsals is resisted by ground reaction forces. The greatest effect of the Windlass-Mechanism in any of these motions, however, is seen

during dorsiflexion of the hallux when the plantar fascia is pulled about the first metatarsal head due to its relatively large structure and curved surface [20]. With any structure existing in the body, however, there is a finite amount of tension it can bear before failure. With the deterioration of the plantar fascia comes irregular stiffness and loading patterns. If the plantar fascia is compromised, it should be seen at the level of the metatarsophalangeal joint about which the medial longitudinal arch is stabilized and speak to medial longitudinal arch integrity. Compromised metatarsophalangeal joint kinematics due to pathology that are correlated with plantar fascia stiffness could illuminate nuances in power transfer not yet identified in other literature.

Like any soft tissue structure in the body, the material properties of the plantar fascia can be influenced by water content, size, and collagen fiber orientation, therefore making these properties difficult to estimate [21]. An in vitro study by Wright and Rennels reported ranges of the modulus of elasticity to fall between recorded measures of other human connective tissue in the lower leg; ligament and tendon, which have experimental upper and lower bounds of about 50 and 1500 MPa, respectively [22-24]. The complex nature of the plantar fascia stemming from its unusual geometry and the trickiness of taking accurate measures of soft structures most likely renders findings of true stiffness to be speculative at best. However, it is ventured that while the plantar fascial material properties are variable, it falls somewhere in between a ligament and tendon [17]. These properties can change in the presence of pathology, specifically plantar fasciitis [25].

Plantar Fasciitis Diagnosis

Plantar Fasciitis (PF) is a degenerative disorder of this connective tissue that typically presents itself as a stabbing pain in the medial heel. A positive diagnosis for PF depends on a combination of risk factors, reported symptoms, and exam findings from a physician [26]. Some of these risk factors include excessive running, high arch, weak intrinsic muscles, pes planus, prolonged time spent on feet, obesity, Achilles tendon tightness, and others [27-30]. It is also common for individuals with symptomatic PF to experience heel tightness following a long period of being seated or in the morning after standing up for the first time of the day. A physical exam usually reveals sensitivity at the medial heel with palpation. Diagnostic evaluation, such as ultrasound or X-ray, is not typically used in diagnosis unless to rule out other causes of heel pain, such as a bone spur.

As such, there are a variety of avenues for treatment to alleviate pain. Early recognition and frequent rest are key in lessening the amount of time to recovery, which is typically in a window of 6-18 months [31-33]. Resting and limiting weight-bearing can often be the most effective and significant source of relief, as well as avoiding footwear with poor support. Arch support and orthotics are other affordable options for PF, which is inclusive of arch taping, strapping, orthotics, or heel cupping [34]. One other low-cost option that has shown significant results in alleviating plantar fasciitis symptoms is stretching and strengthening exercises tailored to targeting the aforementioned functional risk factors such as Achilles tightness and weak intrinsic muscles [35].

While contention still exists as to the pathogenesis of plantar fasciitis, it is believed to be a similar mechanism to tendinosis (tendon inflammation). A general consensus exists that extended overuse and overload of the plantar fascia results in microtears in the fascia, which

triggers an inflammatory response for repair [17, 36]. The inflammatory response, though, is not quickly successful as the sufferer continues heel strike and prolongs microtrauma to result in a painful chronic inflammation [37-40]. Plantar Fasciitis can be debilitating for everyday activities for those that suffer from it, and the Windlass Mechanism can provide a plausible explanation as to why. Increased forces on the first metatarsal head and hallux create an increased tension on the plantar fascia [6]. Upon stretching, the individual may feel pain in the plantar fascia, at the attachment to bone, or both.

When coping with the pain of plantar fasciitis, individuals adopt alternative loading patterns during gait to alleviate pain. When compared to controls, individuals with symptomatic plantar fasciitis experience less significant vertical ground force peaks, which suggest a lower overall energetic gait profile likely due to avoidance of a normal loading of the heel [41, 42]. Multiple studies have been done that evaluate heel kinetics (contact duration, peak pressure, hindfoot impulse) in plantar fasciitis symptomatic individuals, but all have concluded that they remain unchanged [42-44]. However, these same studies disagree regarding forefoot and midfoot loading. Bedi and Love showed plantar fasciitis resulting in lower midfoot impulses during gait and increased forefoot impulse, while Kato et al. showed the opposite [42, 44]. As such, there is not a definitive agreement as to loading trend in a symptomatic plantar fascia foot. This also speaks to the poor understanding of joint mechanics, especially at the first metatarsal joint. Mechanical overload is necessary to plantar fasciitis development, and because of the plantar fascial driven Windlass-Mechanism about the first metatarsal head, it is entirely possible that effects from loading pattern can actually be seen in kinematic changes at the first metatarsophalangeal joint rather than simply in plantar pressures and identify relationships not yet identified in other literature.

Diabetes Background, Pathology, and Diagnosis

Diabetes Mellitus affects millions of people in the United States alone. In 2018, the Centers for Disease Control (CDC) reported an estimated 26.9 million people of all ages - roughly 8.2% - had diagnosed diabetes [45]. The two overwhelming categories of diabetes are Type 1 and Type 2 Diabetes. Type 1 diabetes is characterized by the destruction of the beta cells produced in the pancreas due to an autoimmune disorder and accounts for roughly 10% of all diabetes cases [46]. Beta cells are responsible for producing insulin for the body to decrease blood sugar, and therefore treatment for this disease requires insulin delivery via routine shots or an insulin pump.

Type 2 Diabetes, which attributes to a much greater percentage of the population of individuals affected by diabetes, is caused by a combination of insulin resistance and subsequent deficiency. The inability for insulin to perform its intended action results in a constant state of hyperglycemia that, if untreated, can lead to extensive damage in a wide range of areas including various organs leading to failure, the eyes, kidneys, nerves, heart, circulatory system [46]. This particular category of diabetes can typically go unnoticed for years because the effects of the initial hyperglycemia can be gradual and non-severe. A large percentage of patients diagnosed with type 2 diabetes are obese, as obesity itself typically results in mild insulin resistance. It is usually when patients begin to experience effects from the hyperglycemia, such as increased thirst, headaches, fatigue, or notice a high blood sugar count, that they seek out medical attention. Diabetes mellitus can be diagnosed from plasma glucose in three different ways; if fasting plasma glucose is ≥ 126 mg/dl, if casual fasting glucose is ≥ 200 mg/dl, or if 2-hour plasma glucose is ≥ 200 mg/dl [47]. For this study, individuals were considered diabetic if they met HbA1c criteria put forth by the American Diabetes Association. HbA1c concentrations is an

objective measure of glycemic control and a positive diagnosis is an HbA1c value greater than or equal to 6.5%. There is a wide variety of diets and medications available to treat the disorder of diabetes mellitus itself, but oftentimes the disease causes other physical complications that require additional treatment methods.

Diabetes can cause an array of problems that can affect kinematics, kinetics, gait, and physical properties in the lower extremities, including but not limited to Charcot Neuropathy, claw toes, hammertoes, hallux valgus, heel pain, and alterations of skin thickness [48-50]. Once diabetics develop peripheral neuropathy, the prescribed treatment is critical in preventing irreversible damage from an assortment of other complications including, but not limited to, increased plantar pressure, foot deformity, or gait instability; all of which are predecessors to diabetic ulceration [49, 51-53]. The pathophysiology of the diabetic ulcer largely explains why peripheral neuropathy in combination with biomechanical alterations is a frequent culprit to blame [54].

The diabetic ulcer typically develops across three stages. In the first stage, a callus forms and can be exaggerated by altered gait patterns [55]. This continued trauma continues into a second stage due to the inability to feel the feet or any pain or irregularity associated with the area. Diabetics then also develop dry skin conditions from autonomic neuropathy, which makes them further susceptible. Finally, the continuous trauma of the callus results in a subcutaneous hematoma that eventually rubs away or bursts to reveal an open wound- an ulcer [55, 56]. These ulcers have a difficult time healing due to the development of extreme atherosclerosis of the blood vessels in the lower extremity. The restricted blood flow makes a diabetic patient exceptionally susceptible to infection and resistance to healing, which, if severe enough, can lead to necrosis, gangrene, and amputation. The severity of the complications that can occur from

altered kinematics and gait patterns detailed thus far call for any identifiable correlations to be investigated. As ulcers are most common in the toe and forefoot area, the kinematics and propulsive forces happening in this region are pertinent [54, 57]. Identifying and understanding trends in feet that do not yet have neuropathy or diabetic ulcers is the most important key in prevention. For example, Birke et al. found that reductions in MTP dorsiflexion play a factor in plantar ulceration of the great toe, and the ability to acknowledge a reduction in the range of motion at the first MTP allows for anticipatory action to be taken to prevent a more severe wound state, such as toe ulceration, from occurring [58].

Because of the metatarsophalangeal joint's role in gait and the possibility that its mechanical function might change in the presence of pathology makes it an interesting focus of study. For example, as loading conditions are altered in the presence of disease, the metatarsophalangeal joint function may change to compensate for a deteriorated loading condition or weight distribution changes, both of which have been associated with skin breakdown and amputation [59]. As earlier described, diabetes, especially diabetes accompanied by peripheral neuropathy, can cause intrinsic muscle and soft tissue deterioration throughout the foot. This has been associated with a decreased range of motion at the first metatarsophalangeal joint and lower maximum power [60]. This decreased range of motion has been associated with increased plantar fascia thickness, as well as increased stiffness and reduced passive range of motion at the first metatarsal [61].

Alterations of the first metatarsophalangeal joint in gait and other biomechanical factors in diabetics are critical to understanding energy profiles and transfer. Most literature concerning these properties is focused on diabetics with peripheral neuropathy, and not as much is available for non-neuropathic diabetics. It is critical that the energy profiles of this population specifically

be explored so that potential preventative measures can be identified for the purpose of avoiding a neuropathic state. To date, it has been shown that the range of motion at the metatarsal heads is decreased in diabetics when compared to non-diabetics, especially at the first metatarsophalangeal joint, and that this reduction is most prominent in those with a history of ulceration [60, 62, 63]. It is clear that some musculoskeletal changes are also at play in diabetics, especially those with neuropathy. For example, intrinsic muscle atrophy leads to a reduced support surface and an increased reliance on bony structures, which leads to significantly higher peak plantar pressures at the mid- and forefoot [64-67]. Moreover, ground reaction forces and plantar pressures are significantly different in diabetics, at both the initial contact and toe-off phases of gait. Intrinsic soft tissues may show signs of deterioration prior to the onset of neuropathy, and so kinematic observations in non-neuropathic diabetics could be enlightening to trends seen in a disease state where prevention measures can still be applied [68]. Therefore, because the relationship has not been studied to date, further research is needed to explore potential causal pathways and to develop an understanding of how plantar fascia stiffness impacts metatarsophalangeal joint function.

Patients of both plantar fasciitis or diabetes experience material property changes and biomechanical changes, but they have only been compared to non-disease state controls [25, 61, 69-74]. Given the importance of the plantar fascia in elastic energy storage, change in material properties could lead to alterations in efficiency energy storage [7, 22]. If plantar fascia stiffness alters other kinematic variables within a pathology group, it would be beneficial to examine how stiffness is related to kinematics outside the disease states. Comparison to another pathologic population could provide insight into alterations of properties of foot structures, their effect on kinematics, and potential energy transfer mechanisms that are otherwise not attainable by

comparisons within pathologic groups or their corresponding healthy controls. This study proposes a novel comparison between gait profiles, power transfer, and kinematic and kinetic differences specific to the metatarsophalangeal joint in both plantar fasciitis and diabetes participants to discern similarities or divergences between variables in pathologies.

METHODS

Subjects:

Forty-eight total participants from a de-identified data set were included in this study and divided into subgroups: Diabetes Type 2 (DT2), Diabetes Type 1 (DT1), Plantar Fasciitis Symptomatic (PFS), Plantar Fasciitis Asymptomatic (PFA), and Control. Fifteen individuals with diabetes (DT1 n=7, DT2 n=8), sixteen healthy controls, eleven individuals with active plantar fasciitis symptoms (PFS), and five individuals with a history of plantar fasciitis symptoms, but currently asymptomatic (PFA). The left and right feet of each patient were considered separately.

Inclusion and Exclusion Criteria

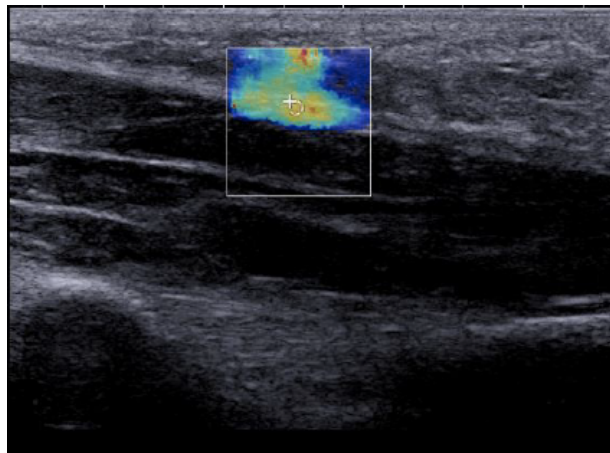
Participants were placed into the PF Symptomatic subgroup if within the past week prior to selection they had experienced the following situations consistent with most plantar fasciitis sufferers: plantar medial heel pain when taking the initial steps following a period of inactivity, heel pain that worsens with prolonged activity/weight-bearing, heel pain triggered by a recent increase in weight-bearing activity, or heel pain when palpated at the proximal PF insertion site. Participants were recruited to the PF Asymptomatic group if they self-reported history of these criteria but had not experienced any heel pain in the past week prior to data collection. Any individual with previous foot surgery or diagnosed osteoarthritis was not considered for the study.

Diabetic participants were recruited, either type 1 or type 2, if they had not had previous foot surgery, diagnosed osteoarthritis, gross foot deformities that affect walking ability, edema, a current foot ulcer, or a wound history less than three months prior to the study. The exclusion

criteria were designed to avoid the inclusion of people with problems impacting on mobility that would likely mask the biomechanical subtleties of the metatarsophalangeal joint. In order to be considered a diabetic, an individual had to meet the standards put forth by the American Diabetic Association and have a Hemoglobin A1c (HbA1c) level of $\geq 6.5\%$.

Elastography Data Collection:

Figure 2 Example shear wave elastography (SWE) measurement of the proximal plantar fascia site including the 1mm circular region of interest.



Bilateral shear wave elastography (SWE) measurements were taken of the Plantar Fascia at a proximal and distal site, located at roughly 45% and 75% of foot length from the most posterior aspect of the heel, respectively. All images were taken in the longitudinal view while the foot was in a prone, relaxed position with the feet hanging off of an examination table above the ankles. Quantitative measurements of stiffness were assessed and quantified with SWE taken on an Aixplorer ultrasound system (SuperSonic Imagine, Aix-en-Provence, France). Shear modulus was determined in a 1 mm circular region of interest placed in the middle of the tissue

at each measurement site (Figure 2). The mean shear modulus of three measurements was averaged and reported as stiffness for both PF proximal and PF distal.

Motion Analysis Data Collection:

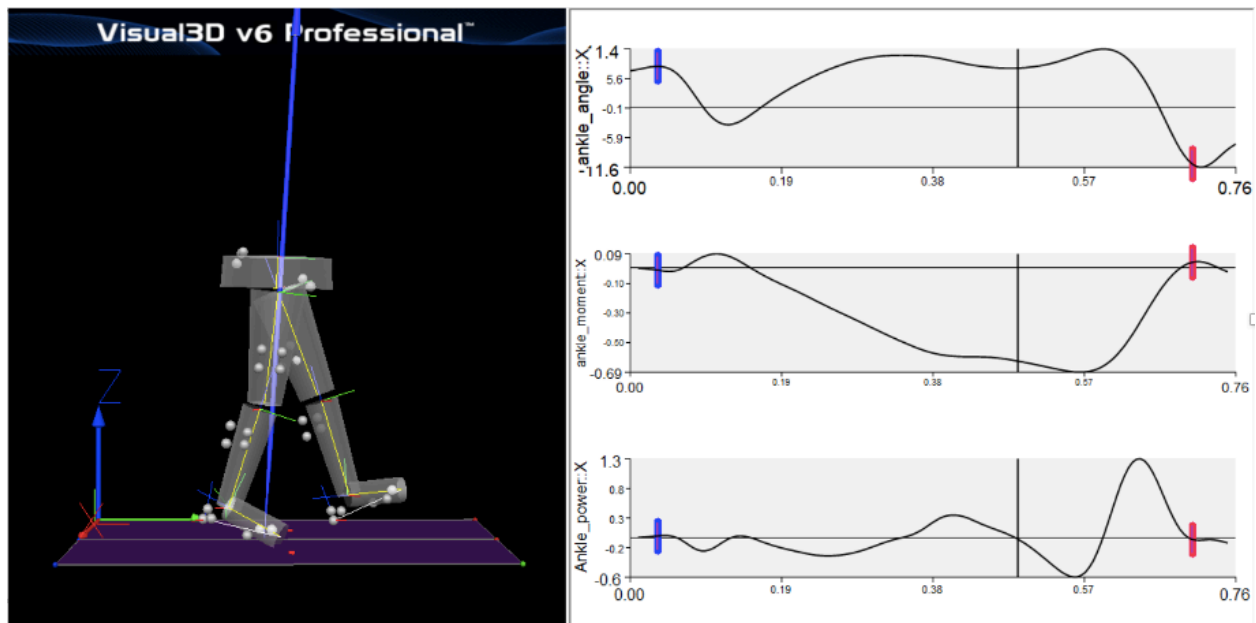
Three-dimensional motion analysis testing was performed using a 12-mm marker set. Reflective markers were placed in the following locations: each iliac crest, the greater trochanters, medial and lateral femoral condyles, medial and lateral proximal tibia, medial and lateral malleoli, the first and fifth metatarsal heads, and the tip of the shoe, as detailed in a similar study by Willson et al. (Figure 3) [75]. An additional marker was placed at the base of the first phalanx to use as a tracking marker for the distal foot segment. These markers were collectively used to create segmental coordinate systems and shank, femur, and pelvis were established as rigid bodies. The foot was broken into three segments; toes, forefoot and rearfoot. After a standing calibration, the anatomical markers were removed so as not to alter the gait pattern of the individual. Throughout the trials, some reflective markers stayed in place and were positioned as a cluster of three markers on the rearfoot of the shoe, a cluster of four markers on the posterior shank, and a cluster of four markers on the lateral thigh. The pelvis was tracked using bilateral anterior and posterior superior iliac spines and the L5–S1 interspace.

Figure 3 Marker placement during standing calibration



Marker data in each condition were collected at 200 Hz using a ten-camera motion capture system (Qualysis AB, Gothenburg, Sweden) positioned around a treadmill (Bertec Corp, Columbus, Ohio, USA). Participants were given a minimum of two minutes of practice to familiarize themselves with the treadmill and performed the trials in conventional footwear. Participants were asked to walk at a speed of 1.3 m/s over a thirty-second interval, as it has been noted in previous literature that faster than preferred walking speeds show more exaggerated changes in propulsive force, moment, and angle in lower limb joints [76-79]. Also, a study by Caravaggi et al. showed that plantar fascia strain remains similar throughout different speeds tested [80].

Figure 4. Screenshot of Visual Studio analysis. Blue and red lines represent heel strike and toe-off, respectively.



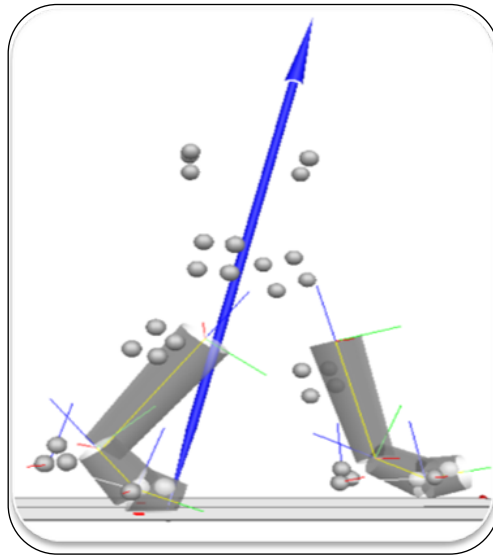
The time when the vertical ground reaction force exceeded 50 N was deemed the first initial contact. Participants successfully demonstrated acceptable foot strike patterns during the experiment, and no data were excluded based on the foot strike pattern. Marker and ground reaction force data were used together to calculate 3D ankle, knee, and hip internal joint moments and joint kinematics (Visual 3D, C-Motion Inc., Rockville, Maryland, USA) (Figure 4). For the MTP, X-direction represented the medial/lateral axis, Y was the anterior/posterior axis, and Z was the vertical axis for the virtual rearfoot and forefoot (Table 1).

Table 1 Foot segment directions of motion

Foot segment angles	Sagittal	Frontal
MTP	Dorsiflexion (DF): +	Inversion: -
	Plantarflexion (PF): -	Eversion: +

The coordinate system for the proximal rearfoot segment, however, did not follow this same convention. The proximal rearfoot is used to create a segment endpoint at the ankle joint, but with a six degree of freedom joint, there is no obvious link connecting the segments. Because Visual 3D recognizes any two segments in proximity to be linked, the proximal rearfoot segment was identified to simulate the motion experienced at the talocrural joint. For the proximal rearfoot segment, X remained the medial/lateral axis, but Y points dorsally and Z points in the direction of the back of the shoe (from distal to proximal endpoints). For all kinematic calculations, the virtual rearfoot was modeled as being flat on the floor with the ankle at 90 degrees in normal standing. An inverse dynamic approach relative to the reference frame of the distal segment at each joint was used to calculate internal joint moments (Figure 5). The inverse dynamics calculations that used marker data and ground reaction force data were digitally filtered using a low pass, fourth-order Butterworth recursive filter at the same cut-off frequency (10 Hz) [81, 82].

Figure 5 Marker placement and inverse dynamics of two segment foot model



Data Processing and Analysis

The number of participants and total number of feet used in the study differed. Each foot of a recruited subject was used as an independent data source. Plantar fasciitis symptoms can be unilateral, as well as ulceration in diabetics, so there is some reason to believe that feet are not directly related to each other in these two circumstances. Due to the feet of diabetics and plantar fasciitis individuals being more independent, considering them individually for analysis was more appropriate. People with plantar fasciitis who had unilateral symptoms had only the affected foot included in the study, where individuals with bilateral symptoms had both feet in the study.

Dependent variables of interest for this study included peak metatarsophalangeal eccentric and concentric power, moment, total range of motion, and joint reaction force. Work for the MTP was determined by integrating and the power time series data of six steps over each stance phase and averaging. These values were all correlated with plantar fascia proximal and

distal stiffness values. The power, moment, and range of motion data of the ankle joint was also considered as a secondary measure for trend comparison. In addition to the analysis, data was also normalized to stance for ease of visualization.

In order to determine a subject's reliance on distal vs. proximal foot muscles in generating positive power during waking, a redistribution ratio (Equation 1) was established from a study by Browne et al. and utilizes stance phase positive MTP and proximal joint work values [83]. A custom Matlab (The Mathworks, Natick, MA) code was developed for visualizing normalized data, including MTP joint angle, power, joint reaction force, and moment (Appendix A). Two custom Python™ programs were also developed to recruit data efficiently from exported .txt files (Appendix B) and to integrate data when necessary (Appendix C).

Equation 1 Redistribution Ratio

$$RR = 1 - \frac{W_{MTP}^+ - W_{Prox}^+}{W_{MTP}^+ + W_{Prox}^+}$$

The Redistribution Ratio (RR) was calculated to quantify the extent that an individual walks with a distal to proximal redistribution (Equation 1). W_{MTP} refers to the total positive work performed by MTP musculature, and W_{Prox} refers to total positive work performed by proximal joint musculature, which is representative of ankle work. Joint work, both positive and negative, was determined by taking the integration of the stride-averaged power versus time profile. The RR is bounded between 0 and 2, where 0 signifies that all positive work was performed about the MTP and 2 signifies that all positive work is performed about the proximal joint musculature. Accordingly, lower and higher RR values denote low and high distal-to-proximal redistribution.

MTP moment impulse and angular impulse were calculated by integrating the joint moment and the force-time integral, respectively. One-way ANOVA was performed on the raw

data for 1st metatarsophalangeal joint total range of motion (TROM), power, joint reaction force (JRF), and moment. Linear regressions and bivariate Pearson correlative analysis were performed between these measures and stiffness of the plantar fascia proximal and distal sections to determine any relationships and measure the strength and direction of the relationship. For post-hoc multiple comparisons of the means, the Tukey test was used. Significance was defined as $p \leq .05$ and trends were defined as $.05 \leq p \leq .10$.

RESULTS

There were no significant differences between groups for height or weight; however, diabetics were found to have higher BMIs of 32.5, and PF Symptomatic individuals were older in age when compared to controls (Table 2). Additionally, BMI trended higher in PFS participants.

Table 2 Subject group demographics. Statistical significance indicated by bold font and * ($p \leq 0.05$) for a difference from controls. Trends indicated by † ($0.05 < p \leq 0.10$).

Demographics	Control	Diabetic	PFA	PFS
N Participants	16	15 (7DT1/8DT2)	5	11
N feet used	32	(12DT1/16DT2)	8	17
Sex	2M/8F	2M/13F	1M/5F	3M/8F
Age (yrs)	36.0 (7.9)	35.9 (11.0)	42.5 (8.5)	50.9 (6.9)*
Height (cm)	170.16 (11.6)	165.27 (12.8)	169.2 (8.5)	171.7 (12.6)
Weight (kg)	75.6 (21.9)	88.8 (19.4)	82.2 (17.3)	92.2 (24.8)
BMI (kg/m ²)	25.75 (4.9)	32.5 (6.0)*	28.8 (4.9)	31.0 (5.8) †
Years with Diabetes		9.4 (9.5)		
Years with Plantar Fasciitis			4.3 (4.1)	2.9 (2.8)

When the elastography data were examined, there was no significant difference in plantar fascia stiffness at either the distal region or proximal between groups. However, on average, PFA and DT2 held the highest stiffness values in both regions (Figure 6). There was high variability of stiffness within participants with type 2 diabetes in both the proximal and distal plantar fascia, as shown by the presence of outliers (Figure 6) and large standard deviations (Table 3).

Figure 6 Boxplots of proximal (A) and distal (B) plantar fascia stiffness in PFS, PFA, Control, DT2, and DT1.

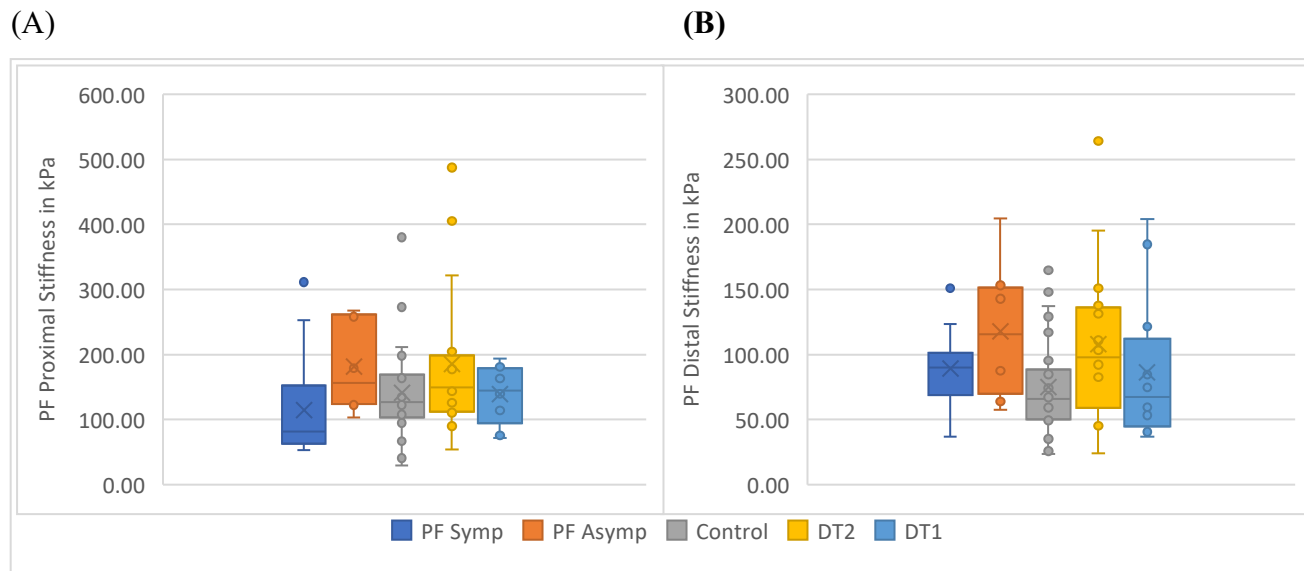


Table 3 Proximal (A) and distal (B) plantar fascia stiffness averages and standard deviation.

(A)				(B)			
PF Prox Stiffness	N	Mean	Std. Deviation	PF Distal	N	Mean	Std. Deviation
PFS	17	114.1	74.1	PFS	17	92.0	31.1
PFA	8	185.4	62.5	PFA	10	114.0	46.4
Control	32	149.3	75.7	Control	32	79.9	42.3
DT2	16	185.8	118.4	DT2	16	108.0	60.4
DT1	12	132.6	44.0	DT1	12	85.0	51.5
Total	91	150.6	82.1	Total	85	91.6	46.9

Spatiotemporal data, shown in Table 4, show that there was no significant difference between groups in step length or steps per minute, but that the DT1 group experienced statistically significant lower overall stride times ($p=.002$) and step time ($p=.000$) when compared to controls. The PFS group also experienced lower step times ($p=.001$).

Table 4 Spatiotemporal data among subgroups

	Stride Time	Step Time	Step Length (m)	Steps/Minute
DT1	.98 (.06) (p=.002)	.49 (.03) (p=.000)	0.63 (.04)	124.1 (8.0)
DT2	1.04 (.04)	.52 (.02)	0.67 (.03)	117.2 (6.1)
Control	1.04 (.09)	.53 (.03)	0.67 (.05)	118.1 (10.3)
PFA	1.04 (.07)	.52 (.04)	0.66 (.05)	118.2 (8.6)
PFS	1.01 (.03)	.51 (.01) (p=.001)	0.65 (.02)	120.0 (3.0)

Plantar fasciitis symptomatic participants experienced a statistically significant lower total range of motion at the MTP ($p=.02$), which can be seen in the range of motion data across 100% of stance (Figure 7). The DT1 group also trended lower in TROM ($p=.063$). Two local maxima were recorded at the MTP as well as an overall minimum angle achieved; however, there were no significant differences in the minimum or either local maximum angles achieved (Table 5 A). There was found to be no correlation between the TROM and PF proximal or distal stiffness values and r correlations, while not significant, varied both positive and negative (Table 5 B).

Figure 7 Total range of motion at the MTP across 100% of stance

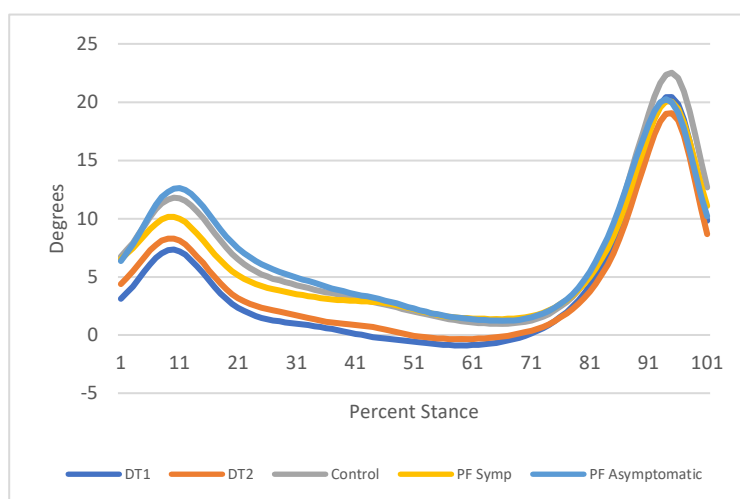


Table 5 Average local maximums and minimum, TROM, and significance (A), and correlation coefficients between the subgroup TROMs versus plantar fascia proximal or distal stiffness (B). Statistical significance indicated by bold font and * ($p \leq 0.05$) for a difference from controls. Trends indicated by † ($0.05 < p \leq 0.10$).

(A)

SubGroup	Max MTP angle from 0-20% stance	Max MTP angle from 80-100% stance	Min MTP angle	TROM	P when compared to control
DT1	7.5 (8.6)	19.0 (9.9)	-3.1 (5.3)	22.1 (8.4)	.063 †
DT2	8.7 (6.7)	19.6 (6.5)	-3.5 (5.4)	23.1 (3.7)	.13
Control	12.0 (11.9)	22.7 (11.4)	-4.2 (6.9)	26.9 (6.1)	
PFA	10.4 (5.5)	20.5 (9.8)	-3.3 (7.2)	23.9 (3.4)	.67
PFS	12.8 (9.7)	20.2 (5.4)	-1.9 (4.9)	22.1 (2.9)*	0.02

(B)

TROM vs. PF Proximal	Pearson's R	Significance
DT1	0.487	0.108
DT2	0.149	0.596
Control	0.118	0.536
PFS	-0.365	0.15
PFA	0.265	0.526
TROM vs. PF Distal		
DT1	0.25	0.433
DT2	0.167	0.537
Control	-0.261	0.164
PFS	-0.388	0.124
PFA	-0.388	0.342

MTP power graphs exhibited a negative eccentric power peak followed by a positive concentric power peak, but there was no significant difference between subgroup MTP maximum or minimum power between subgroups when compared to control (Figure 8 A, Table 6 A), likely due to large value distribution among participants (Figure 8 B). DT2 minimum power did, however, differ significantly from DT1 when compared ($p=.038$) While not significant, the control group had the lowest average concentric (positive) power, and PFA had

the highest, while DT2 had the lowest eccentric (negative) power, and the Control group had the largest. The plantar fascia proximal and distal stiffness of each subgroup was compared individually against both maximum and minimum power values. Statistically significant correlations were found between PFA minimum power and PF proximal as well as PFA maximum power and PF distal, and one trend was noted in the PFS group between maximum power and PF proximal (Table 6 B).

Figure 8 Subgroup average MTP power vs. percent stance (A) and eccentric power distribution (B)

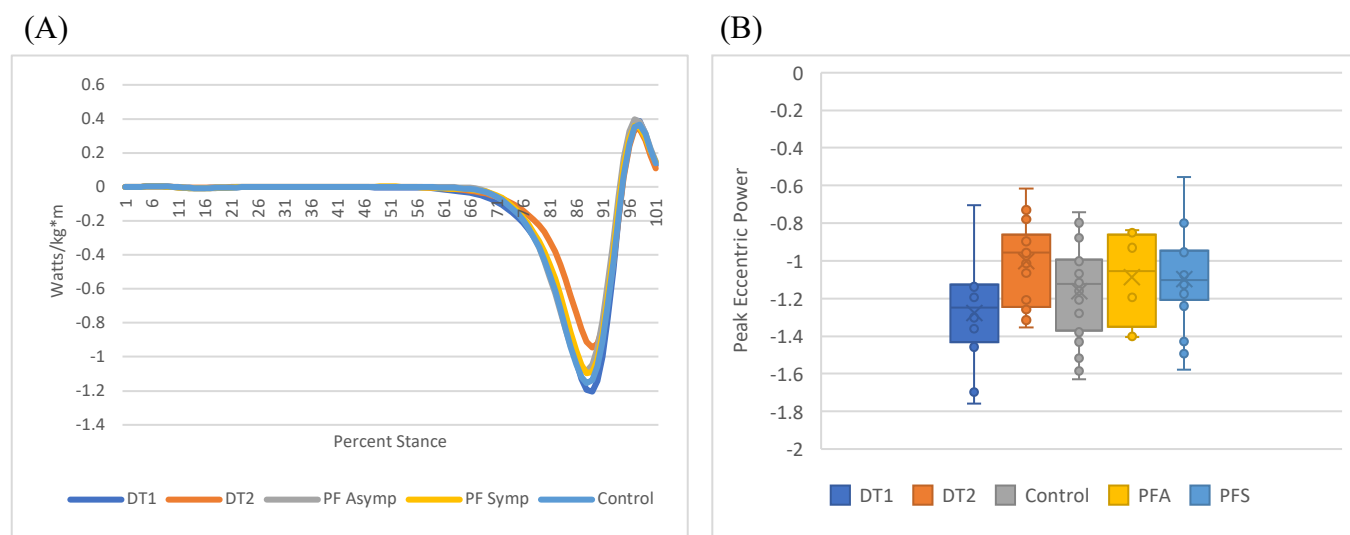


Table 6 Subgroup average maximum (concentric) power and negative (eccentric) power and standard deviation (A), Correlation coefficients and significance for MTP concentric and eccentric power vs. plantar fascia proximal and distal (B). Statistical significance indicated by bold font and * ($p \leq 0.05$) for a difference from controls. Trends indicated by † ($0.05 < p \leq 0.10$).

(A)

Subgroup	Avg. Max Power	P when compared to Control	Avg Min power	P when compared to Control
DT1	0.40 (.19)	.786	-1.18 (.45)	.642
DT2	0.38 (.16)	.998	-1.03 (.23)	.249
Control	0.3753 (.14)		-1.16 (.24)	
PFA	0.47 (.12)	.251	-1.05 (.25)	.941
PFS	0.37 (.11)	.983	-1.10 (.25)	.92

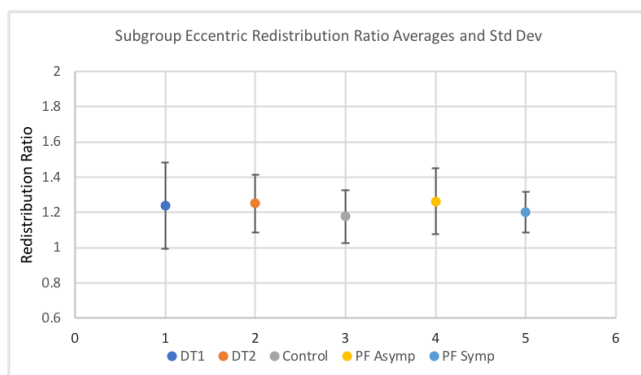
(B)

Maximum Power vs. PF Proximal	Pearson's R	Significance
DT1	-0.059	0.855
DT2	0.178	0.525
Control	0.278	0.136
PFS	0.468	0.058 †
PFA	0.255	0.542
Minimum Power vs. PF Proximal		
DT1	-0.062	0.848
DT2	-0.193	0.474
Control	0.026	0.893
PFS	-0.242	0.35
PFA	0.897	0.003*
Maximum Power vs. PF Distal		
DT1	0.132	0.681
DT2	-0.047	0.864
Control	0.084	0.658
PFS	-0.34	0.182
PFA	-0.72	0.044*
Minimum Power vs. PF Distal		
DT1	-0.369	0.238
DT2	0.186	0.489
Control	0.098	0.607
PFS	0.382	0.13
PFA	0.176	0.677

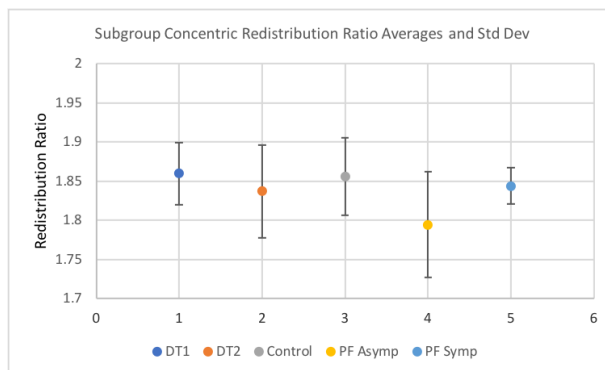
Following MTP power-time integration, there were no significant differences between subgroups in concentric or eccentric work. Concentric redistribution ratios revealed that the plantar fasciitis asymptomatic group average was significantly less when compared with controls ($p = .06$), but eccentrically, the RR was not significantly different between groups (Figure 9).

Figure 9 Eccentric (A) and Concentric (B) Redistribution Ratios and standard deviations in subgroups

(A)



(B)



A correlative relationship between the Redistribution Ratio was found between both Concentric and Eccentric and the PF proximal in the PF Asymptomatic subgroup ($p=.020$, $p=.001$, respectively) (Table 7). However, no other subgroup, either concentrically or eccentrically, correlated strong with either the plantar fascia distal section (Figure 10 A-D). One trend was noted in the PFS group between concentric RR and PF distal ($p=.077$). When the concentric and eccentric RRs of all participants, regardless of subgroups, were compared with PF proximal and PF distal, there also was only one overall correlation; Concentric vs. PF Proximal ($r=-.277$, $p=.012^*$), Eccentric vs. PF Proximal ($r=-.001$, $p=.964$), Concentric vs. PF Distal ($r=.081$, $p=.471$), Eccentric vs. PF Distal $r=-.078$, $p=.484$).

Figure 10 Individual subject Eccentric Redistribution Ratio (RR) value for organized by subgroups vs. plantar fascia proximal stiffness (A), Eccentric Redistribution Ratio vs. plantar fascia distal stiffness (B), Concentric Redistribution Ratio vs. plantar fascia proximal stiffness (C), Eccentric Redistribution Ratio vs. plantar fascia distal stiffness (D)

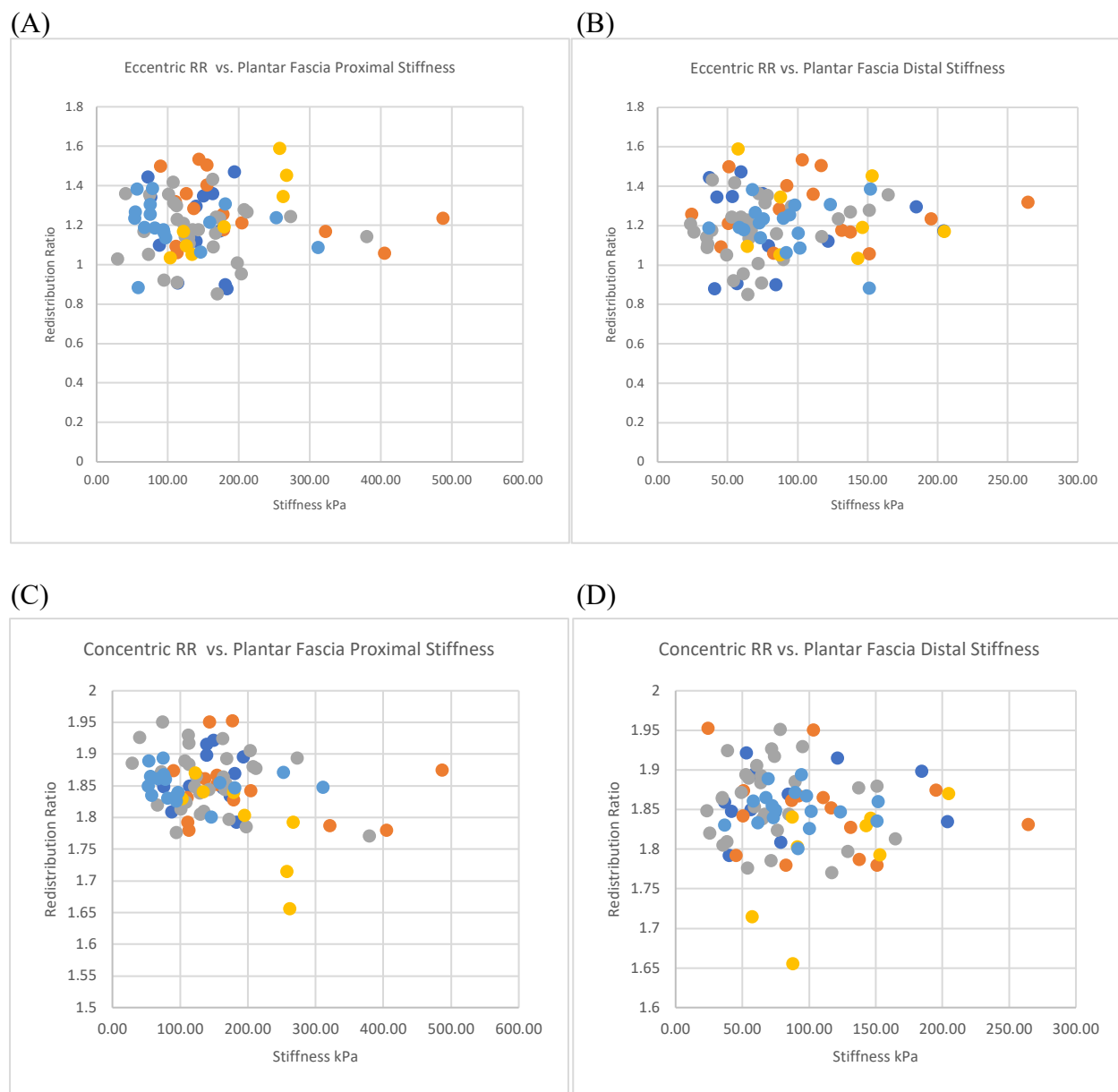


Table 7 Correlation coefficients and significance for MTP concentric and eccentric RR vs. plantar fascia proximal and distal. Statistical significance indicated by bold font and * ($p \leq 0.05$) for a difference from controls. Trends indicated by † ($0.05 < p \leq 0.10$).

Concentric RR vs. PF Proximal	Pearson's R	Significance
DT1	0.133	0.679
DT2	-0.171	0.542
Control	-0.267	0.153
PFS	-0.108	0.681
PFA	-0.79*	0.02*
Eccentric RR vs. PF Proximal		
DT1	-0.199	0.535
DT2	-0.379	0.163
Control	-0.066	0.73
PFS	-0.154	0.556
PFA	0.914*	0.001*
Eccentric RR vs. PF Distal		
DT1	-0.031	0.923
DT2	-0.026	0.925
Control	0.234	0.214
PFS	-0.219	0.602
PFA	-0.142	0.587
Concentric RR vs. PF Distal		
DT1	0.169	0.6
DT2	-0.239	0.392
Control	-0.073	0.703
PFS	0.656	0.077†
PFA	-0.024	0.927

The largest joint reaction forces at the MTP occurred as a small inversion during toe-off, and all forces in other directions were negligible (Figure 11). No significant difference between subgroups was found for MTP average joint reaction force during metatarsal inversion (Table 8). When correlated against the plantar fascia, there was no significant relationships identified.

Figure 11 Normalized Joint Reaction Force vs. percent stance

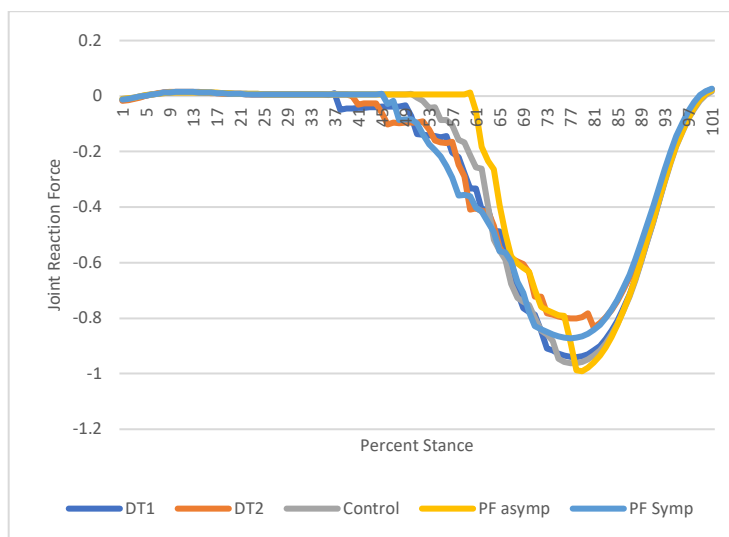


Table 8 Subgroup MTP inversion JRF average, standard deviation, and significance.

Subgroup	Mean peak JRF	Std. Deviation	p
DT1	-0.16	0.040	.904
DT2	-0.16	0.033	.481
Control	-0.17	0.024	
PFA	-0.16	0.022	.784
PFS	-0.18	0.019	1.00

Normalized MTP moment was similar in magnitude (Figure 12, Table 9), but the average percent stance where the moment was engaged varied by an average of 21%, with DT2 being the earliest in stance to engage moment at 41% and PF Asymptomatic being the latest at 61%.

Figure 12 Average Subgroup MTP Moment vs. Percent Stance (A) and Moment participant distribution (B)

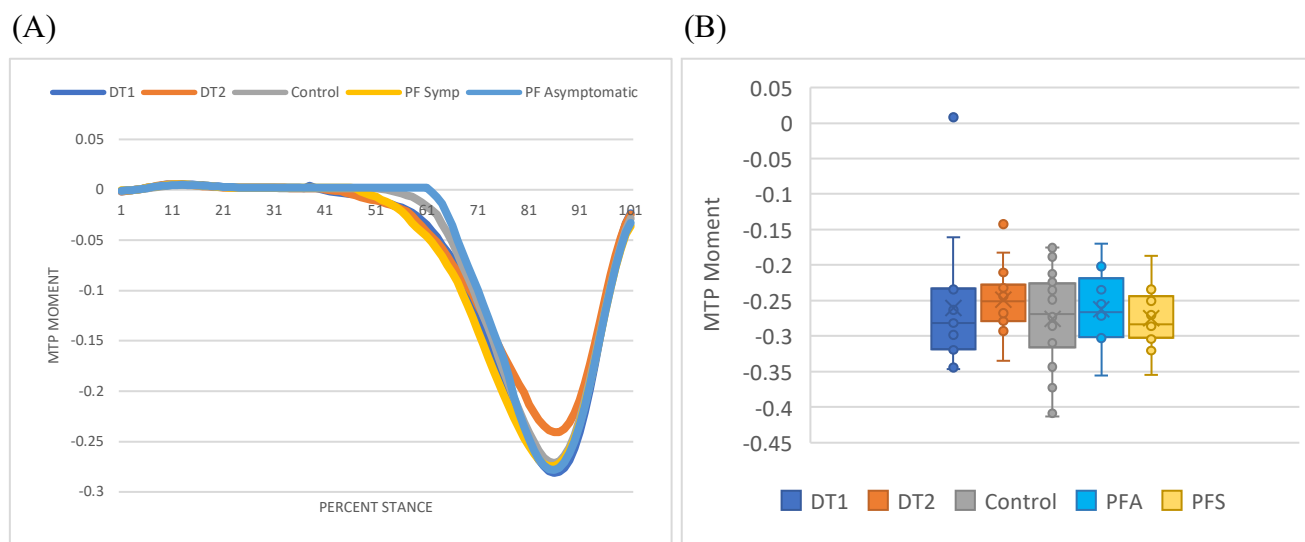
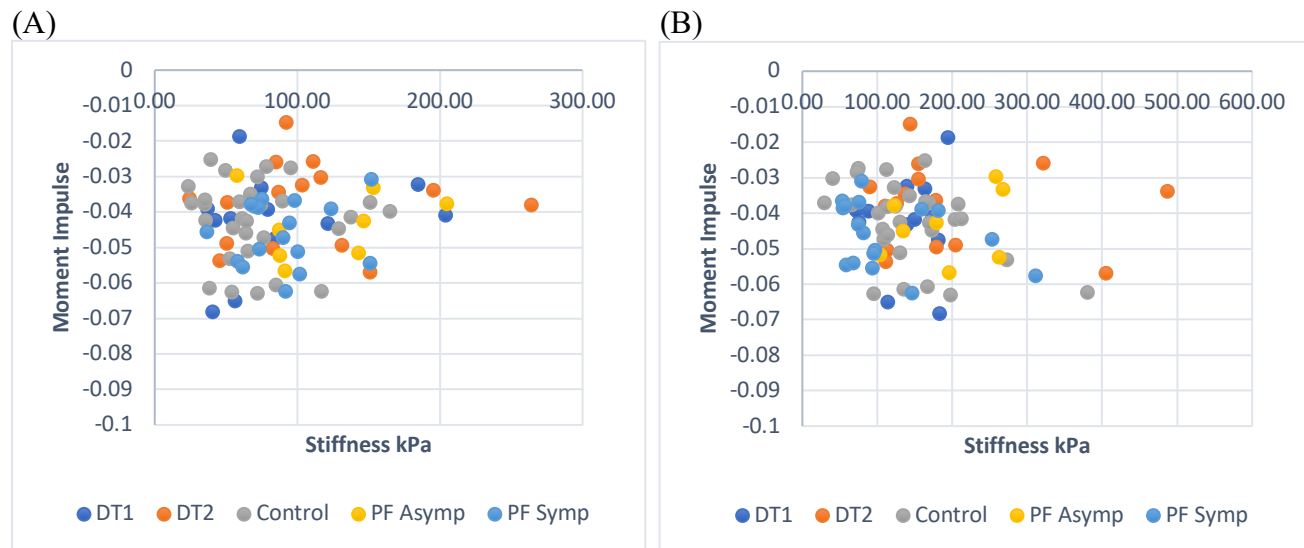


Table 9 Subgroup averages minimum MTP Moment and standard deviation

Subgroup	Mean	p when compared to control
DT1	-0.26 (.10)	.939
DT2	-0.25 (.04)	.543
Control	-0.28 (.06)	
PFA	-0.26 (.06)	.973
PFS	-0.28 (.04)	1

Following integration, there was no significant difference between subgroups for average plantarflexion MTP moment impulse, but one correlative relationship was found between moment impulse and plantar fascia proximal in the control group ($r=-.046$, $p=.011$), while no other correlations were found (Figure 13 A, B, Table 10).

Figure 13 Individual Moment Impulse vs. PF Proximal Stiffness (A) and PF Distal Stiffness (B).

Table 10 Subgroup Moment Impulse vs. PF Proximal Stiffness and PF Distal Stiffness correlation coefficients and significance. Statistical significance indicated by bold font and * ($p \leq 0.05$) for a difference from controls. Trends indicated by † ($0.05 < p \leq 0.10$).

Moment Impulse vs. PF Distal	Pearson's R	Significance
DT1	0.251	0.432
DT2	0.036	0.898
Control	-0.067	0.727
PFS	0.106	0.684
PFA	0.159	0.708
Moment Impulse vs. PF Proximal		
DT1	0.068	0.833
DT2	-0.086	0.761
Control	-0.46	.011*
PFS	-0.326	0.201
PFA	0.315	0.448

For trend comparison to the MTP, average peak maximum power at the ankle joint was compared and found to be significantly different for DT1 when compared to controls ($p=.019$) (Figure 14). When compared against the stiffness of the proximal and distal plantar fascia, only

one correlative relationship was found in the PFA group between the stiffness of the proximal plantar fascia and peak ankle concentric power ($r=-.748$, $p=.033$) that indicates as stiffness increases, the peak concentric power decreases. Work was calculated from integrating power, and these values were also used in the determination of the Redistribution Ratio as W_{Prox} . When means were compared of eccentric and concentric work, there was no significant difference between groups when compared to each other or to controls (Table 11). When correlated with PF proximal and distal, there were two trends noted between PFS and PFA concentric work and the stiffness of the plantar fascia proximal ($p=.075$, $p=.093$, respectively). Two statistically significant relationships were found between eccentric work. PFA held a positive relationship between eccentric work and the PF proximal ($p=.04$) and PFS held a positive relationship between eccentric work and the PF distal ($p=.046$) (Table 12).

Figure 14 Ankle power vs. percent stance

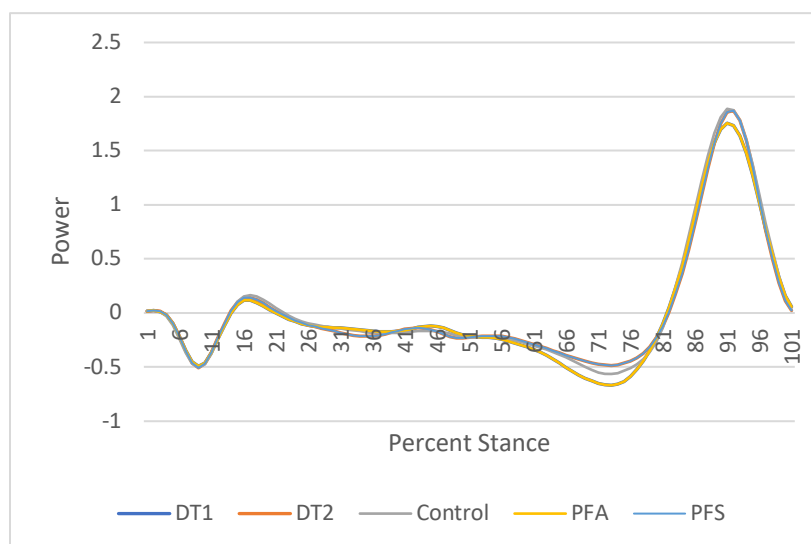


Table 11 Subgroup Ankle Eccentric and Concentric work averages

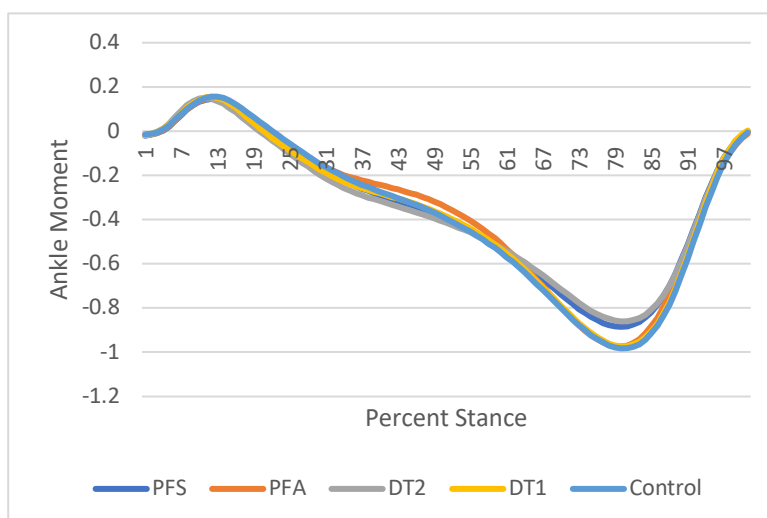
Subgroup	Eccentric Work	Concentric Work
DT1	-0.14 (.03)	0.16 (.03)
DT2	-0.13 (.02)	0.13 (.03)
Control	-0.13 (.03)	0.15 (.03)
PFA	-0.14 (.03)	0.15 (.05)
PFS	-0.13 (.03)	0.14 (.04)

Table 12 Correlation coefficients and significance for Ankle concentric and eccentric work vs. plantar fascia proximal and distal. Statistical significance indicated by bold font and * ($p \leq 0.05$) for a difference from controls. Trends indicated by † ($0.05 < p \leq 0.10$).

Concentric Work vs. PF Proximal	Pearson's R	Significance
PFS	0.443	0.075†
PFA	-0.632	0.093†
Control	0.207	0.273
DT2	-0.147	0.601
DT1	-0.165	0.607
Concentric Work vs. PF Distal		
PFS	-0.379	0.134
PFA	0.088	0.835
Control	0.156	0.409
DT2	-0.371	0.173
DT1	0.27	0.397
Eccentric Work vs PF Proximal		
PFS	-0.031	0.906
PFA	-0.729	0.04*
Control	0.076	0.69
DT2	0.291	0.293
DT1	0.294	0.353
Eccentric Work vs PF Distal		
PFS	0.491	0.046*
PFA	0.214	0.61
Control	-0.17	0.37
DT2	0.313	0.256
DT1	-0.155	0.631

Minimum ankle moment varied significantly between subgroups. When compared with controls, DT2 and PFS experienced significantly smaller minimums, $p=.000$ and $p=.003$, respectively (Figure 15). PFS also experienced a significant correlation between minimum moment and the plantar fascia proximal stiffness ($r=-.750$, $p=.001$), while diabetics were found to have a significant relationship between the plantar fascia distal stiffness ($r=.547$, $p=.035$).

Figure 15 Ankle moment vs. percent stance



Moment impulse was calculated from the integration of ankle moment and did not vary significantly between groups, nor did it correlate significantly with the stiffness of the PF proximal or distal regions (Table 13). One trend was noted in the control group when moment impulse was correlated against PF proximal.

Table 13 Correlation coefficients and significance for ankle moment impulse vs. plantar fascia proximal and distal. Statistical significance indicated by bold font and * ($p \leq 0.05$) for a difference from controls. Trends indicated by † ($0.05 < p \leq 0.10$).

Moment Impulse vs. PF Proximal	Pearson's R	Significance
DT1	0.163	0.613
DT2	0.417	0.122
Control	-0.318	0.087†
PFS	-0.409	0.103
PFA	-0.271	0.516
Moment Impulse vs. PF Distal		
DT1	0.003	0.993
DT2	0.218	0.435
Control	0.031	0.871
PFS	0.375	0.138
PFA	0.118	0.78

There was no significant difference found between subgroups for ankle local minimum, maximum, or total range of motion when compared and no correlative relationships were identified between TROM and plantar fascia distal or proximal (Figure 16, Table 14).

Figure 16 Ankle total range of motion vs. percent stance

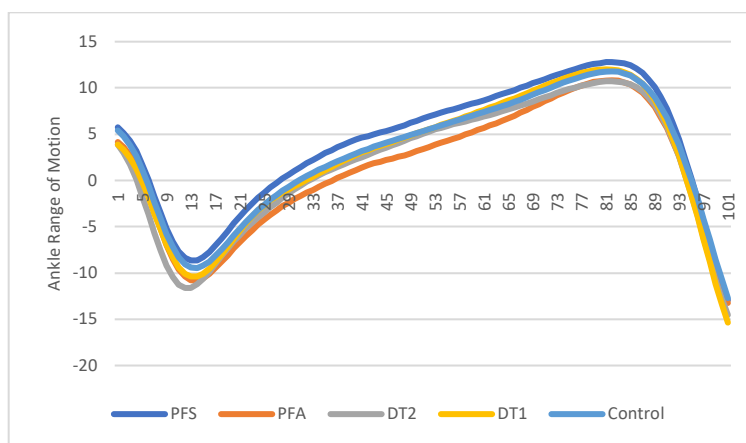


Table 14 Ankle minimum, maximum, and total range of motion averages and standard deviation

Ankle	Local Minimum Angle	Maximum Angle	TROM
Control	-9.6 (2.9)	11.9 (3.8)	21.6 (3.7)
PFS	-9.0 (2.0)	13.0 (2.5)	22.0 (3.2)
DT2	-11.7 (3.3)	10.8 (3.0)	22.4 (3.6)
DT1	-10.8 (2.2)	12.1 (3.3)	22.9 (2.5)
PFA	-11.1 (3.3)	11.3 (3.9)	22.4 (3.2)

DISCUSSION

Significant changes in material and structural properties occur in both plantar fasciitis and diabetic individuals. The plantar fascia has been widely studied in both disease states because of its importance in gait function and overall foot stability [22, 25, 42, 60, 61, 70, 72, 74, 84-88]. The purpose of this study was to identify or determine if there are any relationships between the material properties of the plantar fascia and power absorption or energy storage characteristics of the metatarsophalangeal joint. It was hypothesized that a correlative relationship could be determined between PF stiffness and kinematic measures at the MTP joint in plantar fasciitis or diabetic individuals. More than one clinical population was studied in order to observe alterations of properties that are otherwise not attainable by comparisons within pathology groups and their corresponding healthy controls. Therefore, this was a novel study investigating the gait profiles, power transfer, and kinematics in populations of PF Asymptomatic, PF Symptomatic, Healthy Controls, Diabetes Type 2, and Diabetes Type 1. Because of the key role the plantar fascia material properties plays in the windlass mechanism and overall gait function, as well as the wealth of literature documenting alterations in structural and material changes in disease states, it was hypothesized that a correlative relationship could be determined between plantar fascia stiffness and kinematic measures at the metatarsophalangeal joint in plantar fasciitis or diabetic individuals.

Stiffness measured by shear Wave Elastography (SWE) evaluation did not reveal statistically significant differences between subgroups at either the plantar fascia proximal or distal regions, which is inconsistent with literature. In plantar fasciitis studies using either compression or Shear Wave Elastography (SWE), results have shown that those with

symptomatic plantar fasciitis experience lower stiffness values in the PF than those with and without a history of plantar fasciitis [69, 70, 89-91]. Multiple *in vivo* studies using either MRI or ultrasound have found that increased stiffness of foot soft tissue has been found in diabetics when compared against a healthy control group [84, 87, 92, 93]. With this in mind, it is likely due to the large subject variability within the diabetic group and the presence of outliers that statistical significance was not observed against the control group. It is speculated that increases in plantar soft tissues, particularly the plantar fascia, may reduce shock-absorbing capacity across the foot, and this is extremely relevant in the diabetic foot as these alterations increase the risk of ulceration. Kinematic changes at the MTP in relation to the plantar fascia stiffness has not been widely studied, and this study sheds some light. It should be noted that there have been documented differences between treadmill and over-ground walking when studying kinematics and human locomotion, and so because this study recorded data on a treadmill, results may not be exactly representative of over-ground kinematics [94-96].

Abnormal soft tissue vascularity and fiber consistency has been seen in plantar fasciitis through ultrasound [88], and similar physiological changes, specifically concerning collagen integrity, can be seen in diabetics as well [86, 97]. This was further cause for speculation that the impaired physiology and function of the plantar function could lead to overall alterations in the dynamic function at the MTP due to the Windlass-Mechanism. From experimental findings, there is moderate evidence that correlative relationships exist between the certain kinematics of subgroups and PF proximal and distal stiffness. Specifically, this study showed a weak correlation between maximum MTP power and PF proximal stiffness ($r=.231$, $p=.037$).

The only significant difference in the TROM comparison between subgroups was the mean MTP total range of motion in the PF symptomatic group, which is consistent with literature

[9, 17]. Because no relationship was found between TROM and open kinetic chain relaxed stiffness measures of either the plantar fascia proximal or distal, it can be speculated that TROM may not experience drastic alterations as a direct result of plantar fascia stiffness. This can also be said for MTP moment during propulsion, as no correlative relationship was found between plantar fascia stiffness and peak moment values. There was, however, a negative relationship found between MTP moment impulse and the stiffness at the plantar fascia distal region for the control group ($r=-.46$, $p=.011$), meaning that as the PF distal increases in stiffness, the control group experienced a downtrend in maximum moment impulse. This suggests that there may be an altered mechanism of moment execution in the plantarflexion propulsion movement.

The plantar fasciitis asymptomatic group had multiple deviances from other subgroups. Despite never statistically differing from the other subgroups in the mean average for any kinematic or stiffness measure, it was found to have the most correlative relationships. The PFA subgroup had a positive relationship between MTP eccentric peak power and the plantar fascia proximal ($r=.897$, $p=.003$), as well as a negative relationship between MTP concentric peak power and the plantar fascia distal stiffness ($r=-.72$, $p=.044$). The PFA also had a correlative relationship between total range of motion at the ankle and plantar fascia proximal stiffness ($r=-.880$, $p=.004$).

In the ankle, few differences and correlations were observed. No significant difference was found between groups for concentric work, eccentric work, minimum angle, maximum angle, total range of motion, or moment impulse. Moment did vary by subgroup, as DT2 and PFS experienced significantly smaller minimums, $p=.000$ and $p=.003$, respectively. PFS also experienced a significant correlation between minimum moment and the plantar fascia proximal stiffness ($r=-.750$, $p=.001$), while diabetics were found to have a significant relationship between

the plantar fascia distal stiffness ($r=.547$, $p=.035$). It has been found that the plantar fascia supplies only a minor amount of energy to push-off at the ankle, roughly 10-15%, which could explain why there was only one correlation between the plantar fascia proximal and ankle power in the PFA group ($r=-.748$, $p=.033$) [98].

In all subgroups, during a concentric motion, the Redistribution Ratio of the MTP to proximal rearfoot, or ankle, trended higher than an eccentric motion. While the groups were not significantly different from each other, it does speak to power transfer mechanisms at the MTP. The redistribution ratio quantifies the extent that an individual walks with a distal to proximal redistribution and may be pertinent to understanding push-off intensity at the MTP in general. When concentrically moving during stance, the RR showed that individuals tended to rely more on the ankle muscles than the MTP when generating power. When eccentrically moving, the RR revealed that the work was more equally shared by the muscles of the ankle and the MTP. The higher the RR during concentric motion has a much higher distal-proximal redistribution. The concentric power experienced during stance at the MTP ensures the propulsion forward of the body, swing initiation, and forward acceleration, so an increased reliance on proximal rearfoot muscles indicates that work performed about the MTP joint may not be as drastically compromised by disease state as previously hypothesized. Changes in distribution can also be seen in a study by Cen et al., who set out to determine relationships between arch stiffness and regional impulse during over-ground walking [99]. The study's results suggest that subjects with less stiff arches had a smaller plantar impulse in the forefoot and larger impulse in the rearfoot, but most notably, overall changes in the distribution of plantar loading.

The PFA group held a positive relationship between ankle eccentric work and the PF proximal ($p=.04$). Most notably, the PFA group was the only subgroup to show a correlative

relationship between the concentric and eccentric Redistribution Ratio with the PF proximal ($p=0.20$, $p=.001$, respectively) which indicates two things: that as stiffness increases in the plantar fascia proximal, the concentric RR decreases while the Eccentric RR increases. Two theories were postulated as to why this trend occurred. One being that individuals who recover from plantar fasciitis may have adopted ways to alter their gait pattern in order to successfully alleviate symptoms. Another is that PFA individuals may have returned to their original way of walking that predisposed them to initially developing plantar fasciitis.

Because redistribution ratios were not correlated with plantar fascia stiffness changes in any other subgroup, it is reasonable to speculate that MTP mechanical power accomplishments may not be affected by the stiffness of the plantar fascia as dramatically as in the PFA group. However, because there are gait differences noted in the lower extremity for both pathology subgroups in literature [10, 17, 72, 73, 100], as well as within this study, power concessions likely happen elsewhere in the foot to account for gait pattern alterations.

The area that this likely occurs is the Achilles tendon. The Achilles tendon supports the Windlass mechanism by acting to control the amount of dorsiflexion present in gait. Plantar fascial loading is not only dependent on the MTP joint angle in feet but also on the tension within the Achilles tendon. Achilles tendons stiffness alterations have been observed in both diabetic and plantar fasciitis populations and subject to lower forces [101, 102] and have been found to affect peak pressures at the heel in plantar fasciitis populations specifically [103]. A study by Giacomozzi et al. supports this theory. Giacomozzi et al. studied the effects that alterations of Achilles tendon, plantar fascia and first MTP joint may have on foot loading [74]. Thickness of the Achilles tendon and plantar fascia was also determined by ultrasound, as well as flexion and extension of the first MTP joint. At the study conclusion, they found that the plantar fascia and Achilles tendons were significantly thicker in diabetics than in controls and that Flexion and

extension of the first MTP joint was significantly smaller in diabetics than in controls. Thus, an increased vertical force under the metatarsals during over-ground walking was strongly related to the changes in the three above parameters. These findings of a thickened plantar fascia and Achilles tendon contribute to the development of a rigid foot, which poorly absorbs shock during landing. It is a combination of alterations in the PF and the Achilles that lead to an overall alteration of the foot–ankle complex motion likely occurs throughout the whole gait cycle, which partly explains the abnormal loading under the forefoot. Tissue thickening is present in both diabetes and plantar fasciitis and so this theory can be applied to both pathology groups [73, 74, 101-103].

Altered properties of the Achilles in these two pathologies paired with the knowledge that no correlation exists between the metatarsophalangeal joint and kinematic factors in most subgroups (excluding PFA), it is possible that more dramatic energy saving concessions are occurring at the Achilles, which contributes towards a higher metabolic cost of walking, but overall less impactful energetic consequence at the MTP. However, this theory is speculative, and gait and energy profiles would need to be assessed at the Achilles Tendon in both pathologies before making such a conclusion about the nature of this relationship.

There are notable limitations to this study. For example, only healthy diabetic individuals with no injury were allowed in this study. This is relevant to the diabetic group as literature reports the most drastic and severe changes in gait and overall foot function to occur in individuals with either history of or current lower extremity ulceration [49, 53]. A second limitation is that the joint kinematics at 1.3 m/s were not compared to other walking speeds on the basis that the most drastic kinematic changes are most often observed in the fastest walking condition [76-79]. Participants wore shoes during motion analysis data collection, which is another limitation. Markers placed on the outside of a shoe rather than directly on the skin can produce less accurate results [104, 105]. Another limitation is measuring the plantar fascia itself.

The plantar fascia stiffness is an inherently difficult measure to obtain *in vivo* due to its complex geometry and structure, as well as its physical location amongst other soft tissues. It is reasonable to assert that the values obtained for plantar fascia stiffness for this study are approximate and variable. Lastly, the stiffness of the plantar fascia was measured in the open kinetic chain in a relaxed position; therefore, it is difficult to know the true stiffness while weight-bearing and in dynamic motion.

Future Work

Specific causes behind a compromised Windlass-Mechanism are still not defined, and further research is necessary to understand the complex consequences that stem from altered plantar fascia in pathology groups. Future work should include correlating kinematic measures of TROM, power, work, moment, impulse, joint force, and redistribution ratios of the proximal rearfoot joint and musculature against the stiffness of the plantar fascia and Achilles tendon to identify more probable locations of biomechanical impact from soft tissue alterations. Another avenue of future work should include investigating and identifying relationships between kinematic and material property changes in more severe disease states, primarily diabetic individuals with neuropathy or ulceration, while still maintaining comparison against other clinical populations to uncover any patterns that may not be evident in one population against controls.

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APPENDICES

Appendix A

```

% Prompts user to select the file they want to graph
% Request user input for how many graphs to create

function analysisdata

close all;
clear all;
clc;

answer = questdlg('How many files do you want to compare?', ...
    'Graphs', ...
    'ONE','MULTIPLE','ONE');
% Handle response
switch answer
    case 'ONE' %if user selects one graph, the file directory
        %will pop up and they will select one file
        [file] = uigetfile('*.*txt');
        if isequal(file,0)
            % if user clicks cancel
            disp('User selected Cancel!');
        else
            disp(fullfile(file));
        end

        T = readtable(file, 'ReadVariableNames',false);
        figure;
        x = T{:,2};
        mean = x %this should print out only the second
        %column of the table which is the x value mean
        plot(mean, '!');

        set(gcf,'NumberTitle','off') %don't show the figure number
        set(gcf,'Name',file) %select the name you want

        str = (file);
        newStr = erase(str, '_');
        title (newStr);
        %title (file);
        xlabel ('X-Axis');

```

```

ylabel ('Mean of X values');
grid

%NEEDS TO BE EDITED
case 'MULTIPLE' % if user selects multiple graphs
    files= uigetfile('* .txt',...
        'Select One or More Files', ...
        'MultiSelect', 'on');
    if isequal(files,0)
        % if user clicks cancel
        disp('User selected Cancel');
    % elseif length(files) == 1
    %     disp('Use other option');
    else
        disp(fullfile(files));

        figure;
        numberOfFiles = length(files) % will display the total number of files you selected
        for i = 1:numberOfFiles
            temp = char(files(i));
            disp(temp);
            T = readtable(temp, 'ReadVariableNames',false);
            x = T{:,2};
            mean = x %this should print out only the second
            %column of the table which is the x value mean
            plot(mean, '!');
            hold on;
        end

        set(gcf,'NumberTitle','off') %don't show the figure number
        set(gcf,'Name','Comparison of Data') %select the name you want

        title ('Comparison of Data');
        xlabel ('X-Axis');
        ylabel ('Mean of X values');
        grid
    end
end

%ask user if they want to generate a new graph
answer = questdlg('Do You Want To Generate Another Graph?', ...
    'New Graph', ...
    'YES','NO', 'YES');
% Handle response
switch answer
    case 'YES'

```



```

    % ask for new excel file
    analysisdata;
    figure;
case 'NO'
    %question box closes
end

```

Appendix B

```

import csv
import os
from collections import defaultdict
import itertools

root_file_path = input("enter folder path: ")

all_columns = []

for filename in os.listdir(root_file_path):
    columns = defaultdict(list)
    try:
        print(filename)
        if filename == "all_data.txt" or filename[-4:] != ".txt":
            continue
        with open(f"{root_file_path}/{filename}", 'r') as csv_file:
            csv_reader = csv.reader(csv_file, delimiter="\t")
            next(csv_reader)
            for row in csv_reader:
                for (i,v) in enumerate(row):
                    columns[i].append(v)
            columns[1].append(filename)
            all_columns.append(columns[1])
    except IndexError:
        print(f"index error in file {filename}")

print(all_columns)
transposed = list(map(list, itertools.zip_longest(*all_columns, fillvalue="-")))
print(transposed)

```

Appendix C

```

import pandas as pd
import numpy as np

f = open("filepath.txt", "r")

```

```
import os
path = f.read()
text_files = [f for f in os.listdir(path) if f.endswith('.txt')]
```

```
def MatClean(Dp):
    Dp=Dp.astype(np.float)
    flag=0
    for i in range(len(Dp)):
        if np.isnan(Dp[i]):
            u=i
            flag=1
            break
    if flag==1:
        Dp=Dp[0:u]
    return(Dp)
```

```
def integration(Dp):
    if isinstance(Dp, str):
        print(Dp)
        raise ValueError
    px=0
    nx=0
    dt=1/200.00
    for i in range(len(Dp)-1):
        if Dp[i]<0 and Dp[i+1]>0:
            g=Dp[i+1]-Dp[i]
            pddt=Dp[i+1]/g*dt
            nddt=dt-pddt
            px=px+Dp[i+1]*pddt/2
            nx=nx+Dp[i]*nddt/2

        if Dp[i]>0 and Dp[i+1]>0:
            px=px+(Dp[i]+Dp[i+1])/2*dt

        if Dp[i]>0 and Dp[i+1]<0:
            g=Dp[i]-Dp[i+1]
            pddt=Dp[i]/g*dt
            nddt=dt-pddt
            px=px+Dp[i]*pddt/2
            nx=nx+Dp[i+1]*nddt/2

        if Dp[i]<0 and Dp[i+1]<0:
            nx=nx+(Dp[i]+Dp[i+1])/2*dt
    return(px,nx)
```

```
def Iterate(num,DP,file):
    global linenum
    num=num
    print(file)
    total = 0
```

```

# clean dataframe and iterate count for average
try:
    x1=MatClean(DP[4:len(DP),1+num])
    total = total + 1
except:
    x1 = "x1 error"
try:
    x2=MatClean(DP[4:len(DP),4+num])
    total = total + 1
except:
    x2 = "x2 error"
try:
    x3=MatClean(DP[4:len(DP),7+num])
    total = total + 1
except:
    x3 = "x3 error"
try:
    x4=MatClean(DP[4:len(DP),10+num])
    total = total + 1
except:
    x4 = "x4 error"
try:
    x5=MatClean(DP[4:len(DP),13+num])
    total = total + 1
except:
    x5 = "x5 error"
try:
    x6=MatClean(DP[4:len(DP),16+num])
    total = total + 1
except:
    x6 = "x6 error"

# calculate p,n
try:
    p1,n1=integration(x1)
except:
    p1=0
    n1=0
    print("p1 error")
try:
    p2,n2=integration(x2)
except:
    p2=0
    n2=0
    print("p2 error")
try:
    p3,n3=integration(x3)
except:
    p3=0
    n3=0
    print("p3 error")

```

```

try:
    p4,n4=integration(x4)
except:
    p4=0
    n4=0
    print("p4 error")
try:
    p5,n5=integration(x5)
except:
    p5=0
    n5=0
    print("p5 error")
try:
    p6,n6=integration(x6)
except:
    p6=0
    n6=0
    print("p6 error")

if num==0:
    print('-----Data corresponding to X-----')
    # file2.write('Average Positive X: '+str(str((p1+p2+p3+p4+p5+p6)/6)))
    # file2.write('\n')
    # file2.write('Average Negative X: '+str(str((n1+n2+n3+n4+n5+n6)/6)))
    # file2.write('\n')
    sheet1.write(linenum, 0, 'Average Positive X:')
    sheet1.write(linenum, 1, str(str((p1+p2+p3+p4+p5+p6)/total)))
    linenum=linenum+1
    sheet1.write(linenum, 0, 'Average negativee X:')
    sheet1.write(linenum, 1, str(str((n1+n2+n3+n4+n5+n6)/total)))
    linenum=linenum+1

elif num==1:
    print('-----Data corresponding to Y-----')
    # file2.write('Average Positive Y: '+str(str((p1+p2+p3+p4+p5+p6)/6)))
    # file2.write('\n')
    # file2.write('Average Negative Y: '+str(str((n1+n2+n3+n4+n5+n6)/6)))
    # file2.write('\n')
    sheet1.write(linenum, 0, 'Average Positive Y:')
    sheet1.write(linenum, 1, str(str((p1+p2+p3+p4+p5+p6)/total)))
    linenum=linenum+1
    sheet1.write(linenum, 0, 'Average negativee Y:')
    sheet1.write(linenum, 1, str(str((n1+n2+n3+n4+n5+n6)/total)))
    linenum=linenum+1

elif num==2:
    print('-----Data corresponding to Z-----')
    # file2.write('Average Positive Z: '+str(str((p1+p2+p3+p4+p5+p6)/6)))
    # file2.write('\n')
    # file2.write('Average Negative Z: '+str(str((n1+n2+n3+n4+n5+n6)/6)))
    # file2.write('\n')

```

```

sheet1.write(linenum, 0, 'Average Positive Z:')
sheet1.write(linenum, 1, str(str((p1+p2+p3+p4+p5+p6)/total)))
linenum=linenum+1
sheet1.write(linenum, 0, 'Average negative Z:')
sheet1.write(linenum, 1, str(str((n1+n2+n3+n4+n5+n6)/total)))
linenum=linenum+1

# print('Positive Average: '+str((p1+p2+p3+p4+p5+p6)/6))
# print('negative Average: '+ str((n1+n2+n3+n4+n5+n6)/6))
# print('\n')

#=====
=====

global file2,linenum
import xlwt
from xlwt import Workbook

wb = Workbook()
sheet1 = wb.add_sheet('Sheet 1')

linenum=0
# file2 = open("Result.txt","w")
for file in text_files:
    if file != 'filepath.txt' and file != 'Result.txt' :
        Data_points = pd.read_csv(file,delimiter = "\t")
        DP=np.asarray(Data_points)
        sheet1.write(linenum, 0, '-----'+file+'-----')
        linenum=linenum+1
        # file2.write('-----'+file+'-----')

        # file2.write('\n')
        # sheet1.write(linenum, 0, '\n')
        # linenum=linenum+1

        for i in range(3):
            Iterate(i,DP, file)
# file2.close()
wb.save('Result.xls')
f.close()

```

VITA

Madeline Pauley was born and raised in Shelby, NC and is a graduate of the North Carolina School of Science and Math in Durham, NC. Prior to attending Old Dominion University, she attended East Carolina University in Greenville, NC, where she earned a Bachelor of Science in Exercise Physiology with a minor in English. She graduated *Magna Cum Laude* in 2018. She also participated in the NSF-funded Biomedical Engineering Simulations, Imaging, and Modeling Research Experience for Undergraduates program at ECU and attended both the Biomedical Engineering Society National conference in Atlanta, GA and South Eastern American College of Sports Medicine Conference in Greenville, SC.

While at Old Dominion, Madeline worked as a Career Counselor for the College of Engineering where she provided resume, cover letter, curriculum vitae editing and guidance to all levels of students. She also worked for the Old Dominion University Research Foundation as a research assistant. She also served as the Professional Outreach chair for the Society of Women Engineers and attended two professional development conferences in Baltimore, MD and Los Angeles, CA.

Currently, Madeline works as a General Engineer at Norfolk Naval Shipyard in Safety Management and Facilities Planning. She lives in Hampton, VA.