The Exploration of Morphological and Mechanical Properties of the Plantar Fascia in Response to Imposed Running Demands

A Dissertation
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Abstract

Morphological and mechanical properties of the plantar fascia have been suggested to play a role in developing plantar fasciitis. Clinically, plantar fasciitis has been characterized by an increase in thickness and a decrease in stiffness of the fascia. However, the true etiology and progression of plantar fasciitis are unknown. A more thorough knowledge of the behavior of plantar fascia tissue properties prior to injury may establish a foundation to detail the relationship between the tissue itself and progression of plantar fasciitis, as there are currently no known preventative strategies. Understanding how healthy plantar fascia tissue responds to imposed mechanical demands and stressors may bridge the literature gap between healthy tissue and plantar fasciitis symptoms, as well as enhance understanding the relationship between the tissue's mechanical properties and symptoms and development of plantar fasciitis. Therefore, there is need to determine the acute effects of imposed running demands on mechanical and morphological properties of the PF. If these properties are related to the progression of plantar fasciitis, these findings may move science towards preventing plantar fasciitis, rather than merely treatment. This dissertation was designed to explore the effects of different running demands on plantar fascia thickness and stiffness. By evaluating the potential relationship between running and foot mechanics with their potential association with plantar fascia.

The first manuscript details the first of the three studies conducted for the present dissertation. It focuses on increased intensity of the mechanical loading due to running speed and intensity, combined with acute fatigue. The purpose of the study was to evaluate the effects of repeated 400 m sprints on plantar fascia thickness and stiffness, while a secondary purpose was to explore the predictability of arch height index measurements on tissue changes. Sixteen participants completed five maximal effort 400 m sprints, followed by additional maximal effort trials until fatigue. For the first study, it is reported that plantar fascia stiffness and thickness decreased acutely in response to a single session of high intensity track repeats. Both properties returned to pre-run values after 30 minutes of rest. Plantar fascia properties also appeared to have been related to arch height index, as there was a decrease in foot arch measurements from pre-to post-run.

The second manuscript focuses on increased duration and frequency of mechanical loading. The purpose of this study was to investigate the effects of three consecutive days of

5-km maximal effort runs on plantar fascia thickness and stiffness in healthy, active individuals. The same 16 participants completed this protocol at least 7 days after they had completed the protocol for study 1. It can be reported that plantar fascia thickness in a rested state (pre-run) increased across three sessions of maximum effort 5 km running on three consecutive days. Within each day, thickness and stiffness decreased post-run and returned to pre-run values after 30 minutes of rest. Mechanical overloading and insufficient rest may induce conformational change of the plantar fascia.

The third manuscript introduces a new population, new running surface, and motion analysis. Manuscript three evaluated people with resolved plantar fasciitis to understand how previously injured tissue recovers, and whether it recovers. Additionally, the manuscript aimed to evaluate run and foot mechanics between aforementioned population and individuals without history of plantar fasciitis. Thus, the purpose of that study was to investigate the effects of 30 minutes treadmill running on plantar fascia properties and running mechanics in individuals with resolved plantar fasciitis (RPF) and those with no history of plantar fasciitis (NPF). It can be reported that both groups experienced the same decrease in thickness and stiffness immediately after the run. However, people with RPF had significantly thicker and stiffer tissue compared to never before injured individuals. Additionally, the stiffness of the tissue appeared to alter foot mechanics as it prevented the RPF group from undergoing vital medial longitudinal arch dorsiflexion during the stance phase. It is unclear whether this finding increases risk of re-injury and whether plantar fasciitis does have long-term effects on both the soft tissue, as well as foot mechanics during running.

Questions remain regarding the possibility of utilizing the morphological and mechanical properties of the plantar fascia to determine risk of plantar fasciitis. However, the present series of studies affirms that the plantar fascia is a viscoelastic material in vivo due to the change in morphological and mechanical properties in response to application and removal of mechanical loading, and that this can be quantified via ultrasound. Individuals, whether without plantar fasciitis history or those with resolved plantar fasciitis, displayed the same biomechanical response to mechanical loading. This response to the plantar fascia occurred regardless of duration, intensity, or frequency of the imposed mechanical demand. Future explorations should strive to further evaluate the relationship between the response of plantar fascia tissue to imposed demands and the occurrence of plantar fasciitis. While this may require longitudinal studies, the evidence presented in this dissertation provides an initial foundation for the continuation of research connecting plantar fascia tissue mechanics to the etiology of plantar fasciitis.

Acknowledgments

I am overcome by sincere gratitude as I sit down to write this section of my dissertation. The support and assistance I have received over the course of my PhD has been truly overwhelming, and I cannot express how grateful I am to all of those who have contributed.

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Dedication

This dissertation and all the hours of work that have gone into it would not have been possible without the loving support of my wife and partner, Mary Judith. I dedicate this PhD dissertation to you. You have been there for me through the good and the bad times. You never stopped believing in me. This work is equally yours as is mine. You sacrificed evenings, weekends, and holidays so I could chase my dream. I am so incredibly thankful for you. Your steadfast support has been the foundation upon which I have built my academic career. You are the most wonderful partner, mother to our children, and best friend I could have ever asked for. Thank you for everything. I love you with all my heart.

I also want to dedicate this dissertation to my children, Heidi and Noah. I love you. I cannot wait to see the great things you will do in your lives. You can do anything you set your minds to and I will always be in your corner supporting you. Dream Big!

Lastly, I want to dedicate this dissertation to my parents and brother who allowed me to spread my wings in a foreign country, speaking a foreign language, more than 10 years ago. Without their support, I would not be here. Danke, Mama, Papa, und Beni für Alles! Ich hab euch lieb.

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Statement of Contribution

This statement serves to acknowledge and clarify the individual contributions made by Lukas Daniel Dominik Krumpl, the candidate, towards the completion of this doctoral dissertation. The research presented in this dissertation is a result of the combined efforts of the candidate, the major professor, and the committee members. The specific contributions of Lukas Daniel Dominik Krumpl are detailed below:

Conceptualization and Research Design: Lukas Daniel Dominik Krumpl developed the initial research idea, formulating research questions, and designing the overall research framework, including methodology under the guidance of major professor, Dr. Joshua P. Bailey. Committee members Dr. Nathan P. Schiele, Dr. Dale Cannavan, Dr. Lindsay Larkins, & Dr. Ann Brown approved the framework of the dissertation.

Data Collection and Analysis: Lukas Daniel Dominik Krumpl took primary responsibility for collecting and assembling the required data for the research. The candidate designed and executed methodology. The candidate also processed and organized the data to ensure suitability for analysis. Under the guidance of Dr. Joshua Bailey, Lukas Daniel Dominik Krumpl conducted the data analysis using appropriate methodologies, equipment, and analysis tools.

Interpretation and Discussion of Results: Lukas Daniel Dominik Krumpl was responsible for interpreting the results of the data analysis, discussing the results, drawing conclusions, and contextualizing the findings. The candidate engaged in critical thinking and discussion with the entire committee to refine the interpretations and develop a comprehensive understanding of the research outcomes.

Writing and Manuscript Preparation: Lukas Daniel Dominik Krumpl took the primary responsibility for drafting, revising, and editing the entirety of the present dissertation, incorporating feedback from major professor Dr. Joshua Bailey, as well as the other committee members. The candidate ensured that the final manuscript adhered to the relevant academic writing standards and formatting guidelines. Chapters 2, 3, and 4 were co-authored by major professor Dr. Joshua Bailey, as well as committee members Dr. Nathan P. Schiele, Dr. Dale Cannavan, Dr. Lindsay Larkins, & Dr. Ann Brown.

Chapter 1

Dissertation Introduction

By

Lukas Daniel Dominik Krumpl

Introduction

The plantar fascia (PF) is a band of connective tissue that originates at the anterior part of the calcaneus and extends distally into the metatarsophalangeal joints. It is made up of three bundles: central, lateral, and medial (Wearing et al., 2006). The central bundle plays the most significant role in structure, support, yet also injury diagnosis (McNally & Shetty, 2010). Per year, PF injuries affect around two million people in the United States, resulting in approximately one million visits to physicians (Young, 2012). The annual cost of treatment for this injury is estimated to be between 192 and 376 million dollars (Young, 2012). Today, researchers and physicians can identify a limited number of anatomical factors associated with PF injuries, which are commonly diagnosed when the thickness of the fascia exceeds 4.0 mm (Gibbon & Long, 1999; Tsai et al., 2002). PF thickness has been identified as one of the most common symptoms of PF related injuries (Gibbon & Long, 1999; Tsai et al., 2002). Plantar fasciitis is commonly diagnosed via MRI, yet ultrasound has been shown to be a reliable tool as well (Jariwala et al., 2011). A healthy PF has a relative thickness of 2-4 mm, while plantar fasciitis patients often display a thickness of 4-7 mm and usually report symptoms of sharp pain at heel contact, specifically in the morning (Buchbinder, 2004). However, most of this research stems from studies with plantar fasciitis symptomatic participants. There is no consensus about the relationship between the symptoms and the PF before the injury occurs, as well as limited research on the effect of continuous stress in form of exercise on the PF in asymptomatic individuals.

Among all PF injuries, plantar fasciitis is the most diagnosed (Barrett & O’Malley, 1999). While the underlying mechanisms of developing plantar fasciitis are still widely unknown, research has suggested that the morphology of the tissue plays a key role (Wang et al., 2009). The PF is a fibrous tissue made up of hyaluronan, a glycosaminoglycan widely distributed in connective tissue. The abundance of hyaluronan makes the PF sensitive to inflammation. Wang (Tsai et al., 2000) described that fibrous structures display viscoelastic biomechanical properties, such as stress relaxation, hysteresis, and tissue creep. Welk et al. (2015) investigated tissue creep in relation to PF thickness in runners and walkers. The proposed mechanical sequence of tissue creep compensation detailed by Frost (1990) suggests that repetitive loading, such as walking or running, would lead to a thinning of the PF immediately post-exercise, followed by an inflammatory reparative process. However, this process of inflammation was not investigated (Welk et al., 2015) and has not been described in the literature thus far. Additionally, the study did not evaluate gait characteristics and their relationship to PF thickness and stiffness. It remains unclear how long and how excessive the repetitive loading stress must be to create a consistent accumulation of microtears and general fibrous degeneration to lead to plantar fasciitis. Therefore, there is dire need for research investigating the effects of various intensities and volumes of running in asymptomatic individuals, both trained and untrained.

Attempting to fill this gap in recent literature, Shiotani et al. (2020) evaluated the effects of a single bout of long-distance running (10 km) on PF thickness and stiffness in asymptomatic trained runners and untrained individuals. In alignment with the tissue creep theory, the researchers found that the PF thickness of untrained individuals decreased slightly, yet this difference was statistically insignificant. Overall, there was no significant change in PF thickness immediately after the run, 30 minutes, and 60 minutes after the termination of running. These results were not surprising as the researchers controlled for both distance and intensity, of which the latter was considerably low for trained runners (10 km/h). The low intensity of a single bout of running appears to be too small of a stimulus to elicit tissue changes in thickness. This suggests the need for not only an increase in duration of running, but also intensity. On the other hand, both trained and untrained individuals displayed a significant decrease in PF stiffness and navicular height, suggesting that one single bout of running may cause mechanical fatigue of the foot arch (Shiotani et al., 2020). Previous literature suggests that a decrease in PF stiffness may induce excess strain to the fascia during exercises such as running, increasing mechanical overload and the possibility of micro tears resulting in plantar fasciitis (Taunton et al., 2002). Assessing stiffness via shear wave elastography is a relatively modern approach to investigate tissue behavior, especially for the PF. Research investigating PF stiffness has been relying on computational modeling of the tissue (Wu et al., 2011). However, the study found that PF stiffness significantly decreases in individuals diagnosed with plantar fasciitis (Wu et al., 2011). This change in stiffness can lead to altered foot kinematics, which can ultimately lead to injury. Thus, more research investigating asymptomatic PF stiffness in response to exercises and altered gait characteristics is needed.

Plantar fasciitis symptomatic individuals display greater total rearfoot eversion, midfoot extension, and peak first metatarsal phalangeal joint (FMPJ) dorsiflexion compared to their healthy counterparts (Chang et al., 2014). Both aforementioned variables are key factors in identifying altered gait characteristics during both walking and running. While rearfoot eversion causes excess mechanical stress to the PF at each foot strike, greater FMPJ dorsiflexion has been shown to increase PF tension and the likelihood for tearing and inflammation, precursors of plantar fasciitis. However, this research is limited to comparisons between plantar fasciitis symptomatic and asymptomatic individuals. It remains uncertain whether these observations can be considered cause or effect from either direction. In other words, it is unknown what came first, the injury or the gait mechanics. Further research on the relationship between gait characteristics and the PF, specifically in asymptomatic individuals, is necessary to paint a more holistic picture about how the PF develops into damaged and injured tissue.

A strategy to observe PF tissue changes due to imposed running demands may be to induce musculoskeletal and neuromuscular fatigue. Research has shown that fatigued runners displayed similar foot and gait kinematics as individuals diagnosed with plantar fasciitis (Giandolini et al., 2016). Fatigue induced similar rearfoot eversion and flatter foot landing in marathon runners (Giandolini et al., 2016), indicating that structural and mechanical adaptations of the foot may cause excess stress to the PF. Therefore, it is not surprising that plantar fasciitis is often diagnosed in running type sports and in people who are exposed to extended periods of time on their feet, such as construction workers or nurses (Sung et al., 2020; Taunton et al., 2002).

To date, there is no consensus among researchers and clinicians about the mechanisms and progression of PF injuries. While plantar fasciitis is the most common cause of heel pain (Buchbinder, 2004), its etiology is still not understood. Understanding how healthy tissue reacts to imposed demands and stressors may drastically change the way PF injuries are treated. Additionally, bridging the literature gap between healthy tissue and plantar fasciitis symptoms would mean a tremendous leap toward the understanding of how the PF behaves. There is need to determine the acute effects of imposed running demands on mechanical and morphological properties of the PF, in the hope of inching one step closer towards preventing plantar fasciitis. Therefore, the purpose of this dissertation was to investigate the effects of different types of running intensities and volumes on the mechanical and morphological properties of the plantar fascia, in order to evaluate whether thickness and stiffness have the potential to be utilized as indicators for PF tissue changes prior to onset of injury.

References

Barrett, S. L., & O'Malley, R. (1999). Plantar fasciitis and other causes of heel pain. *American Family Physician*, *59*(8), 2200.

Buchbinder, R. (2004). Plantar fasciitis. *New England Journal of Medicine, 350*(21), 2159-2166.

Chang, R., Rodrigues, P. A., Van Emmerik, R. E., & Hamill, J. (2014). Multi-segment foot kinematics and ground reaction forces during gait of individuals with plantar fasciitis. *Journal of Biomechanics*, *47*(11), 2571-2577.

Freund, W., Weber, F., Billich, C., & Schuetz, U. H. (2012). The foot in multistage ultra-marathon runners: Experience in a cohort study of 22 participants of the Trans Europe Footrace Project with mobile MRI. *BMJ Open*, *2*(3).

Frost, H. M. (1990). Skeletal structural adaptations to mechanical usage (SATMU): 4. Mechanical influences on intact fibrous tissues. *The Anatomical Record*, *226*(4), 433-439.

Giandolini, M., Gimenez, P., Temesi, J., Arnal, P. J., Martin, V., Rupp, T., ... & Millet, G. Y. (2016). Effect of the fatigue induced by a 110-km ultramarathon on tibial impact acceleration and lower leg kinematics. *PloS One*, *11*(3), e0151687.

Gibbon, W. W., & Long, G. (1999). Ultrasound of the plantar aponeurosis (fascia). *Skeletal Radiology, 28*(1), 21-26.

Goff, J. D., & Crawford, R. (2011). Diagnosis and treatment of plantar fasciitis. *American Family Physician*, *84*(6), 676.

Jariwala, A., Bruce, D., & Jain, A. (2011). A guide to the recognition and treatment of plantar fasciitis. *Primary Health Care*, *21*(7), 22-24.

McNally, E. G., & Shetty, S. (2010). Plantar fascia: Imaging diagnosis and guided treatment. *Seminars in Musculoskeletal Radiology, 14*(3), 334-343. doi:10.1055/s-0030-1254522

Shiotani, H., Mizokuchi, T., Yamashita, R., Naito, M., & Kawakami, Y. (2020). Acute effects of long-distance running on mechanical and morphological properties of the human plantar fascia. *Scandinavian Journal of Medicine & Science in Sports, 30*(8), 1360-1368.

Sung, K. C., Chung, J. Y., Feng, I. J., Yang, S. H., Hsu, C. C., Lin, H. J., ... & Huang, C. C. (2020). Plantar fasciitis in physicians and nurses: A nationwide population-based study. *Industrial Health*, 58(2), 153-160.

Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., & Lloyd-Smith, D. R. (2002). Plantar fasciitis: a retrospective analysis of 267 cases. *Physical Therapy in Sport*, *3*(2), 57-65.

Tsai, W. C., Chiu, M. F., Wang, C. L., Tang, F. T., & Wong, M. K. (2000). Ultrasound evaluation of plantar fasciitis. *Scandinavian Journal of Rheumatology*, *29*(4), 255-259.

Wang, H. Q., Wei, Y. Y., Wu, Z. X., & Luo, Z. J. (2009). Impact of leg lengthening on viscoelastic properties of the deep fascia. *BMC Musculoskeletal Disorders*, *10*(1), 105.

Wearing, S. C., Smeathers, J. E., Urry, S. R., Hennig, E. M., & Hills, A. P. (2006). The pathomechanics of plantar fasciitis. *Sports Medicine*, *36*(7), 585-611.

Welk, A. B., Haun, D. W., Clark, T. B., & Kettner, N. W. (2015). Use of high-resolution ultrasound to measure changes in plantar fascia thickness resulting from tissue creep in runners and walkers. *Journal of Manipulative and Physiological Therapeutics*, *38*(1), 81-85.

Wu, C. H., Chang, K. V., Mio, S., Chen, W. S., & Wang, T. G. (2011). Sonoelastography of the plantar fascia. *Radiology*, *259*(2), 502-507.

Young, C. (2012). Plantar fasciitis. *Annals of Internal Medicine*, *156*. doi:10.7326/0003-4819-156-1-201201030-0100

Chapter 2

Plantar Fascia Thickness and Stiffness in Response to High Intensity Interval Running

By

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Co-authored by

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Significance of the Chapter

Establishing a theory to prevent plantar fascia injuries necessitates a fundamental understanding of the underlying mechanisms behind plantar fascia injury development. Theories suggest that continuous mechanical overloading of the foot may play a role in plantar fascia deterioration. However, not only do these theories remain uncertain, but questions also continue about the framework of mechanical loading: What is the duration, distance, or intensity of the mechanical loading that causes plantar fascia injuries? Prior to evaluating the progression of a healthy to injured plantar fascia tissue, it was necessary to first investigate the effects of varying intensities, durations, and frequencies of mechanical loading on plantar fascia properties linked to injury. Chapter two focuses on increased intensity of the mechanical loading due to running speed combined with acute fatigue on properties of the plantar fascia. Plantar fascia thickness has been a consistent variable used to differentiate healthy and injured tissue. Plantar fascia stiffness, on the other hand, is a novel variable linked to plantar fascia deterioration. New developments in ultrasound technology, specifically shear wave elastography, have introduced tissue stiffness as a promising property of plantar fascia research.

Understanding how plantar fascia thickness and stiffness respond to varying imposed demands of mechanical loading in form of overground running would provide existential new information. The aim of this study was to initiate a series of investigations evaluating the outcomes of different types of running intensities, durations, and frequencies on mechanical and morphological properties of the plantar fascia. This chapter specifically focuses on plantar fascia properties in response to high intensity running to induce acute cardiovascular, neuromuscular, and mechanical fatigue.

Abstract

Plantar fascia (PF) thickness and stiffness properties have been linked to plantar fasciitis. However, it is unknown whether these properties are the cause of or the response to developing plantar fasciitis. Thus, the purpose of the present study was to evaluate the effects of high intensity track intervals on PF thickness and stiffness in healthy, asymptomatic individuals. A secondary purpose was to explore the predictability of arch height index measurements on PF tissue changes. Sixteen participants completed five maximal effort 400 m sprints with a 1:1 work to rest ratio, followed by additional maximal effort trials until fatigue. Thirteen participants reached fatigue after 7 laps total, three participants after 8 laps total. PF properties at two sites along the PF length were collected before (pre), after (post), and 30 minutes post-run, and arch height measurements were taken pre- and post-run. PF thickness and stiffness decreased post-run (0.4 mm; $p < 0.001$) and increased 30 minutes post-run (0.3 mm; $p < 0.002$). No significant difference was found between pre-run and 30 minutes post-run thickness ($p = 0.577$) and stiffness ($p = 0.071$). Pre-run arch height was positively correlated to pre-run PF thickness ($p = 0.045$, $r = 0.54$). Arch height decreased post-run and was negatively correlated to relative change in PF stiffness from pre- to post-run ($p = 0.047$, $r = 0.54$). These findings indicate that although high intensity interval running to fatigue altered both PF thickness and stiffness, 30 minutes of rest allowed the non-injured PF tissue to recover.

Keywords

Plantar fascia, thickness, stiffness, ultrasound, shear wave elastography, arch height index

Introduction

Plantar fascia (PF) injuries affect around two million people in the United States per year (Young, 2012). While plantar fasciitis is the most diagnosed PF injury, its etiology is not fully understood (Buchbinder, 2004). Researchers and physicians have associated morphological and mechanical properties with plantar fasciitis, such as PF thickness and stiffness (Gibbon & Long, 1999; Tsai et al., 2000; Schillizzi et al., 2021). PF thickness has been identified as one of the most common diagnostic criteria of plantar fasciitis (Gibbon & Long, 1999; Tsai et al., 2000). Additionally, PF stiffness has been implicated as a feasible diagnostic tool with decreased stiffness related to symptomatic plantar fasciitis (Schillizzi et al., 2021), but little information exists regarding both properties prior to injury.

While the underlying mechanisms of plantar fasciitis are still widely unknown, tissue response to loading may play a key role (Stecco et al., 2013). The PF displays viscoelastic biomechanical properties, such as stress relaxation, hysteresis, and creep (Pavan et al., 2011; Zhang et al., 2018). Continued repetitive loading, such as running, results in tissue creep and could lead to a progressive lengthening and thinning of the PF followed by an inflammatory reparative process (Frost, 1990). A reduction in PF thickness due to tissue creep during repetitive loading cycles has been documented, but the time course of tissue thickness recovery has not been described in the literature thus far (Welk et al., 2015). It remains unclear how accumulated magnitudes of repetitive loading create fibrous degeneration and lead to plantar fasciitis.

Prior studies found that training may impact the magnitude of creep in the PF in asymptomatic individuals. A submaximal 10 km effort failed to decrease PF thickness in trained runners but showed a trend toward a decrease in untrained runners (Shiotani et al., 2020). While these are coexisting findings among healthy individuals, there are missing details on how PF creep and thickness are impacted by maximal effort. More specifically, shorter maximal effort bouts such as interval runs may place greater loads on the PF per foot contact and consequently induce greater changes in the tissue compared to running at submaximal effort.

Current knowledge of PF stiffness is mostly based on computational modeling of the tissue (Cheung et al., 2004; Wang et al., 2016). However, advancements in technology are providing the ability to supplement modeling research with human subject research.

Assessing stiffness via ultrasound shear wave elastography (SWE) is a relatively modern noninvasive approach to investigate tissue structure and mechanical properties. Research utilizing SWE suggests that PF stiffness significantly decreases in individuals diagnosed with plantar fasciitis (Wu et al., 2011). A decrease in PF stiffness may increase mechanical overload through excess strain on the fascia during running. This could diminish the functionality of the Windlass Mechanism and decrease foot stability, leading to fascial micro tears, and thus increase risk of developing plantar fasciitis (Taunton et al., 2002). Furthermore, a relative decrease in arch height correlated to a decrease in PF stiffness following submaximal running in asymptomatic individuals (Shiotani et al., 2020). Thus, it is reasonable to postulate that a loss in stiffness diminishes the PF's capacity to prevent the foot from overpronation due to a decreased effectiveness of the Windlass Mechanism, during which the PF coils around the metatarsals during toe dorsiflexion to provide arch stability. Given the likelihood that load affects the tissue, an investigation of high intensity running may provide further evidence into previous findings of submaximal running regarding the connection between PF properties and foot architecture.

Therefore, the purpose of the present study was to investigate the effects of high intensity interval running on PF thickness and stiffness in healthy, asymptomatic individuals. A secondary purpose was to evaluate the predictive relationship of arch height to PF properties. It was hypothesized that PF thickness and stiffness would decrease immediately after the exercise protocol compared to before, and that PF thickness and stiffness would increase after 30 minutes of rest following completion of the intervals. A secondary hypothesis was that increased arch height pre-run would predict greater PF thickness and stiffness, and that greater arch height decrease from pre- to post-run would predict greater relative decrease in PF thickness and stiffness.

Materials and Methods

Participants

Sixteen healthy individuals participated in the present study (9 females, 7 males; Age: 28.6 yrs (± 8.9), Height: 171.6 cm (± 7.5), Mass: 66.3 kg (± 8.7)). Participants were considered physically active by having participated in at least 30 minutes of exercise, three times per week, for the past three months. Exclusion criteria were previously diagnosed PF injuries or identified previous plantar fasciitis, plantar heel, Achilles' tendon, or general foot and ankle pain. This study was approved by the Institutional Human Research Ethics Committee and was carried out in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants before data collection.

Protocol

Participants were asked to refrain from physical activity, caffeine, and alcohol consumption for 24 hours prior to data collection. Furthermore, participants were instructed to avoid non-steroidal anti-inflammatory drug consumption or topical cream application to the plantar aspect of their feet. Participants reported to the university laboratory and completed maximal effort 400 m interval runs until fatigue. Participants wore their own running shoes and exercise clothing during the running trials. PF thickness and stiffness measurements were taken via ultrasound at three time points: before running, immediately post-run, and following a 30-minute rest. Arch height measurements were taken pre- and post-run. All measurements were taken bilaterally and performed by the same investigator. During the 30 minutes of rest, participants remained on the treatment table and their feet did not have contact with the ground.

Ultrasound Measurements

B-mode ultrasonography was used to determine PF thickness (Logiq S8; GE Healthcare, Waukesha, WI, USA). All images were taken with a linear ray transducer (9L-D; GE; field of view of 43 mm, measurement length of 5.31 x 13.8 mm) at 10 Hz (default sampling rate), with a gain of 50 (to optimize brightness), and a depth of 3.5 cm (to capture the appropriate tissue). Ultrasonograms of the PF occurred with participants lying in a prone position on a treatment table with knees resting in extension and bare feet and ankles hanging relaxed over the edge of the table. Two locations along a longitudinal line (proximal [at the PF insertion near the calcaneal tuberosity] and distal [at the level of the navicular tuberosity]) were marked with a waterproof marker prior to taking the measurements (Jariwala et al., 2011). PF thickness was measured as the distance between the deep and superficial fascia boundaries at the calcaneal origin (proximal) and at the navicular tuberosity (distal) (Figure 1). B-mode live images (5 seconds per image gave 5 images) were collected and the three middle images per measurement were used for analysis, as the mean of three images has been identified to produce the most reliable results (Skovdal Rathleff et al., 2011).

SWE was used to determine PF stiffness. A region of interest (ROI) box was manually placed over the visually identified measurement sites in the PF. Three colorized images were taken and used for later analysis. PF stiffness measurement was calculated using the mean shear wave velocity of the region of interest (Figure 2). For both properties, the mean measurement of three images was used as a single value representative of the data. A single trained researcher collected all images.

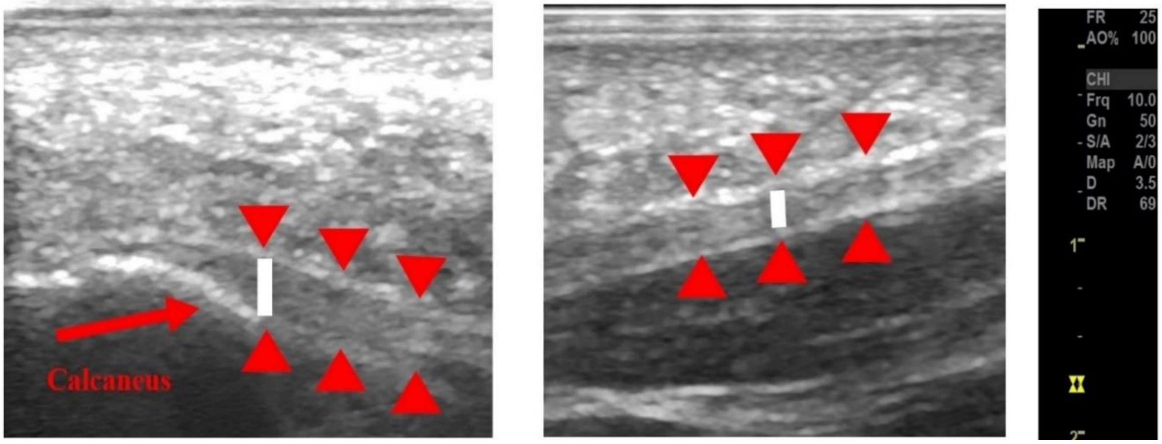

Figure 1. Representation of B-mode ultrasound images to measure PF thickness (white vertical bar) at the proximal (left) and distal (right) sites. The red arrows aid to visualize the trajectory of the PF. The legend on the right displays the image settings ang the scale bar in centimeters.

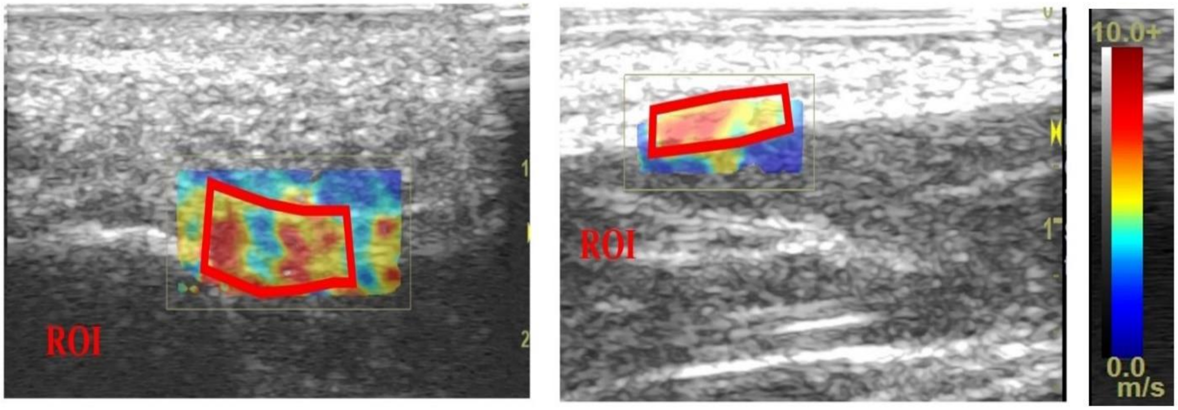

Figure 2. ROI; Region of Interest. Representation of shear wave elastography ultrasound images to measure PF stiffness at the proximal (left) and distal (right) sites. The color legend on the right represents the shear wave velocity in meters per second. Greatest velocity (stiffer tissue) is shown in red, lowest velocity (less stiff tissue) is shown in blue.

Arch Height Index

Arch height index was measured bilaterally before and after the exercise protocol. Participants sat on an adjustable chair which was set at a height of 90-degree knee flexion with full ground contact of the feet at rest (Butler et al., 2008). A standard measurement tape was used to measure the following foot dimensions: foot length, truncated foot length, and dorsum height at 50% of foot length (Butler et al., 2008). Arch height index, a unitless value, was then calculated with the following equation:

$$Arch\ Height\ Index = \frac{Dorsum\ Height\ at\ 50\%\ of\ Foot\ Length}{Truncated\ Foot\ Length}$$

400 m Interval Run

Participants performed a single session of maximal effort 400 m intervals on an outdoor track; intervals were repeated until volitional fatigue. Prior to performing the 400 m intervals, participants performed a self-selected dynamic warm-up for a minimum of 5 minutes. They were then instructed to run a single lap around the track as fast as they could. The time to complete the trial was recorded and used to establish a 1:1 work-rest ratio; this time was adjusted for each lap such that the 1:1 ratio changed based on cumulative fatigue. The mean time for the first 5 intervals was calculated to determine the percentage-based fatigue index (FI) (Morin et al., 2011). The FI score was set as 5% below the average interval time to indicate volitional fatigue for stopping the intervals beyond the first 5 interval runs (Morin et al., 2011). When participants were no longer able to maintain the FI score for two consecutive intervals they were stopped.

Statistical Analysis

Dependent variables (PF thickness and stiffness at two measurement sites) were analyzed by two-way (2 measurement site x 3 time points) repeated measures analyses of variance (ANOVA) to evaluate the effect of time (pre, post, and 30 min post-run) on PF thickness and stiffness, and whether time affected the measurement differently. Main effects were followed up with *post-hoc* analyses for pairwise comparisons using Bonferroni adjustments. Interactions were followed up with simple main effects and pairwise comparisons using Bonferroni adjustments. Effect sizes were calculated as partial eta-squared (η_p^2) for the ANOVA and Cohen's *d* for the post-hoc analyses. Arch height measurements were analyzed with dependent t-tests to evaluate potential changes pre- and post-run. Linear regression analyses estimated changes in PF properties and arch height predictability. To demonstrate reasonableness of fit, standard error and R^2 values were calculated. Additionally, two-sample t-tests with PF thickness and stiffness were conducted to evaluate potential differences between right and left limb, males and females, and relative change (%Δ) from pre- to post-run. An *a priori* alpha level was set at $\alpha = 0.05$. Statistical analyses were performed using IBM SPSS Statistics v.28.

Results

Across each time point, PF thickness and stiffness were not significantly different between right and left foot ($p > 0.05$), as well as between males and females ($p = 0.067$). Similarly, the relative change in thickness and stiffness did not differ between males and females ($p > 0.05$) from pre- to post-run. No significant differences in foot dimensions were found between the right and left side for each participant. Thus, the mean values of the right foot were used for statistical analysis.

PF thickness had a significant main effect across measurement site ($F[1, 15] = 140.6$, $p < 0.001$, $\eta_p^2 = 0.92$) and time ($F[2, 28] = 14.6$, $p < 0.001$, $\eta_p^2 = 0.53$) (Figure 3). PF thickness was greater at the proximal site than the distal site at each timepoint (pre: 3.46 vs. 1.66; post: 3.1 vs. 1.49; 30 min post: 3.35 vs 1.63 mm, respectively; $p < 0.001$). PF thickness decreased from pre- to post-run at the proximal (3.5 to 3.1 mm; $p < 0.001$; d = 1.6), but not the distal (1.6 to 1.5; $p = 0.074$; d = 0.68) site. PF thickness significantly increased from post-run to 30 minutes post-run at the proximal (3.1 to 3.4 mm; $p = 0.015$; d = 0.9) and the distal (1.5 to 1.63; $p = 0.012$; d = 0.94) site. There was no significant difference in PF thickness between pre-run and 30 min post-run at either measurement site ($p = 0.577$ and $p = 1.0$, respectively).

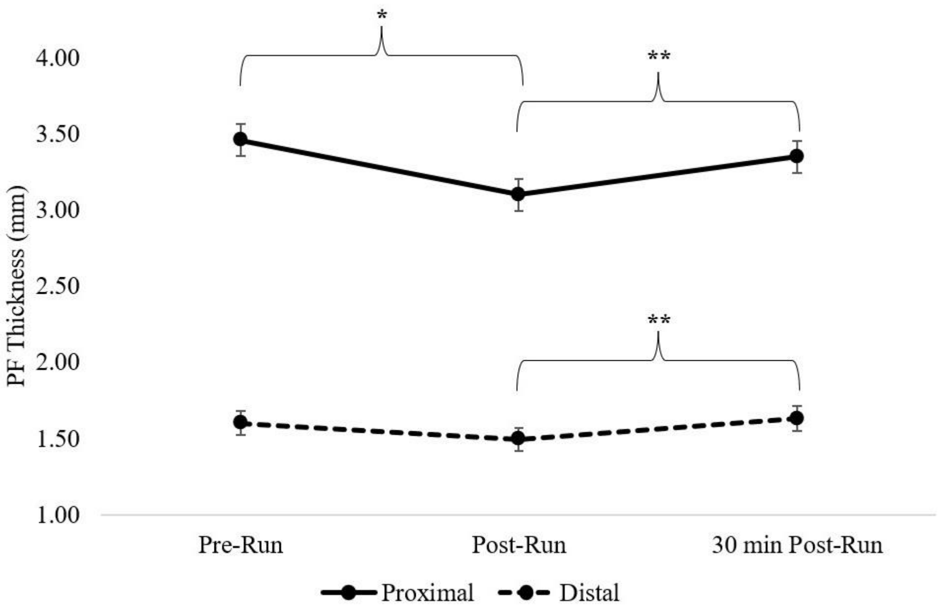

Figure 3. PF thickness for proximal and distal measurement sites at each measurement time (pre-run, post-run, 30 minutes post-run). * Denotes a significant decrease in PF thickness between pre- and post-run measurements. ** Denotes a significant increase in PF thickness between post- and 30 minutes post-run measurements.

PF stiffness had a significant interaction between measurement site and time ($F[2, 28] = 4.34$, $p = 0.024$, $\eta_p^2 = 0.25$) (Figure 4). PF stiffness had significant simple main effects across time at the proximal ($F[2, 28] = 28.58$, $p < 0.001$, $\eta_p^2 = 0.69$) and distal ($F[2,28] = 5.61$, $p = 0.009$, $\eta_p^2 = 0.31$) measurement sites. Pairwise comparison analyses revealed a significant decrease in PF stiffness from pre- to post-run at the proximal (4.49 to 2.99 m/s; $p < 0.001$; d = 2.0) and the distal (3.67 to 2.88 m/s; $p < 0.001$; d = 0.68) sites. PF stiffness significantly increased from post-run to 30 minutes post-run at the proximal site (2.99 to 4.00 m/s; $p = 0.001$; 1.24). However, there was no significant difference between these two measurements at the distal site (2.88 to 3.28 m/s; $p = 0.08$; d = 0.65). Both sites did not differ significantly between pre- and 30 minutes post-run protocol ($p = 0.071$ and p = 0.059, respectively). PF stiffness had significant main effects across measurement sites pre-run ($F(1,15) = 7.07$, $p = 0.02$, $\eta_p^2 = 0.35$) and 30 minutes post-run ($F(1,15) = 4.78$, $p = 0.048$, $\eta_p^2 = 0.27$). There was no significant main effect for PF stiffness across measurement sites post-run ($F(1,15) = 0.40$, $p = 0.54$, $\eta_p^2 = 0.03$). Pairwise comparison analyses revealed a greater PF stiffness at the proximal versus the distal measurement sites pre-run (4.49 vs. 3.68 m/s, *p* = 0.02, d = 0.71), and 30 minutes post-run (4.00 vs. 3.28 m/s, *p* = 0.048, d = 0.58).

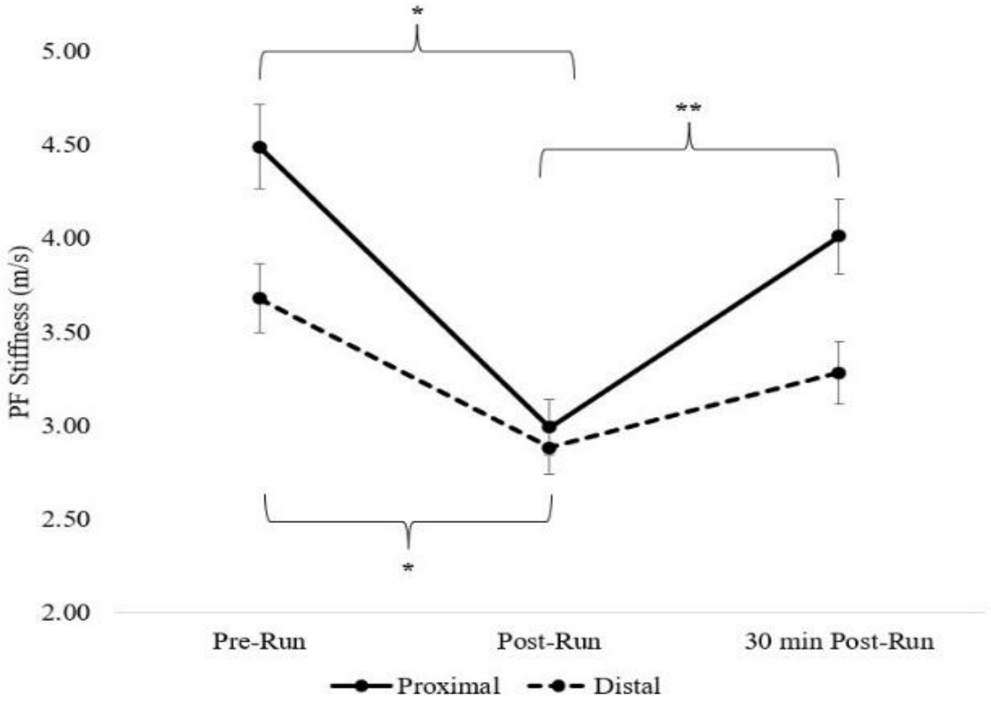

Figure 4. PF stiffness for proximal and distal measurement sites at each measurement time (pre-run, post-run, 30 minutes post-run). * Denotes a significant decrease in PF stiffness between pre- and post-run measurements. ** Denotes a significant increase in PF stiffness between post- and 30 minutes post-run measurements.

Dorsum height and arch height index decreased significantly from pre- to post-run (*p* = 0.02 and *p* = 0.009, respectively). Table 1 displays dorsum height and mean arch height index values for the overall sample population and each group separately.

Table 1

Mean (± SD) values of dorsum height and arch height index

	Pre-Run	Post-Run
DH (cm)	7.2 (0.91)	6.8 (0.91)†
AHI	0.306 (0.03)	0.293 (0.03)†

note. †Significant difference pre- to post-run ($p < 0.05$)

SD, Standard Deviation; DH, Dorsum Height; AHI, Arch Height Index

Pre-run PF thickness showed a significant positive relationship to arch height index (*p* = 0.045, r = 0.54) (Figure 5), but not for dorsum height. Arch height index explained approximately 30% of the variance in PF thickness values. No relationship was found for pre-run stiffness and arch height measurements. Relative change of PF stiffness showed a significant relationship to pre-run arch height index (*p* = 0.047, r = 0.54) (Figure 6), but not dorsum height. Arch Height Index explained approximately 30% of the variance in relative change in PF stiffness from pre- to post-run. No relationship was found for relative change of PF thickness and arch height measurements.

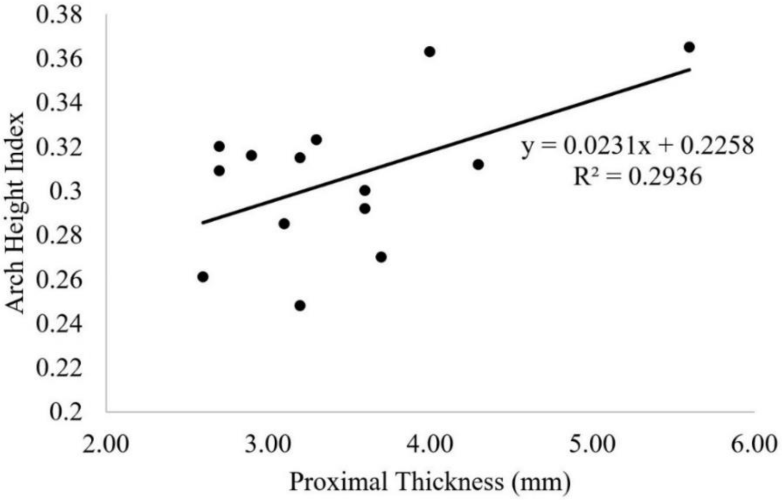

Figure 5. Linear regression analysis between proximal PF thickness and arch height index indicating that greater arch height index is related to an increased PF thickness.

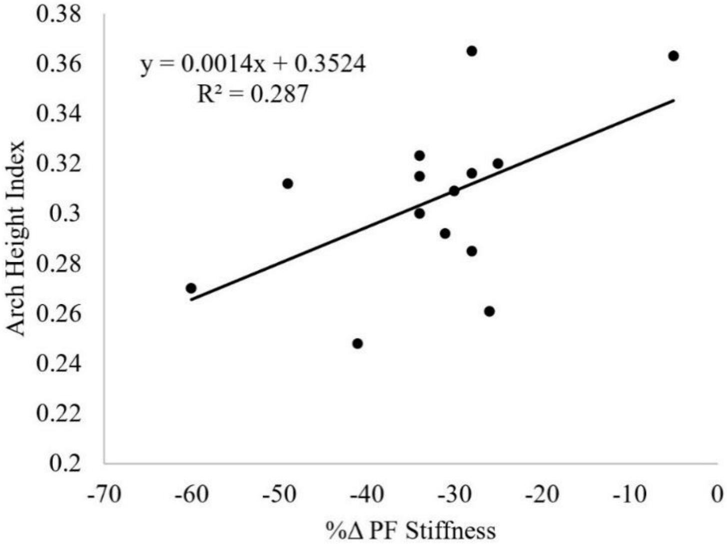

Figure 6. Linear regression analysis between relative change of PF stiffness from pre- to post-run and arch height index indicating that a greater arch height index is related to a

Discussion

The decrease in PF thickness and stiffness immediately post-run, and the consequent increase of both properties approximating pre-run values after 30 minutes of rest, align with the initial hypothesis. Concurrently, there was a significant decrease in arch height index immediately post-run. These findings indicate that high intensity 400 m intervals until fatigue induced acute morphological and mechanical changes to the PF, as well as acute deformation of the medial longitudinal arch. However, these values returned to baseline after 30 minutes of recovery in healthy individuals without prior PF injuries.

PF thickness and stiffness changes were found for both the proximal and the distal site, indicating that the PF responds similarly to high intensity running near its origin and more proximally towards its insertion. Thus, the changes in PF tissue thickness and stiffness appear to be a natural response of the PF to mechanical loading, indicative of the viscoelastic behavior of the fascia (Cheung et al., 2004). Specifically, healthy PF tissue has been shown to experience hysteresis due to mechanical loading at various loading rates and magnitudes (Crary et al., 2003). The initial decrease post-run, and recovery of PF thickness and stiffness by 30 minutes in the present study suggests the occurrence of hysteresis in vivo, preceded by tissue creep throughout the interval running (Crary et al., 2003; Frost, 1990).

The change in PF thickness was expected especially at the proximal site, as it is widely considered the area of greatest mechanical loading, and most affected part of the tissue in people with plantar fasciitis (Cheng et al., 2008; League, 2008; Lin et al., 2014). The decrease in thickness at the distal site suggests that increased mechanical loads due to high intensity running affect the PF beyond its proximal site. Tissues under continuous or constant mechanical loading will experience creep (e.g., an increased strain or elongation) (Wren et al., 2003). As the PF is cyclically stretched in the longitudinal direction throughout the stance phase, from each initial contact to push off, the transverse direction is expected to decrease due to the Poisson effect. The decrease in PF thickness after running may be due in part to the lengthening of the PF and the resulting tissue volume loss from fluid flow (Lavagnino et al., 2014; Swedberg et al., 2014). Thus, the return to pre-run PF thickness after 30 minutes of rest may be due to fluid resorption in the PF and a return to pre-run PF length. These potential mechanisms warrant further investigation. Furthermore, the decrease in thickness immediately following a bout of running aligns with previous findings (Shiotani et al., 2020).

The intensity and consequent impact load of the 400 m intervals were likely greater than the 10 km run at a prescribed pace (Shiotani et al., 2020). Thus, the maximal effort running in the present study may have exceeded a threshold of loading to cause a decrease in PF thickness.

The decrease in stiffness also aligns with previous findings, with a significant decrease in stiffness at the proximal and distal site (Shiotani et al., 2020). The decrease was followed by a return to near-baseline values after 30 minutes of rest at the proximal but not at the distal site. As the proximal site of the PF experiences the greatest amount of stress and strain (Cheng et al., 2008; Lin et al., 2014), the difference in PF stiffness at that site was not surprising. Changes in PF stiffness with running as measured by SWE may be due to changes in tissue hydration, collagen fiber organization, or tissue laxity due to creep induced lengthening along the loading direction. Yet, the underlying mechanisms are unclear and require further investigation. Finite modeling analysis of gait has identified that reduction in stiffness caused increased midfoot pronation (Cheung et al., 2004). Furthermore, plantar fasciitis symptomatic individuals present with decreased PF stiffness (Baur et al., 2021), suggesting further injury risk due to altered gait mechanics associated with the decrease in stiffness (Cheung et al., 2004). In asymptomatic individuals, a decrease in PF stiffness coincided with a decrease in arch height (Shiotani et al., 2020), indicative of a similar effect on gait mechanics as in injured individuals. A reduction in PF stiffness reduces the tension along the medial longitudinal arch and changes the mechanical function of the Windlass Mechanism, increasing mechanical load and stress to the plantar aspect of the foot (Cheung et al., 2004). The relationship between the relative change in PF stiffness and arch height index in the present study aligns with the secondary hypothesis, suggesting that PF stiffness plays an integral role in the support of the foot during mechanical loading.

The present findings should be interpreted with the following limitations in mind. The analysis included individuals without history of plantar fasciitis only. Differences in PF thickness and stiffness have been identified in individuals with plantar fasciitis compared to asymptomatic individuals (Irving et al., 2006). However, the response of PF tissue properties to exercise in people with current and with resolved plantar fasciitis remains undocumented. Further, participants were instructed to provide maximal effort, yet effort was subjective and the desire to end the exercise protocol may have altered performance nearing the end of it.

Additionally, PF length was not assessed at any point throughout the data collection. Creep likely affected the length of the tissue (Purslow et al., 1998), alongside the changes found in thickness.

Conclusion

PF thickness and stiffness showed significant changes in response to high intensity intervals in healthy individuals. Both properties decreased initially, yet recovered after 30 minutes of resting, aligning well with the expected viscoelastic tissue responses to cyclic mechanical loading. The running protocol also decreased arch height index, and a significant relationship was identified between PF stiffness and arch height index. These findings are reflective of both males and females, as there were no differences in thickness and stiffness between sexes. This warrants an investigation between relative and absolute impact loads regarding changes in PF tissue properties. Future research should focus on the repetitive nature of running as well as an increase in intensity and duration of the running, time to recover, and their effects on the PF over an extended period of time.

Conflict of Interest

There is no conflict of interest to be declared by the authors.

References

Baur, D., Schwabl, C., Kremser, C., Taljanovic, M. S., Widmann, G., Sconfienza, L. M., Sztankay, J., Feuchtner, G., & Klauser, A. S. (2021). Shear wave elastography of the plantar fascia: Comparison between patients with plantar fasciitis and healthy control subjects. *Journal of Clinical Medicine*, *10*(11), 2351.

Buchbinder, R. (2004). Plantar fasciitis. *New England Journal of Medicine*, *350*(21), 2159-2166.

Butler, R. J., Hillstrom, H., Song, J., Richards, C. J., & Davis, I. S. (2008). Arch height index measurement system: establishment of reliability and normative values. *Journal of the American Podiatric Medical Association*, *98*(2), 102-106.

Cheng, H. Y. K., Lin, C. L., Wang, H. W., & Chou, S. W. (2008). Finite element analysis of plantar fascia under stretch—the relative contribution of windlass mechanism and Achilles tendon force. *Journal of Biomechanics*, *41*(9), 1937-1944.

Cheung, J. T. M., Zhang, M., & An, K. N. (2004). Effects of plantar fascia stiffness on the biomechanical responses of the ankle–foot complex. *Clinical Biomechanics*, *19*(8), 839-846.

Crary, J. L., Hollis, J. M., & Manoli, A. (2003). The effect of plantar fascia release on strain in the spring and long plantar ligaments. *Foot & Ankle International*, *24*(3), 245-250.

Frost, H. M. (1990). Skeletal structural adaptations to mechanical usage (SATMU): 4. Mechanical influences on intact fibrous tissues. *The Anatomical Record*, *226*(4), 433-439.

Gibbon, W. W., & Long, G. (1999). Ultrasound of the plantar aponeurosis (fascia). *Skeletal Radiology*, *28*, 21-26.

Irving, D. B., Cook, J. L., & Menz, H. B. (2006). Factors associated with chronic plantar heel pain: A systematic review. *Journal of Science and Medicine in Sport*, *9*(1-2), 11-22.

Jariwala, A., Bruce, D., & Jain, A. (2011). A guide to the recognition and treatment of plantar fasciitis. *Primary Health Care*, *21*(7).

Lavagnino, M., Bedi, A., Walsh, C. P., Sibilsky Enselman, E. R., Sheibani-Rad, S., & Arnoczky, S. P. (2014). Tendon contraction after cyclic elongation is an age-dependent phenomenon: in vitro and in vivo comparisons. *The American Journal of Sports Medicine*, *42*(6), 1471-1477.

League, A. C. (2008). Current concepts review: plantar fasciitis. *Foot & Ankle International*, *29*(3), 358-366.

Lin, S. C., Chen, C. P. C., Tang, S. F. T., Chen, C. W., Wang, J. J., Hsu, C. C., Hsieh J. S., & Chen, W. P. (2014). Stress distribution within the plantar aponeurosis during walking — a dynamic finite element analysis. *Journal of Mechanics in Medicine and Biology*, *14*(04), 1450053.

Morin, J. B., Dupuy, J., & Samozino, P. (2011). Performance and fatigue during repeated sprints: what is the appropriate sprint dose?. *The Journal of Strength & Conditioning Research*, *25*(7), 1918-1924.

Pavan, P. G., Stecco, C., Darwish, S., Natali, A. N., & De Caro, R. (2011). Investigation of the mechanical properties of the plantar aponeurosis. *Surgical and Radiologic Anatomy*, *33*, 905-911.

Purslow, P. P., Wess, T. J., & Hukins, D. W. (1998). Collagen orientation and molecular spacing during creep and stress-relaxation in soft connective tissues. *The Journal of Experimental Biology*, *201*(1), 135-142.

Schillizzi, G., Alviti, F., D’Ercole, C., Elia, D., Agostini, F., Mangone, M., Paoloni, M., Bernetti, A., Pacini, P., Polti, G., Minafra, P., & Cantisani, V. (2021). Evaluation of plantar fasciopathy shear wave elastography: A comparison between patients and healthy subjects. *Journal of Ultrasound*, *24*, 417-422.

Shiotani, H., Mizokuchi, T., Yamashita, R., Naito, M., & Kawakami, Y. (2020). Acute effects of long-distance running on mechanical and morphological properties of the human plantar fascia. *Scandinavian Journal of Medicine & Science in Sports*, *30*(8), 1360-1368.

Skovdal Rathleff, M., Moelgaard, C., & Lykkegaard Olesen, J. (2011). Intra-and interobserver reliability of quantitative ultrasound measurement of the plantar fascia. *Journal of Clinical Ultrasound*, *39*(3), 128-134.

Stecco, C., Corradin, M., Macchi, V., Morra, A., Porzionato, A., Biz, C., & De Caro, R. (2013). Plantar fascia anatomy and its relationship with Achilles tendon and paratenon. *Journal of Anatomy*, *223*(6), 665-676.

Swedberg, A. M., Reese, S. P., Maas, S. A., Ellis, B. J., & Weiss, J. A. (2014). Continuum description of the Poisson′ s ratio of ligament and tendon under finite deformation. *Journal of Biomechanics*, *47*(12), 3201-3209.

Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., & Zumbo, B. D. (2002). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine*, *36*(2), 95-101.

Tsai, W. C., Chiu, M. F., Wang, C. L., Tang, F. T., & Wong, M. K. (2000). Ultrasound evaluation of plantar fasciitis. *Scandinavian Journal of Rheumatology*, *29*(4), 255-259.

Wang, H. Q., Wei, Y. Y., Wu, Z. X., & Luo, Z. J. (2009). Impact of leg lengthening on viscoelastic properties of the deep fascia. *BMC Musculoskeletal Disorders*, *10*, 1-6.

Wang, Y., Wong, D. W. C., & Zhang, M. (2016). Computational models of the foot and ankle for pathomechanics and clinical applications: A review. *Annals of Biomedical Engineering*, *44*, 213-221.

Welk, A. B., Haun, D. W., Clark, T. B., & Kettner, N. W. (2015). Use of high-resolution ultrasound to measure changes in plantar fascia thickness resulting from tissue creep in runners and walkers. *Journal of Manipulative and Physiological Therapeutics*, *38*(1), 81-85.

Wren, T. A., Lindsey, D. P., Beaupré, G. S., & Carter, D. R. (2003). Effects of creep and cyclic loading on the mechanical properties and failure of human Achilles tendons. *Annals of Biomedical Engineering*, *31*(6), 710–717.

Wu, C. H., Chang, K. V., Mio, S., Chen, W. S., & Wang, T. G. (2011). Sonoelastography of the plantar fascia. *Radiology*, *259*(2), 502-507.

Young, C. (2012). Plantar fasciitis. *Annals of Internal Medicine*, *156*(1), ITC1-1.

Zhang, J., Nie, D., Rocha, J. L., Hogan, M. V., & Wang, J. H. (2018). Characterization of the structure, cells, and cellular mechanobiological response of human plantar fascia. *Journal of Tissue Engineering*, *9*, 1-16.

Chapter 3

Morphological and Mechanical Properties of the Plantar Fascia in Response to Imposed Running Demands over Three Consecutive Days

By

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Significance of the Chapter

The plantar fascia (PF) exhibits viscoelastic biomechanical properties such as stress-relaxation, hysteresis, and creep under isolated conditions with cadaveric tissue. In-vivo, research has shown that the PF exhibits creep during exercise, as the tissue exhibits continuous stress which leads to lengthening and thinning (Welk et al., 2015). After exercise, as demonstrated in Chapter Two's interval run, the PF has lost significant thickness and stiffness in healthy individuals (Shiotani et al., 2020). It is hypothesized that the thinning of the PF makes the tissue more susceptible to microfractures. Insufficient rest, or progressive overloading of the PF may cause these microfractures to persist, cause inflammation, and potentially lead to plantar fasciitis. Additionally, the decrease in stiffness may affect the structure of the medial longitudinal arch, as well as the support thereof.

Chapter 2 indicated that arch height decreases significantly after a bout of running, coinciding with the decrease in PF stiffness. Nevertheless, the changes in the tissue disappeared with a short rest period, suggesting that these properties require continuous overloading to forego sufficient recovery. In theory, the decrease in thickness, stiffness, and arch height are the main contributors to the development of a PF injury. However, this theory has not been evidenced in the literature. There is a gap in understanding the mechanistic etiology of PF injuries. The significance of this chapter is to expand the knowledge of the potential relationship of tissue creep in the PF and a decrease in thickness. Furthermore, does the decrease in stiffness introduce a mechanical fatigue effect altering the medial longitudinal arch. Therefore, the aim of this study was to evaluate the effects of maximal effort 5 km runs on three consecutive days on mechanical and morphological properties of the PF. The intent was to provide an overload to the tissue at a relatively high intensity, reduce recovery time, and repeat the load stimulus to identify the ability of the tissue to return to the original properties.

Abstract

Objective: To investigate the effects of consecutive day 5 km maximal effort run on morphological mechanical properties of the plantar fascia (PF) in healthy, active individuals.

Materials and Methods: Sixteen recreational runners, with a mean running distance of 22.4 kilometers (± 8.9) in the last month completed the protocol consisting of three 5 km maximal effort runs separated by 24 hours, with ultrasound imaging of the PF before, after, and 30 minutes after each run. Arch height index was evaluated before and after each run. Outcome measures were PF thickness, stiffness, and arch height index. Multiple two-way (3 session x 3 measurement) repeated measures ANOVAs were used to evaluate the effect of session and measurement on PF properties.

Results: PF thickness and stiffness decreased from pre- to post-run during session 1 (3.19 to 2.98 mm, $p = 0.008$, $d = 0.90$), session 2 (3.34 to 3.04 mm, $p = 0.041$, $d = 0.76$), and session 3 (3.52 to 3.04 mm, $p < 0.001$, d = 1.33), yet returned to baseline values after 30 minutes of recovery ($p > 0.05$). PF thickness at the pre-run measurement increased between session 1 and session 2 (3.19 to 3.34 mm, $p = 0.003$, $d = 1.12$), and between session 1 and session 3 (3.19 to 3.52 mm, $p = 0.003$, $d = 1.8$). While arch height also decreased after each run, PF stiffness and arch height did not change between session.

Conclusion: The increase in PF thickness following session 1 may indicate the importance of adequate recovery time between high intensity runs in response to repeated mechanical loading to allow the appropriate inflammatory response in healthy tissue. This finding may inform running programs to emphasize rest days and consider low intensity runs to avoid further damage to the PF.

Highlights

- PF thickness and stiffness decrease after each of three 5 km running bouts.
- Pre-run PF thickness increased progressively from session 1 to session 3.
- Evidence of PF tissue change may inform training programs.

Introduction

The plantar fascia (PF) provides vital structural support to the foot and the medial longitudinal arch during locomotion. During the stance phase of the gait cycle, the PF prevents the arch from excessive eversion and collapse by lengthening during weight-bearing, and then recoiling after removal of the applied load [1]. The viscoelastic properties of the tissue allow absorption of the applied forces and assist with minimizing changes in arch height throughout the gait cycle [2]. However, this functionality makes the PF susceptible to overloading if continuous stress is applied and recovery is insufficient to retain its viscoelastic properties. Thus, PF injuries are amongst the most identified ankle and foot pathologies in runners [3]. These injuries are primarily located at the origin near the calcaneal tuberosity, which is the most proximal site [4]. Plantar fasciitis is the most diagnosed of all heel pain related injuries [5]. It accounts for up to 15% of all foot related symptoms [6]. While the underlying mechanisms of developing plantar fasciitis are still widely unknown, the morphological and mechanical properties of the tissue are theorized to be key etiological factors [7].

Thickness and stiffness can be evaluated via ultrasonographic imaging. Increased PF thickness is one of the most common symptoms of PF related injuries, such as plantar fasciitis [8,9]. PF thickness of asymptomatic individuals generally ranges from 2-4 mm [6]. Individuals diagnosed with plantar fasciitis show a thickness of 4-7 mm and generally indicate sharp pain around heel region [6]. However, knowledge is limited on the progression of PF thickness prior to the diagnosis of plantar fasciitis, and on the effect of continuous mechanical loading in form of running on the PF in asymptomatic individuals. Asymptomatic runners have demonstrated changes in PF that lead to a non-significant decreased thickness following exercise [10,11]. Asymptomatic runners PF recovered as quickly as 30 minutes following cessation of exercise [10]. While thickness has been a frequently utilized property to determine injury status, it remains unclear whether PF morphology in asymptomatic runners progressively changes until pain or injury occurs.

PF stiffness can be evaluated via shear-wave elastography and may provide essential information regarding the structural support the PF can provide to the foot and the medial longitudinal arch [12]. Individuals with plantar fasciitis show a significantly lower PF stiffness to their healthy counterparts [13, 14]. Furthermore, continuous long-distance running induced a significant decrease in PF stiffness, accompanied by a decrease in medial longitudinal arch height [10]. This suggests a potential connection between PF stiffness and its capacity to prevent the foot from overpronation or eversion. A decrease in PF stiffness may induce excess strain to the fascia during exercises such as running, increasing mechanical overload and the possibility of micro tears resulting in plantar fasciitis [15]. While decreased PF stiffness has been identified as a symptom of plantar fasciitis, it is currently unknown whether this mechanical property exhibits a pattern of decline under overloading conditions which may eventually lead to injury.

Therefore, the purpose of the present study was to investigate the effects of maximal effort 5 km running on three consecutive days on morphological and mechanical properties of the plantar fascia. It was hypothesized that (1) high intensity distance running will decrease plantar fascia thickness and stiffness acutely as measured immediately after completion, (2) consecutive days of high intensity distance running will increase resting plantar fascia thickness and decrease stiffness, and (3) any relative changes in PF stiffness predict relative changes in arch height index between pre- and post-run, and between days of measurements.

Material and Methods

Participants

Sixteen healthy individuals participated in the present study (9 Females, 7 Males; Age: 28.6 yrs (± 8.9), Height: 171.6 cm (± 7.5), Mass: 66.3 kg (± 8.7)). All participants were considered physically active by having participated in at least 30 minutes of exercise, three times per week, for the past three months [16]. Participants indicated a mean running distance of 22.4 kilometers (± 8.9) within the last month, with a low of 8 and a high of 43.5 kilometers. Participants were excluded if previously diagnosed with a PF injury or have experienced PF, plantar heel, Achilles' tendon, or general foot and ankle pain within the last two years. Additional exclusion criteria were existing diseases (cardiovascular disease, metabolic disease, renal disease), any history of lower-extremity injuries and surgeries within the past 6 months, current musculoskeletal injuries, wearing prescription inserts, and regular use of non-steroidal anti-inflammatory drugs (NSAIDs) or topical creams. This study was approved by the Institutional Human Research Ethics Committee and was carried out in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants before data collection.

Protocol

The present study was designed as a repeated measures quasi-experimental pre-test, post-test design. Participants were asked to refrain from additional physical activity, caffeine, and alcohol consumption for 24 hours prior to each run as well as throughout the days of data collection. Furthermore, participants were instructed to avoid non-steroidal anti-inflammatory drug consumption or topical cream application to the plantar aspect of their feet for the entire time of their enrollment. Participants reported to the university laboratory for three consecutive days (24 hour between sessions) and were asked to complete a maximal effort 5-km run an outdoor track per day. For the protocol, participants wore their own shoes and exercise clothing. However, no participant used a shoe that would be confounding to the data analysis, such as minimalist or maximalist shoes. Immediately pre-, and post-run, and after 30 minutes of recovery, plantar fascia thickness and stiffness measurements were taken via ultrasound, and arch height measurements were taken pre- and post-run. All measurements were taken on the right side of the participants, as research has shown no significant difference between sides in asymptomatic individuals [17]. During the 30 minutes of rest, participants remained on the treatment table and their feet did not have contact with the ground.

Ultrasound Measurements

Ultrasound imaging was used to evaluate morphological and mechanical properties of the PF (Logiq S8; GE Healthcare, Waukesha, WI, USA) with a linear array transducer (9L-D; GE). B-mode imaging provides the measurement of distances between anatomical landmarks (thickness), while shear wave elastography measures velocity of propagation (stiffness) by acoustic push pulses sent through soft tissue. All ultrasound measures were taken by a single researcher. Ultrasound measures were taken with the participant in a prone position on a treatment table. Their lower limbs were in full extension with bare feet over the edge of the table so that their feet and ankles were in a relaxed position. The proximal site of the PF near the calcaneal tuberosity was manually palpated and marked with a waterproof marker prior taking the measurements [18]. Ultrasound gel was applied to the transducer to increase conductivity between the foot and transducer during measurement along the longitudinal orientation of the PF. All images were taken at 12 Hz (default sampling rate), a gain of 50 (to optimize brightness), and a depth of 4 cm (to capture the appropriate tissue). PF thickness was measured via B-mode live images (5 seconds per image). The middle three images of five captured were used for analysis. Plantar fascia stiffness was measured with shear wave elastography. A region of interest box with a size of approximately 0.1 mm^2 was placed manually over the measurement site to indicate the measurement area. Three color images were taken of the measurement area and analyzed for thickness and stiffness. All analyses were completed by the same researcher that collected all US images.

Arch Height Index

Arch height index was collected before and after each 5km run. Participants sat on an individually adjustable chair with 90-degree knee flexion, and full ground contact of the feet [19]. A measurement tape was used to record the following foot dimensions: foot length, truncated foot length, and dorsum height at 50% of foot length [19]. After measurements were recorded, arch height index, a unitless value, was calculated with the following equation:

$$Arch\ Height\ Index = \frac{Dorsum\ Height\ at\ 50\%\ of\ Foot\ Length}{Truncated\ \ Foot\ Length}$$

5km Run

Participants performed a maximal effort 5km run each day for three consecutive days, totaling three 5km runs within a 72-hour period. Each run was completed on a standard 400-meter loop outdoor track and conducted in the same direction (counter-clockwise) and at the same time of day for each participant. All participants were able to complete the run maximally without having to break into a walk or take a break altogether. Verbal encouragement was provided during each lap.

Statistical Analysis

The present study was designed to be a within-subjects design, comparing variables across multiple timepoints and trials. Dependent variables (PF thickness and stiffness) were analyzed using multiple two-way (3 session x 3 measurement) repeated measures analyses of variance (ANOVA) to evaluate the effect of repeated running bouts (sessions: day 1, 2, and 3), and individual running bouts (measurement: pre, post, 30 min post run) on plantar fascia thickness and stiffness. If an interaction between these factors was found, one-way repeated measure ANOVAs were performed for session and measurement separately. *Post-hoc* analysis with Bonferroni adjustments were made for pairwise comparisons. Effect sizes were calculated as partial η^2 (η_p^2) for the ANOVA and Cohen's *d* for the post-hoc analyses. Arch height measurements were analyzed with dependent t-tests to evaluate potential changes in arch height pre- and post-run and between sessions, and linear regression analyses to determine the predictability of relative change of PF properties. To demonstrate reasonableness of fit, standard error (SE) and R^2 values were calculated. To analyze PF thickness, the distance between the deep and superficial boundaries at the calcaneal origin was measured (mm) using the ultrasound measurement functionality (Figure 1). To analyze PF stiffness, the mean shear wave velocity of the region of interest was used (m/s) (Figure 2). Measurements were taken on the right foot and for both properties, the mean of three images was taken to obtain a single value representing the data. A priori alpha level was set to 0.05. Statistical analyses were performed using IBM SPSS Statistics v.28.

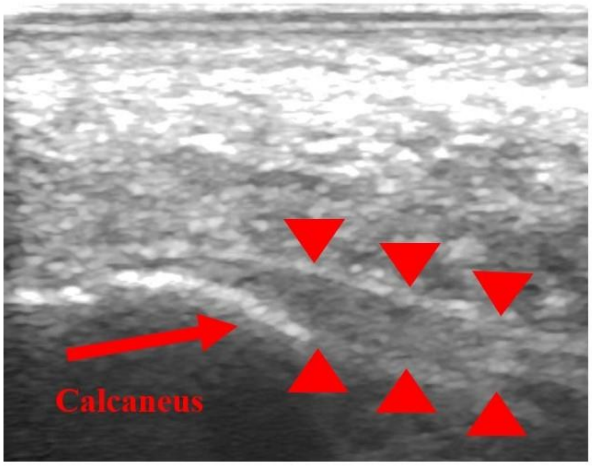

Figure 1. Representation of a B-mode ultrasound image to measure PF thickness at the proximal site.

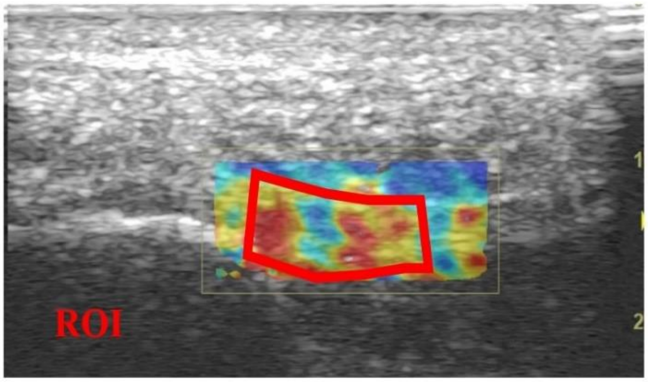

Figure 2. Representation of a shear wave elastography ultrasound image to measure PF stiffness at the proximal site.

Results

Run times and speeds did not differ significantly between days. Mean run times for runs 1, 2, and 3 were 28:35, 28:07, and 28:47 minutes, respectively. Mean run speed for runs 1, 2, and 3 were 3.38, 3.42, and 3.36 m/s, respectively.

An interaction was found for PF thickness between sessions and measurements ($F(4, 60) = 4.41$, $p = 0.004$, $\eta_p^2 = 0.25$). Therefore, simple main effects were run. PF thickness had significant main effect differences across measurements at session 1 ($F(2,30) = 19.46$, $p < 0.001$, $\eta_p^2 = 0.60$), session 2 ($F(2,30) = 9.20$, $p < 0.001$, $\eta_p^2 = 0.42$), and session 3 ($F(2,30) = 22.60$, $p < 0.001$, $\eta_p^2 = 0.64$). Pairwise comparisons revealed a significant decrease in PF thickness between pre-run and post-run measurements at session 1 (3.19 to 2.98 mm, $p = 0.008$, d = 0.90), session 2 (3.34 to 3.04 mm, $p = 0.041$, d = 0.76), and session 3 (3.52 to 3.04 mm, $p < 0.001$, d = 1.33). Thickness significantly increased between the post-run and 30-minutes post exercise measurements at session 1 (2.98 to 3.31, $p < 0.001$, d = 1.73), session 2 (3.04 to 3.37, $p < 0.001$, d = 1.31), and session 3 (3.04 to 3.45 mm, $p < 0.001$, d = 1.84). PF thickness had a significant main effect across sessions at the pre-run measurement only ($F(2,30) = 11.37$, $p < 0.001$, $\eta_p^2 = 0.47$). Pairwise comparisons revealed a significant increase in PF thickness at the pre-run measurement between session 1 and session 2 (3.19 to 3.34 mm, $p = 0.003$, d = 1.12), and between session 1 and session 3 (3.19 to 3.52 mm, $p = 0.003$, d = 1.8). There was no significant main effect across sessions at the post-run ($F(2,30) = 0.86$, $p = 0.44$, $\eta_p^2 = 0.06$) and the 30 minutes post-run measurement ($F(2,30) = 3.11$, $p = 0.06$, $\eta_p^2 =$

0.19). Figure 3 displays mean PF thickness as a function of measurement, Figure 4 displays mean PF thickness as a function of session.

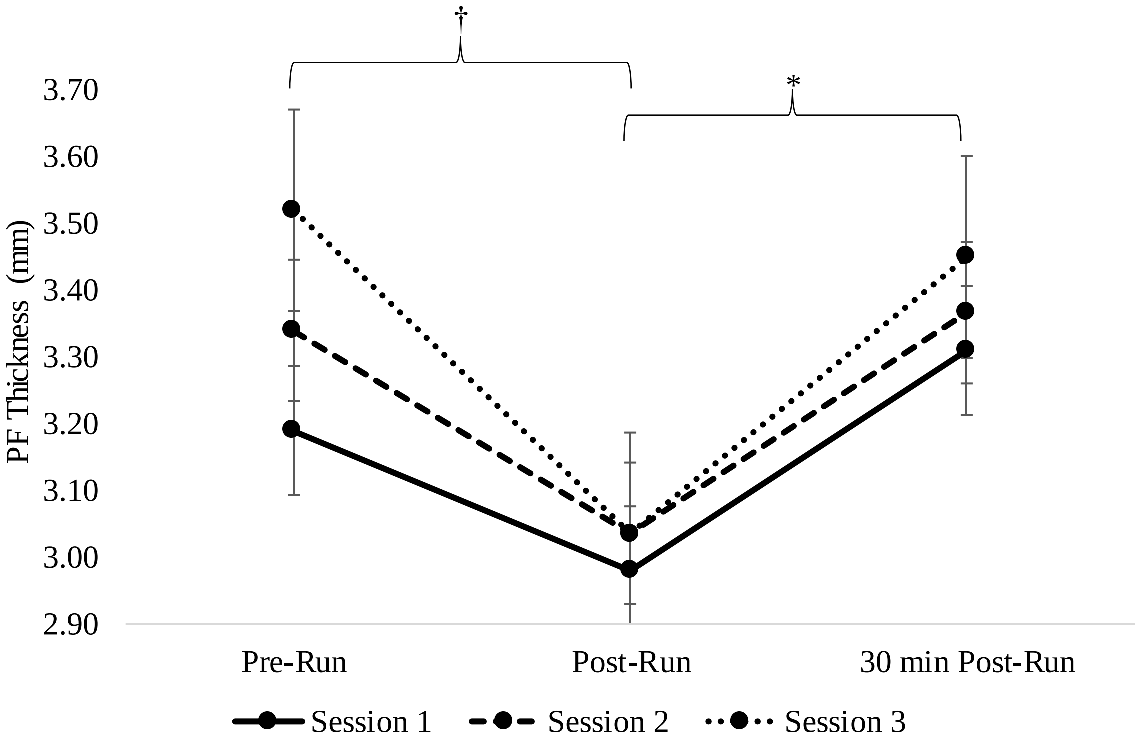

Figure 3. Mean plantar fascia thickness (mm) values at each measurement (pre-run, post-run, 30 min post run) separated by session. † Denotes a significant decrease in PF thickness between pre-run and post-run for all session 1 (*p* = 0.008), session 2 (*p* = 0.041), and session 3 (*p* < 0.001). * Denotes a significant increase in PF thickness between post-run and 30-minute post-run for all three sessions (*p* < 0.001).

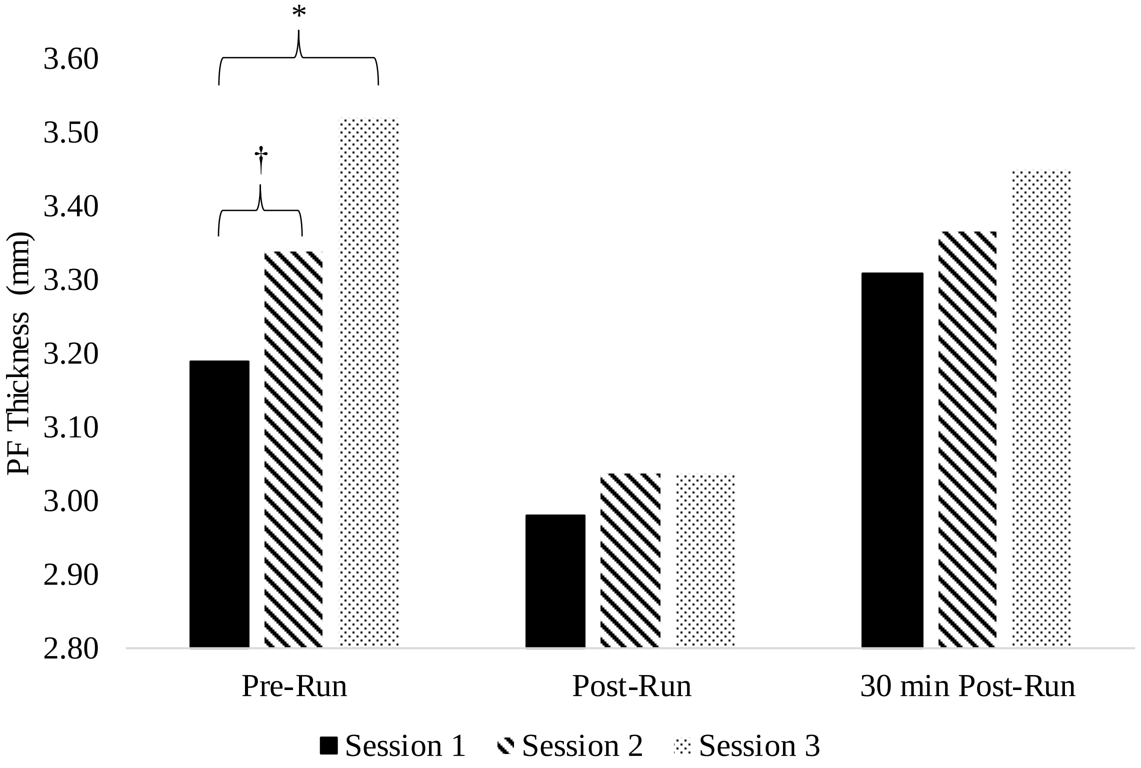

Figure 4. Mean plantar fascia thickness (mm) values at each session (1, 2, and 3) separated by run. † Denotes a significant increase in PF thickness between session 1 and 2 (*p* = 0.003) at the pre-run measurement. * Denotes a significant increase in PF thickness between session 1 and 3 (*p* = 0.003) at the pre-run measurement.

There was an interaction for PF stiffness between sessions and measurements ($F(4, 60) = 3.44$, $p = 0.014$, $\eta_p^2 = 0.21$). Therefore, simple main effects were run. PF stiffness had significant main effect differences across measurements at session 1 ($F(2,30) = 12.65$, $p < 0.001$, $\eta_p^2 = 0.49$), session 2 ($F(2,30) = 19.805$, $p < 0.001$, $\eta_p^2 = 0.60$), and session 3 ($F(2,30) = 15.53$, $p < 0.001$, $\eta_p^2 = 0.54$). Pairwise comparisons revealed a significant decrease in PF stiffness between pre- and post-run measurements at session 1 (4.64 to 3.27 m/s, $p = 0.002$, d = 1.20), session 2 (3.99 to 3.02 m/s, $p = 0.001$, d = 1.28), and session 3 (4.16 to 2.90 m/s, $p = 0.001$, d = 1.25). No significant change in PF stiffness was found from post-run to 30-minute post run measurements at session 1 (3.27 to 3.60 m/s, $p = 0.76$). However, PF stiffness significantly increased at session 2 (3.02 to 4.08 m/s, $p < 0.001$, d = 1.61), and session 3 (2.90 to 4.03, $p = 0.002$, d = 1.16). PF stiffness had a significant main effect across sessions at the pre-run ($F(2,30) = 3.39$, $p = 0.049$, $\eta_p^2 = 0.21$), and the 30 minutes post-run measurements ($F(2,30) = 3.45$, $p = 0.047$, $\eta_p^2 = 0.21$), yet not for the post-run measurements ($F(2,30) = 0.81$, $p = 0.46$, $\eta_p^2 = 0.06$). Pairwise comparisons revealed no significant differences between sessions 1, 2, and 3 at the pre-run (4.64, 4.00, 4.16 m/s; $p = 0.13$) and 30 minutes post-run measurements (3.59, 4.08, 4.03 m/s; $p = 0.42$). Figure 5 displays mean PF stiffness as a function of measurement.

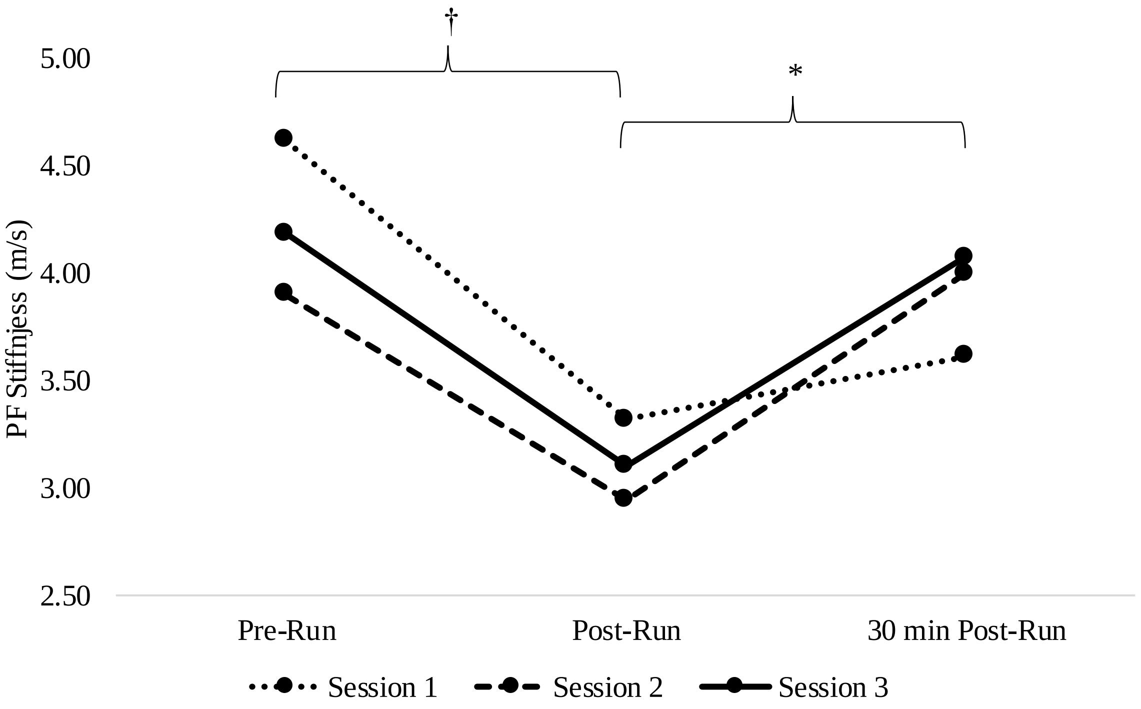

Figure 5. Mean plantar fascia stiffness (m/s) values at each measurement (pre-run, post-run, 30 min post run) separated by session. † Denotes a significant decrease in PF stiffness between pre-run and post-run for all three sessions ($p < 0.003$). * Denotes a significant increase in PF thickness between post-run and 30-minute post-run for sessions 2 ($p < 0.001$) and 3 ($p = 0.002$) only.

Paired-samples t-test analyses revealed a significant decrease in arch height index from pre-to post-run at sessions 1 (0.417 to 0.399, $p < 0.001$, d = 1.8), 2 (0.416 to 0.398, $p < 0.001$, d = 2.1), and 3 (0.417 to 0.400, $p < 0.001$, d = 1.8). There was no change in arch height index between sessions. Linear regression analyses failed to show a significant relationship between relative change of arch height index and relative change of PF thickness, and stiffness between pre- and post-run measurements at session 1 ($p = 0.35$, $R^2 = 0.07$, SE = 18.3), session 2 ($p = 0.48$, $R^2 = 0.04$, SE = 13.5), session 3 ($p = 0.39$, $R^2 = 0.06$, SE = 23.4). The decrease in arch height index did not explain the decrease in morphological and mechanical properties at any session or measurement.

Discussion

This study looked to examine the effects of repeated bouts of high intensity running across consecutive days on morphological and mechanical properties of the PF. The main findings were PF thickness and stiffness decreased between pre-exercise and post-run; and PF thickness increased across sessions (1-3) at the pre-exercise measurement. These findings align with the initial hypothesis of the present study regarding PF thickness yet are partially accepted for PF stiffness. The PF is known to exhibit viscoelastic behavior under mechanical loading which can be interpreted as acute changes within the tissue. Following the 30-minute rest period of each run the acute effects of running on PF properties returned to baseline. The viscoelastic response is similar to the recovery following a 10-km one hour run [10]. However, part of the hypothesis must be rejected as PF stiffness did not increase as the running session progressed.

The decrease in PF thickness and stiffness immediately post-run was expected [10,11]. The repetitive nature of the runs produced continuous mechanical loading which may have induced the PF tissue to creep [20,21]. This creep mechanism likely caused the thinning of the tissue due to continuous repetitive tensile loading during the running session. The consequent increase in thickness 30 minutes after cessation of running suggests the occurrence of hysteresis, which has been documented in asymptomatic PF tissue [22]. While the PF appears to operate within the elastic region of its stress and strain curve throughout each of the three runs, the increase in thickness from day 1 to day 3 suggests an acute deformational change within the tissue. This discrepancy requires further investigation of in vivo PF properties in response to continued mechanical loading. The mechanical loading response of the PF appears to be similar to other fascia tissues (e.g. fascia lata) and was found to experience failure level with increasing strain over time [23]. While the present study did not experience failure level, the increased thickness at the initial session each day is reflective of deformation caused by the repetitive loading and lack of recovery from the previous session. An increased deformation over time may exceed the PF’s ability to withstand stress, yet that the PF has the ability to experience stress-relaxation under consistent strain [23]. Therefore, the increased PF thickness across sessions may be reflective of the increasing amount of strain to the tissue without sufficient recovery time and strategies. However, future studies are needed to solidify this theory with in-vivo studies.

Another theory regarding the increase in PF thickness relates to morphology of the tissue. The PF is a fibrous tissue made up of hyaluronan, a glycosaminoglycan widely distributed in connective tissue. The hyaluronan makes the PF sensitive to inflammation, as accumulation thereof increases inflammation in soft tissues [24,25]. The tissue creep compensation suggests that repetitive loading would lead to a thinning of the PF immediately post-exercise, followed by an inflammatory reparative process [26]. However, this process of inflammation in the PF of asymptomatic individuals has not been described in the literature thus far and the degree of inflammation was outside the scope of the present study and factors such as echogenicity were not evaluated. Nevertheless, the increase in PF thickness identifies a need for running training programs to implement adequate recovery time to allow PF property recovery.

While the decreased PF stiffness immediately post-run was an expected outcome, the hypothesis regarding a progressive decrease in stiffness is rejected as PF stiffness did not change across sessions. A decrease in PF stiffness has been linked to an increased risk of mechanical overload, overpronation, and the possibility of micro tears resulting in plantar fasciitis as a result of excessive strain [15]. Individuals diagnosed with plantar fasciitis present with decreased PF stiffness [27], leading to altered foot mechanics, which can ultimately lead to injury [15]. However, the present study did not evaluate gait mechanics and any implications regarding altered running mechanics should be stated with caution. Arch height index also decreased after each run yet had no change across sessions. While the mechanical fatigue induced by the 5k intensity induced acute changes to PF stiffness and arch height, the linear regression analyses failed to display a significant relationship between relative changes of arch height and PF stiffness, which means the initial hypothesis must be rejected. Thus, it remains unclear whether PF properties and changes in arch height, and potential gait mechanics adaptations are connected.

Although pain was not evaluated in the present study, participants stated that they did not experience any pain at the proximal site of the PF. As a healthy PF has a relative thickness of 2 to 4 mm, it is likely that any inflammatory effects to the PF were insufficient to elicit a pain receptor response and recovered after finishing the protocol of the present study. No participant experienced a tissue thickness exceeding 4 mm, a threshold used in plantar fasciitis patients [6]. These thickness values align with previous findings [10]. The increase in PF thickness across sessions warrants further investigation in the number of repetitive days needed to cross said thickness threshold, and if said threshold coincides with occurrence of pain.

The findings of the present study should be interpreted with the following limitations in mind. First, participants were instructed to provide maximal effort during the 5 km runs. However, effort was subjective and the monotony of circling a 400 m track may have altered performance, specifically nearing the end of each session. Additionally, participants wore their own shoes in the present study, which may have contributed to different responses to the tissue based on footwear. Yet, all participants wore shoes that would not be categorized as either minimalist or extreme cushioning variants. While not specifically evaluated in the present study, participants did not experience any discomfort with the morphological and mechanical changes of the plantar fascia. Thus, it cannot be determined whether the increase in PF thickness from across sessions was an adaptive or degenerative response. Lastly, while the exercise protocol induced changes to the tissue, the duration of the protocol may have been too short to bring about more impactful changes to the tissue leading to injury. A continuation of the protocol to consistently overload the PF with minimal recovery may provide further insight whether the tissue changes could be utilized as means to monitor individuals prior to injury. Future studies may address this by evaluating tissue changes following increasingly numerous bouts of running or exercising across multiple days. The increase in PF thickness across three days may be a first indicator of the predictability of PF injuries. However, it remains unclear whether morphological and mechanical properties can be used as predictors as no PF injury occurred in the present study, and no long-term injury tracking was conducted.

Conclusions

The present study showed that the PF exhibits viscoelastic behavior in response to maximal effort 5km running by displaying a decrease in thickness and stiffness immediately after the cessation of the exercise. A 30-minute recovery period was sufficient to return both properties to baseline values, suggesting that any conformational changes are acute. However, the increase in PF thickness from session 1 to session 3 at the pre-run measurements may indicate a first sign toward tissue deterioration in form of accumulated PF inflammation. The change in PF stiffness and arch height immediately after each run suggests mechanical fatigue of the foot after each run; however, there is no progressive change in PF stiffness throughout the sessions.

References

[1] Kim W, Voloshin AS. Role of plantar fascia in the load bearing capacity of the human foot. J Biomech 1995;28(9):1025-33. doi:10.1016/0021-9290(94)00163-x.

[2] Pavan PG, Stecco C, Darwish S, Natali AN, De Caro R. Investigation of the mechanical properties of the plantar aponeurosis. Surg Radiol Anat 2011;33(10):905-11. doi:10.1007/s00276-011-0873-z.

[3] Tenforde AS, Yin A, Hunt KJ. Foot and ankle injuries in runners. Phys Med Rehabilit Clin 2016;27(1):121-37. doi:10.1016/j.pmr.2015.08.007.

[4] Chen YN, Chang CW, Li CT, Chang CH, Lin CF. Finite element analysis of plantar fascia during walking: a quasi-static simulation. Foot Ankle Int 2015;36(1):90-7. doi:10.1177/1071100714549189.

[5] Barrett, SL, O'Malley R. Plantar fasciitis and other causes of heel pain. Am Fam Physician 1999;59(8):2200.

[6] Buchbinder R. Plantar fasciitis. N Eng J Med 2004;350(21):2159-66.

[7] Wang HQ, Wei YY, Wu ZX, Luo ZJ. Impact of leg lengthening on viscoelastic properties of the deep fascia. BMC Musculoskelet Disord 2009;10(1):105. doi10.1186/1471-2474-10-105

[8] Gibbon WW, Long G. Ultrasound of the plantar aponeurosis (fascia). Skelet Radiol 1999;28(1):21-6. doi:10.1007/s002560050467

[9] Tsai WC, Chiu MF, Wang CL, Tang FT, Wong MK. Ultrasound evaluation of plantar fasciitis. Scand J Rheumatol 2000;29(4): 255-9. doi:10.1080/030097400750041415

[10] Shiotani H, Mizokuchi T, Yamashita R, Naito M, Kawakami Y. Acute effects of long-distance running on mechanical and morphological properties of the human plantar fascia. Scand J Med Sci Sports 2020;30(8):1360-8. doi:10.1111/sms.13690

[11] Welk AB, Haun DW, Clark TB, Kettner NW. Use of high-resolution ultrasound to measure changes in plantar fascia thickness resulting from tissue creep in runners and walkers. J Manip Physiol Ther 2015;38(1):81-5. doi:10.1016/j.jmpt.2014.10.008

[12] Gatz M, Bejder L, Quack V, Schrading S, Dirrichs T, Tingart M, et al. Shear wave elastography (SWE) for the evaluation of patients with plantar fasciitis. Acad Radiol 2020;27(3):363-70. doi:10.1016/j.acra.2019.04.009

[13] Baur D, Schwabl C, Kremser C, Taljanovic MS, Widmann G, Sconfienza LM, et al. Shear wave elastography of the plantar fascia: Comparison between patients with plantar fasciitis and healthy control subjects. J Clin Med 2021;10(11):2351. doi:10.3390/jcm10112351

[14] Schillizzi G, Alviti F, D'Ercole C, Elia D, Agostini F, Mangone M, et al. Evaluation of plantar fasciopathy shear wave elastography: A comparison between patients and healthy subjects. J Ultrasound 2021;24(4):417-22. doi:10.1007/s40477-020-00474-7

[15] Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD. A retrospective case-control analysis of 2002 running injuries. Br J Sports Med 2002;36(2):95-101. doi:10.1136/bjsm.36.2.95

[16] Haskell WL, Lee IM, Pate RR, Powell KE, Blair SN, Franklin BA, et al. Physical Activity and public health: updated recommendation for adults from the American College of Sports Medicine. Med Sci Sports Exerc 2007;39(8):1423-34. doi:10.1249/mss.0b013e3180616b27

[17] Abul K, Ozer D, Sakizlioglu SS, Buyuk AF, Kaygusuz MA. Detection of normal plantar fascia thickness in adults via the ultrasonographic method. J Am Podiat Med Assoc 2015;105(1):8-13.

[18] Jariwala A, Bruce D, Jain A. A guide to the recognition and treatment of plantar fasciitis. Prim Health Care, 2011;21(7):22-4. doi:10.7748/phc2011.09.21.7.22.c8687

[19] Butler RJ, Hillstrom H, Song J, Richards CJ, Davis IS. Arch height index measurement system: establishment of reliability and normative values. J Am Podiatr Med Assoc 2008;98(2):102-6. doi:10.7547/0980102

[20] Solomonow M. Neuromuscular manifestations of viscoelastic tissue degradation following high and low risk repetitive lumbar flexion. J Electromyogr Kinesiol 2012;22:155-75.

[21] Maganaris CN. Tensile properties of in vivo human tendinous tissue. J Biomech 2002;35:1019-27.

[22] Crary JL, Hollis, JM, Manoli, A. The Effect of Plantar Fascia Release on Strain in the Spring and Long Plantar Ligaments. Foot Ankle Int, 2003;24(3):245–250.

[23] Chaudhry H, Huang CY, Schleip R, Ji Z, Bukiet B, Findley T. Viscoelastic behavior of human fasciae under extension in manual therapy. J Bodyw Mov Ther 2007;11(2):159-67. doi:10.1016/j.jbmt.2006.08.012

[24] Hascall VC, Majors AK, De La Motte CA, Evanko SP, Wang A, Drazba JA, et al. Intracellular hyaluronan: a new frontier for inflammation? Biochim Biophys Acta-Gen Subj 2004;1673(1-2):3-12. doi:10.1016/s0304-4165(04)00068-6

[25] Petrey AC, de la Motte CA. Hyaluronan, a crucial regulator of inflammation. Front Immunol, 2014;5:101. doi:10.3389/fimmu.2014.00101

[26] Frost HM. Skeletal structural adaptations to mechanical usage (SATMU): Mechanical influences on intact fibrous tissues. Anat Rec, 1990;226(4):433-9.

[27] Wu CH, Chang KV, Mio S, Chen WS, Wang TG. Sonoelastography of the plantar fascia. Radiol, 2011;259(2):502-507.

Chapter 4

The Effects of a Submaximal Treadmill Run on Plantar Fascia Properties and Run Mechanics in Individuals with Resolved Plantar Fasciitis

By

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Significance of the Chapter

The plantar fascia has been shown to play an integral role in maintaining foot and arch control during the stance phase of the gait cycle. The results reported in chapter 2 and 3 showed that the plantar fascia significantly decreases in thickness and stiffness immediately after running but experiences quick recovery approximating pre-running values after 30 minutes of recovery. This was the case after a high intensity interval running bout until performance fatigue, as well as a 5km run repeated on three consecutive days. While there was an increase in thickness between day 1 and day 3 in study 2, values did not exceed what is generally identified as the 4 mm thickness threshold for increased injury risk (Buchbinder, 2004; Stecco et al., 2013).

Interestingly, there is possibility of an intensity threshold that could be surpassed to create an adaptation effect to the plantar fascia, making it more resistant to imposed demands (Shiotani et al., 2022). A population who may have crossed this intensity threshold without leading to adaptation of the tissue, but rather an injury, are individuals with resolved plantar fasciitis. However, at this point, it cannot be concluded that neither plantar thickness nor stiffness are known predictors of a future plantar fascia injury. The difference in thickness (injured tissue is thicker), and stiffness (injured tissue is less stiff) in symptomatic individuals compared to asymptomatic individuals may be a remaining symptom present after injury occurrence.

Thus, in order to provide further understanding of the behavior of the tissue and its role in the development of injury, evaluating the difference in plantar fascia response to mechanical loading of individuals with resolved plantar fasciitis and those without history of plantar fasciitis may provide important context. First, it is currently unknown whether plantar fascia tissue recovers in terms of its morphological and mechanical properties. Secondly, it is unknown whether the tissue of healthy and previously injured individuals respond differently to continuous running.

Therefore, the purpose of the proposed study was to investigate the a) effects of imposed treadmill running demands on plantar fascia thickness and stiffness, and b) identify potential differences in gait mechanics in individuals with resolved plantar fasciitis, and individuals with no history of plantar fasciitis.

Abstract

While the mechanism of developing plantar fasciitis is uncertain, properties of the plantar fascia (PF) such as thickness and stiffness may possess indicators of tissue degradation. These properties are affected by repetitive mechanical loading such as running. However, little is known as to whether changes to PF tissue properties remain altered post-injury. Thus, the purpose of the present study was to investigate the effects of a submaximal treadmill run on PF properties and running mechanics in individuals with resolved plantar fasciitis. Twenty participants (12 without plantar fasciitis history, eight had resolved plantar fasciitis) completed a 30-minute treadmill run at 80% of their speed at ventilatory threshold 2. PF measurements were collected before, post-, 15 min post-, and 30 min post-treadmill run. Motion capture data were collected at minutes 1:30, 15:00, and 29:30 during the run. PF thickness and stiffness decreased post-run ($p < 0.001$), increased 15 min- ($p < 0.001$), and 30 min ($p < 0.001$) post-run in both groups. The RPF group had a thicker and stiffer PF before the run ($p < 0.001$). While thickness was greater for all four measurements, stiffness was different at pre-run and 30 minutes post-run only. Leg and vertical stiffness did not change throughout the run and were not different between groups. NPF group had a significantly greater midfoot dorsiflexion during the stance phase, specifically during the midway point (15 minutes). While this was a retrospective study missing information on PF properties of the RPF group pre-injury, these findings indicate that resolved plantar fasciitis may maintain a thicker tissue compared to a previously uninjured PF. However, the difference in morphology did not alter the PF’s response to mechanical loading. Resolved plantar fasciitis reduced lowering of the medial longitudinal arch during the stance phase. This may result in diminished foot arch functioning during running as well as a decreased foot spring mechanism to properly transmit forces.

Key Words

Tissue thickness & stiffness, ultrasound, shear wave elastography, leg & vertical stiffness, foot mechanics, statistical parametric mapping

Introduction

The etiology and underlying mechanisms of plantar fasciitis are still unknown. Theories regarding the mechanical sequence of tissue creeps suggest that repetitive loading, such as walking or running, would lead to an initial thinning of the plantar fascia (PF), followed by an inflammatory reparative process (Frost, 1990). Continued repetitive loading may cause chronic thickening of the PF, as well as a loss of stiffness (Baur et al., 2021; Welk et al., 2015). Both properties, but especially thickness have been utilized as clinical factors to diagnose plantar fasciitis (Buchbinder, 2004; Stecco et al., 2013). Individuals with plantar fasciitis show increased PF thickness (Goff & Crawford, 2011) and decreased PF stiffness (Baur, 2021). As theorized, PF thickness and stiffness decrease significantly after one running bout, but approximate pre-exercise values after 30 minutes of recovery in individuals without a history of plantar fasciitis (Shiotani et al., 2020, Welk et al., 2015). The immediate decrease and consequent return of thickness and stiffness after running in asymptomatic individuals affirms the viscoelastic load and rate dependent response of the PF to mechanical loading (Shiotani, 2020). The concurrent decrease in arch height suggests that changes in these PF tissue properties affect lowering of the medial longitudinal arch and thus potentially increase risk for injury to the tissue. (Shiotani, 2020). Whether this sequence of decrease in thickness and stiffness occurs in previously injured PF tissue, and the connection between PF tissue properties and running gait mechanics have not been evaluated thus far. A theory suggesting a different response of tissue and running mechanics in individuals with resolved plantar fasciitis is the occurrence of scar tissue build-up during the inflammatory phase of the healing process (Grant et al., 2012). Scar tissue shows reduced load compliance compared to healthy tissue affecting how the PF responds to induced continuous mechanical loading in an injured and resolved state (Corr et al., 2009; Corr et al., 2013).

The PF also plays an integral part in maintaining foot and arch control during the stance phase of the gait cycle (Gefen, 2003). The involvement of the PF in the *Windlass Mechanism* allows it to react to being loaded during ground contact by coiling around the toes and providing tension within the foot to control midfoot pronation and dorsiflexion under weightbearing conditions in asymptomatic individuals (Erdemir, 2004; Gefen, 2003; Stecco, 2013). This function is impaired in people with plantar fasciitis (Crary, 2003). Furthermore, apart from the commonly reported heel pain, individuals with plantar fasciitis display increased midfoot extension and eversion, synonymous with flattening of the medial longitudinal arch, and decreased forefoot dorsiflexion during initial contact compared to asymptomatic individuals (Chang et al., 2014; Wiegand et al, 2022).

While running, lower extremity muscles and tendons act as springs, storing and releasing elastic energy, forming the basis of the "spring-mass model" (Morin et al., 2006; McMahon & Cheng, 1990). Thus, measurements for the spring-mass model require an interaction of various anatomical structures, including fascia, tendons, muscles, cartilage, and bones. The mechanical theory examined in the spring-mass model is leg stiffness, which is calculated as the maximum force divided by the maximum leg compression at the midpoint of the stance phase (Morin et al., 2006). Additionally, vertical stiffness simulates the vertical movement of the center of mass during ground contact phase (Morin et al., 2006). It is determined as the maximum force divided by the maximum downward vertical displacement of the CM. Information regarding the occurrence of soft tissue foot injuries in relation to leg and vertical stiffness is conflicting. Both greater and lower values for leg and vertical stiffness have been associated with lower extremity injuries (Davis & Gruber, 2021). In particular, decreased stiffness may increase the risk of soft tissue foot injuries, such as plantar fasciitis or sesamoiditis, due to excessive joint motion (Davis & Gruber, 2021; Williams et al., 2001). As leg and vertical stiffness both influence the way forces are transmitted through the lower extremities during mechanical loading, these factors may play a role in the development or exacerbation of plantar fasciitis as a soft tissue injury.

Plantar fasciitis symptomatic individuals report increased lower extremity vertical stiffness during the initial loading phase of the stance phase (from foot strike to vertical ground reaction force exceeding 75% bodyweight), while leg stiffness remains undocumented (Johnson et al., 2020). However, it is unclear if the mechanical changes during running in people with plantar fasciitis are related to changes in PF tissue mechanical properties. Furthermore, little is known as to whether PF property and run mechanic adaptations maintain after injury and pain have subsided. Despite plantar fasciitis being a frequently diagnosed running injury (Taunton et al., 2002), limited research has evaluated running mechanics in people with resolved plantar fasciitis (Wiegand et al., 2022). There were no differences in multi-segment foot kinematics between individuals with resolved plantar fasciitis and individuals with no injury history (Wiegand et al., 2022). However, their protocol was not a continuous run and thus may have not induced the required magnitude or volume of loading and stress to illicit differences in gait mechanics. This is important because potential differences in the tissue's response to running can be connected to changes in foot and run mechanics and provide a better understanding of potential long-term effects of plantar fasciitis, even after being resolved.

Waveform analyses depicting multi-segment foot angles from foot strike to toe-off have been shown to indicate differences in forefoot and midfoot kinematics (Leardini et al., 2007). This analysis technique enables the evaluation of potential differences in medial longitudinal arch control between healthy and previously injured individuals during the entire stance phase rather than discrete timepoints. This analysis would be of specific importance as research has shown that the PF experiences the greatest strain at the end of stance phase, rather than during initial contact (Lin, 2014).

Given the evidence that the PF's response to mechanical loading is quantifiable via ultrasound (Shiotani et al., 2020), and that change in PF properties can be used clinically to identify plantar fasciitis (Baur et al., 2021; Buchbinder, 2004), thickness and stiffness of the tissue have the potential to monitor progression of tissue degradation prior to an injury. Especially in the absence of pain, progressive change in PF properties and concurring compensations of running mechanics may remain unnoticed. Thus, foot and running mechanics via kinematic gait analyses may provide supplemental information related to changes to PF properties alongside investigations of tissue properties. Therefore, the purpose of the present study was to investigate the effects of submaximal treadmill running on PF properties and run mechanics in individuals with resolved plantar fasciitis (RPF). It was hypothesized that (1) the RPF group would possess thicker and less stiff (more compliant) PF at rest (pre-run) and (2) that the 'no history of plantar fasciitis' (NPF) group, but not the RPF group, would exhibit a decrease in PF thickness and stiffness after running. It was also hypothesized that the RPF group would have greater midfoot dorsiflexion and eversion and reduced forefoot flexion during the stance phase at the middle and at the end of the 30-minute run.

Methods

Population

Twenty healthy individuals participated in the present study (6 females; age: 24.3 yrs [± 7.5]; mass: 70.0 kg [± 10.1], height 178.0 cm [± 8.64]). A sample size of 16 participants, 8 per group, was determined via a priori ($\alpha = 0.05$, $\beta = 0.8$, effect size = 0.6) power analysis based upon previous research on individuals with plantar fasciitis using thickness and stiffness powered variables (Shiotani et al., 2020). Eight participants were individuals with resolved plantar fasciitis (4 females; age: 25.1 yrs [± 9.8]; mass: 69.4 kg [± 12.2], height 180.2 cm [± 11.3]). Resolved plantar fasciitis was defined as having had no symptoms for at least one month prior to participant in the study (Wiegand et al., 2022). Participants reported previous plantar fasciitis as far as 7 years ago and as close as 2.5 months ago, with a mean duration of 2 months. All RPF participants stated that they believe their plantar fasciitis was exercise related. Three participants experienced unilateral plantar fasciitis on the right, two experienced unilateral plantar fasciitis on the left, and three participants experienced it bilaterally. Twelve participants were individuals without a history of plantar fasciitis (2 females; age: 23.7 yrs [± 5.4]; mass: 70.8 kg [± 8.5], height 177.5 cm [± 7.1]). Participants were physically active (ACSM) and recreational runners with a minimum monthly running distance of 5 kilometers (km). The average monthly running distance for the RPF group was 50.3 km (± 40.1), while the NPF group reported 85.0 km (± 81.4). A two-sample t-test revealed no significant difference between the two groups ($p = 0.13$). All participants indicated their ability to currently run pain free and to run on a motorized treadmill comfortably. Exclusion criteria were existing diseases (cardiovascular disease, metabolic disease, renal disease), any history of lower-extremity injuries and surgeries within the past 6 months, current musculoskeletal injuries, wearing prescription inserts, and regular use of non-steroidal anti-inflammatory drugs (NSAIDs) or topical creams. This study was approved by the Institutional Human Research Ethics Committee and was carried out in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants before data collection.

Procedures

The present study was designed as a repeated measures quasi-experimental pre-test, post-test design. Participants were instructed to avoid non-steroidal anti-inflammatory drug consumption and topical cream application to the superficial aspect of the plantar fascia prior to participation. Additionally, participants were asked to refrain from vigorous physical activity (such as high intensity running or weightlifting), alcohol (potential inflammatory effect), and caffeine consumption for 24 hours prior to participation.

Participants had performed a maximal effort graded exercise test (GXT) on a motorized treadmill (4FRONT, Woodway, Waukesha, WI, USA) at least 48 hours prior to the submaximal 30-minute treadmill run. This session functioned to determine individual ventilatory threshold 2 (VT2) (TrueOne 2400; Parvo Medics, Salt Lake City, UT, USA). VT2 was determined by visual inspection of a concomitant increase in VE/VO2 and VE/VCO2 (Elsangedy et al., 2013). The individualized speed for the 30-minute treadmill run was 80% of the speed VT2 was achieved at. For participants who did not reach VT2 during the GXT, 80% of the speed at test termination was used. This was the case for five of the 20 participants.

Upon reporting to the lab for a second session, participants performed a 30-minute run on a motorized treadmill at their 80% VT speed with their own running shoes. Prior to the run, participants underwent bilateral ultrasound imaging to determine PF thickness and stiffness. Participants were then equipped with retro-reflective markers (14 mm) using a custom cluster-based model for the torso, pelvis, and lower extremities. A multi-segment foot model was used to equip the shoes to represent three segments of the foot model (Leardini et al., 2007; Wiegand et al., 2022). Dynamic trial markers were attached bilaterally to the shoe according to Leardini et al. (2007), anterior superior iliac spine (ASIS), iliac crest, posterior superior iliac spine (PSIS), sacrum, manubrium, xyphoid process, and acromion. Bilateral rigid clusters were attached on the lateral aspect of the shank and thigh. Static trial markers were attached bilaterally to the medial and lateral malleoli, medial and lateral epicondyle of the femur, and greater trochanter (Wiegand et al., 2022). Three-dimensional marker trajectories were collected with an eight-camera motion capture system (250 Hz; VICON, Oxford Metric Ltd., Oxford, UK). Following a static calibration and removal of calibration markers, a 5-minute warm-up at a self-selected speed was completed before the 30-minute run on the same treadmill.

Run trials were collected as 20-second intervals at minutes 1:30, 15:00, and 29:30 during the 30-minute run. Participants were not aware when the trials were being recorded. Following the completion of the run, participants transitioned to have three more ultrasound recordings collected (immediately post-, 15 minutes post-, and 30 minutes post-run) bilaterally. To ensure the PF was in the same position during each measurement, participants' feet were positioned by the researcher to hang off the treatment table. To reduce any post run loads on the PF, participants remained on the treatment table and their feet did not have contact with the ground for the 30 minutes following the run.

Ultrasound measurements

Ultrasound imaging was used to evaluate thickness and stiffness of the PF (Logiq S8; GE Healthcare, Waukesha, WI, USA), with a linear array transducer (9L-D; GE). Participants were positioned in a prone position on a treatment table with their lower limbs in full extension and their bare feet hanging over the edge of the table. The proximal site of the PF near the calcaneal tuberosity was marked with a waterproof marker prior taking the measurements (Jariwala et al., 2011). After locating the PF on the ultrasound, markings were placed around the transducer head to ensure the same location for all measurements. Ultrasound gel was applied to the transducer to increase conductivity between the skin and the probe, evaluating the PF in a longitudinal orientation. All images were taken at 12 Hz, a gain of 50, and a depth of 4 cm. PF thickness was measured via B-mode imaging (5 seconds per image). After taking a total of five images per measurements, the three middle images were used for analysis (Skovdal Rathleff et al., 2011). PF stiffness was measured with shear wave elastography. A region of interest with a size of 0.1 mm^2 was used to identify the measurement area. Three color images were collected and used for later analysis. All measurements were performed by the same examiner, with the transducer manually operated.

Data Analysis

To analyze PF thickness, the distance between the deep and superficial boundaries at the calcaneal origin was measured (mm) using the ultrasound measurement application. To analyze PF stiffness, the mean shear wave velocity of the region of interest was identified (m/s). The mean value of three thickness and three stiffness images was used to obtain a mean (SD) for each measurement time (pre-, post-, 15 min post-, and 30 min post-run). For participants within the RFP group that reported unilateral plantar fasciitis history, PF measurements were taken on the involved limb and used for analysis. For participants within the RFP group that reported bilateral plantar fasciitis history, PF measurements were taken bilaterally. PF measurements were also taken bilaterally for those participants within the NPF group. For the NPF and bilateral RFP participants, the relative difference between pre- and post-run thickness and stiffness values were calculated bilaterally. The limb selected per participant was chosen based on which limb had the greatest combined relative difference of both thickness and stiffness. This combined difference of thickness and stiffness was calculated as the relative change of PF properties. Therefore, the limb with the greatest relative change was used for analysis for the NPF and bilateral RFP participants.

Kinematic variables were computed using Visual 3D (v.6, C-Motion, Germantown, MD, USA) following preliminary processing within Vicon Nexus (v.2.11, Vicon, Oxford, UK). Marker trajectories were filtered using a lowpass fourth-order Butterworth filter at 8 Hz (Arampatzis et al., 1999; Edwards et al., 2008). Joint angles were calculated using a standard Cardan sequence (XYZ). The multi-segment foot model separates the foot into three segments (Leardini et al., 2007). The present study utilized the midfoot (rearfoot-midfoot) and forefoot (midfoot-forefoot) segments for analyses, to determine motion of the medial longitudinal arch and toe sagittal plane motion during the stance phase, respectively (Leardini et al., 2007; Wiegand et al., 2022). A positive sagittal and negative frontal angle of the midfoot described medial longitudinal arch decrease, while a negative sagittal angle and positive frontal angle of the midfoot described medial longitudinal arch increase (Wiegand et al., 2022). A positive sagittal angle of the forefoot described toe dorsiflexion (Wiegand et al., 2022).

Midfoot and forefoot angles were extracted and normalized to 100% of the stance phase. Stance phase was defined as foot strike to toe off. A custom Matlab (The Mathworks Inc., Boston, MA, USA) code was used to identify the initial contact and toe-off events to determine stance phase based on marker trajectories (Handsaker et al., 2016). Duration of contact time, flight time, and estimated peak vertical ground reaction forces were used to calculate leg and vertical stiffness during the stance phase at the three time points during the treadmill run (Morin et al., 2005). Mean (SD) of 10 strides were used for kinematic and stiffness variables.

Statistical Analysis

The present study was designed to be a between-subjects design, comparing variables across multiple timepoints and trials. For the primary purpose, changes in PF thickness and stiffness were analyzed by multiple mixed model (2 group x 4 measurement) repeated measures analyses of variance (ANOVA) to evaluate the effects of plantar fasciitis injury history (NPF, RPF) and time (pre, post, 15 min post, and 30 min post run measurements) on plantar fascia thickness and stiffness, and a potential interaction between these factors. Any interactions were followed up with individual simple main effects analyses using one-way ANOVAs and independent *t*-tests following Bonferroni corrections. Statistically significant main effects were further investigated using *post-hoc* Bonferroni corrections for pairwise comparisons. Effect sizes were calculated as partial eta-squared (η_p^2) for the ANOVA and Cohen's *d* (0.2 = small, 0.5 = medium, 0.8 = large) (Lakens, 2013) for the post-hoc analyses.

Leg and vertical stiffness were analyzed by multiple mixed model (2 group x 3 measurement) repeated measures ANOVA, with the same follow-up procedures for main effects and interactions as described for PF thickness and stiffness. Midfoot and forefoot sagittal and frontal angle waveforms were analyzed via statistical parametric mapping (SPM) (Moisan et al., 2021). Multiple two-way repeated measures ANOVA SPM (2 group x 3 time) followed by *post-hoc* two-sample *t-test* SPM were used to compare midfoot and forefoot angles at each percentage (0-100%) of stance phase (Moisan et al., 2021). As with the previous variables, significant main effects or interactions were followed up with pairwise comparisons. Running velocity was not used as a covariate for the present analyses, as there was no difference ($p = 0.54$) in velocity between the RPF group (3.14 m/s ± 0.49) and the NPF group (3.25 m/s ± 0.36). For all analyses, an *a priori* alpha level was set to 0.05. Statistical analyses were performed using IBM SPSS Statistics v.28 and MATLAB.

Results

No significant interaction was found PF thickness between time and groups, $F(3, 54) = 0.651$, $p = 0.59$, $\eta_p^2 = 0.035$. There was a significant main effect of time for PF thickness at the four different measurements, $F(3, 54) = 77.277$, $p < 0.001$, $\eta_p^2 = 0.811$. There was also a significant main effect of group for PF thickness between the RPF and NPF groups, $F(1, 18) = 5.241$, $p = 0.034$, $\eta_p^2 = 0.226$. Between groups, *post-hoc* pairwise comparisons revealed that the RPF group had a greater PF thickness compared to the NPF group at the pre-run ($p = 0.017$; 3.86 vs. 3.19 mm; $d = 0.56$), the post-run ($p = 0.049$; 3.3 vs. 2.72 mm, $d = 0.60$), the 15 min post-run ($p = 0.037$; 3.6 vs. 2.98 mm, $d = 0.60$), and the 30 min post-run ($p = 0.045$; 3.83 vs. 3.18, $d = 0.61$) measurements (Figure 1). Regardless of group, *post-hoc* comparisons revealed that thickness decreased between pre- and post-run ($p < 0.001$; 3.53 to 3.01 mm, $d = 0.21$) & increased from post- to 15 min post-run ($p < 0.001$; 3.01 to 3.29 mm, $d = 0.16$) and from 15 min post- and 30 min post-run ($p < 0.001$; 3.29 to 3.53 mm, $d = 0.15$) (Figure 1).

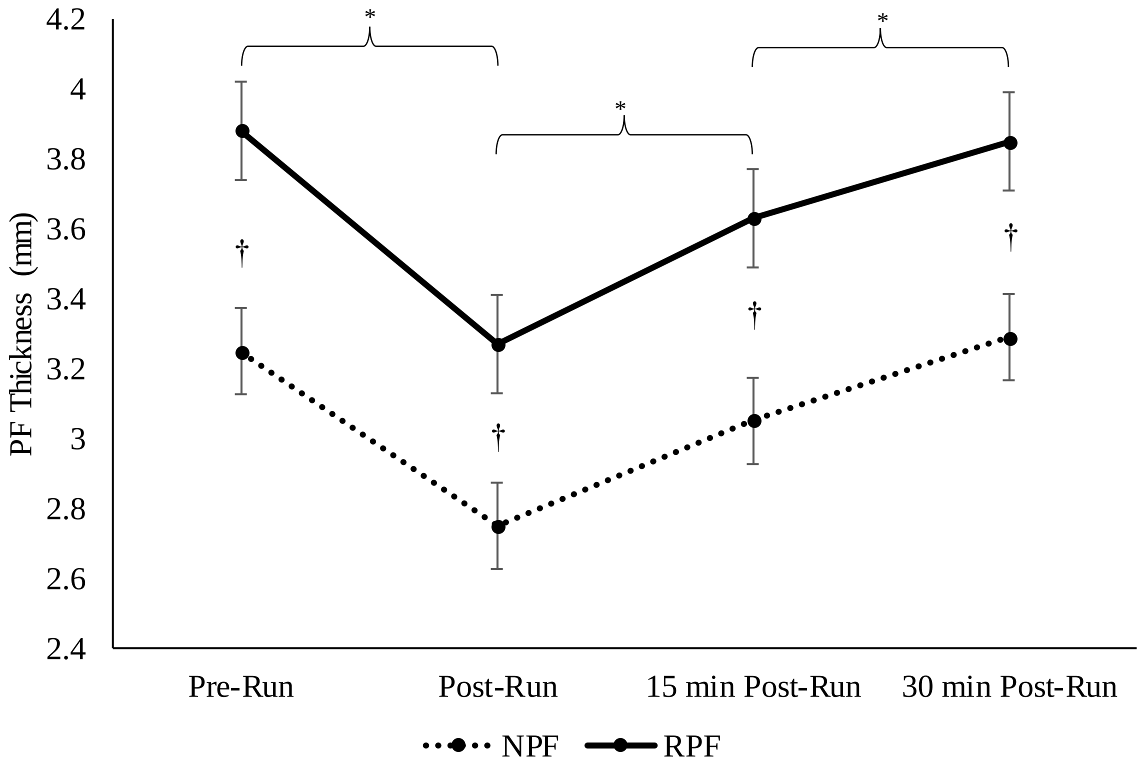

Figure 1. PF Thickness (mm) measurements (means ± SD) for the no plantar fasciitis (NPF) and resolved plantar fasciitis groups (RPF). *Denotes a significant difference between the two adjacent PF measurements regardless of group. †Denotes a significant difference in PF thickness measurements between the two groups.

No significant interaction effect was found for PF stiffness between time and groups, $F(3, 54) = 0.634$, $p = 0.59$, $\eta_p^2 = 0.034$. There was a significant main effect of time for PF stiffness at the four different measurements, $F(3, 54) = 27.171$, $p < 0.001$, $\eta_p^2 = 0.602$. There was also a significant main effect of group for PF stiffness between the RPF and NPF groups, $F(1, 18) = 5.293$, $p = 0.034$, $\eta_p^2 = 0.227$. Between groups, *post-hoc* pairwise comparisons revealed that the RPF group had a greater PF stiffness compared to the NPF group at the pre-run ($p = 0.048$; 4.58 vs. 3.76 m/s, $d = 0.83$), and the 30 min post-run ($p = 0.007$; 4.63 vs. 3.67 m/s, $d = 0.68$) measurements. No differences were found at the post-run ($p = 0.087$; 3.46 vs. 2.79 m/s, $d = 0.80$) and the 15 min post-run ($p = 0.146$; 4.10 vs. 3.47 m/s, $d = 0.91$) measurements (Figure 2). Regardless of group, *post-hoc* comparisons revealed that stiffness decreased between pre- and post-run ($p < 0.001$; 4.18 to 3.13 m/s, $d = 0.49$) & increased from post- to 15 min post-run ($p < 0.001$; 3.13 to 3.79 m/s, $d = 0.55$). No difference in stiffness was found from 15 min to 30 min post-run ($p = 0.057$; 3.79 to 4.15 m/s, $d = 0.56$) (Figure 2).

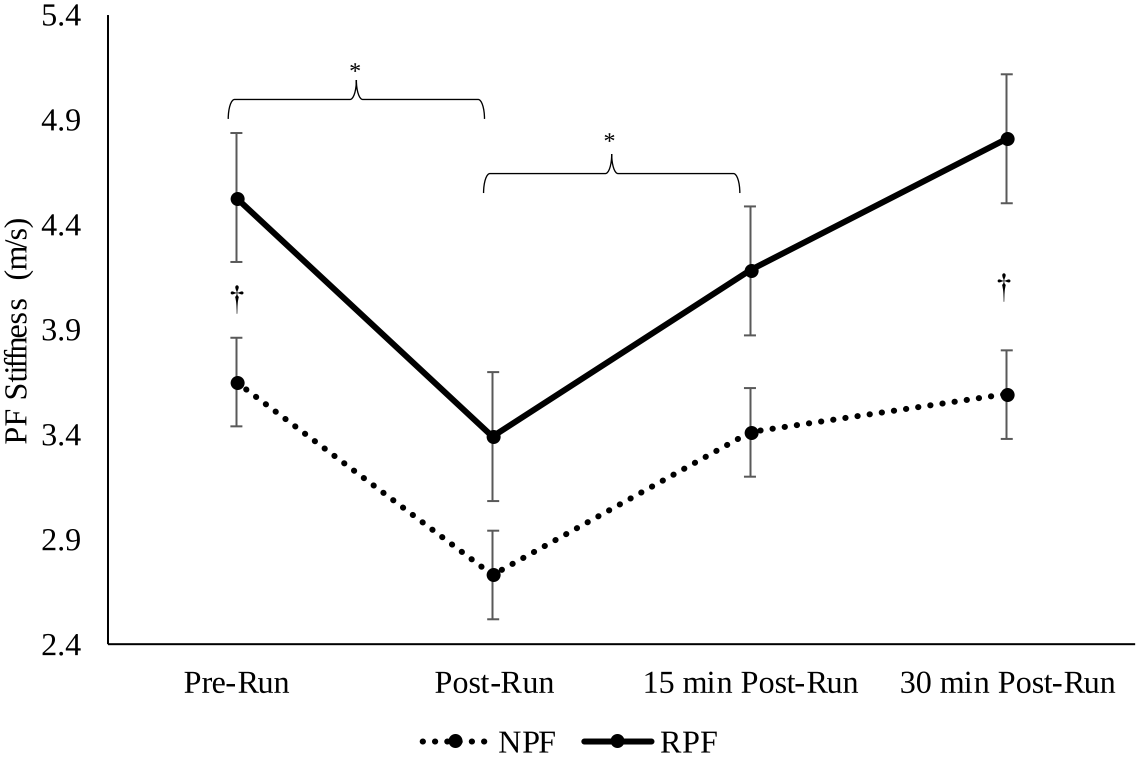

Figure 2. PF Stiffness (m/s) measurements (means ± SD) for the no plantar fasciitis (NPF) and resolved plantar fasciitis groups (RPF). *Denotes a significant difference between the two adjacent PF measurements regardless of group. †Denotes a significant difference in PF thickness measurements between the two groups.

No significant interaction effect was found for leg stiffness between time and groups, $F(2, 28) = 0.086$, $p = 0.92$, $\eta_p^2 = 0.006$. There was no significant main effect of time for leg stiffness at three measurements during the 30-minute treadmill run, $F(2, 28) = 1.257$, $p = 0.30$, $\eta_p^2 = 0.082$. Also, no significant main effect of group between the RPF and NPF groups for leg stiffness was found, $F(1, 14) = 3.774$, $p = 0.072$, $\eta_p^2 = 0.212$. (Figure 3).

No significant interaction effect was found for vertical stiffness between time and groups, $F(2, 28) = 0.238$, $p = 0.79$., $\eta_p^2 = 0.017$. There was no significant main effect of time for vertical stiffness at three measurements during the 30-minute treadmill run, F(2, 28) = 1.598, p = 0.22, $\eta_p^2 = 0.102$. Further, there was no significant main effect of group between the RPF and NPF groups for vertical stiffness, $F(1, 14) = 1.174$, p = 0.297, $\eta_p^2 = 0.077$ (Figure 4).

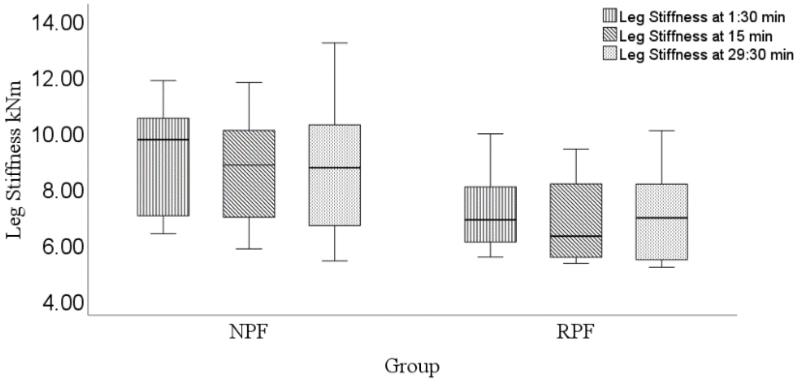

Figure 3. Boxplots displaying leg stiffness (kNm) by group (NPF, RPF) at minutes 1:30, 15, and 29:30.

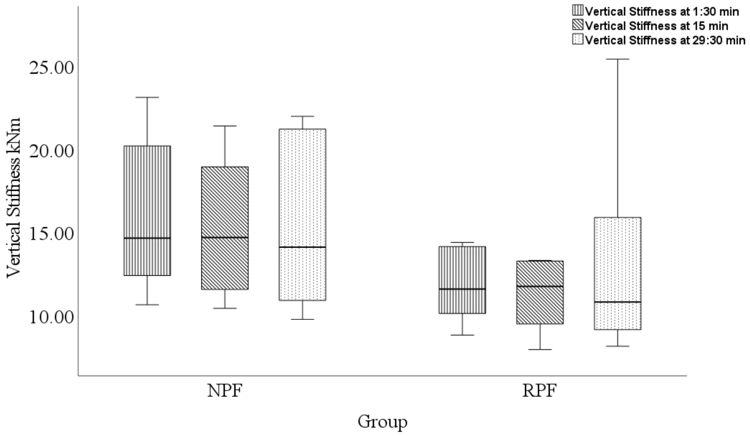

Figure 4. Boxplots displaying vertical stiffness (kNm) by group (NPF, RPF) at minutes 1:30, 15, and 29:30.

The SPM analysis indicated no significant main effects for neither group, nor time for forefoot (Figure 5), and midfoot frontal angles (Figure 6). There were also no interactions between group and time.

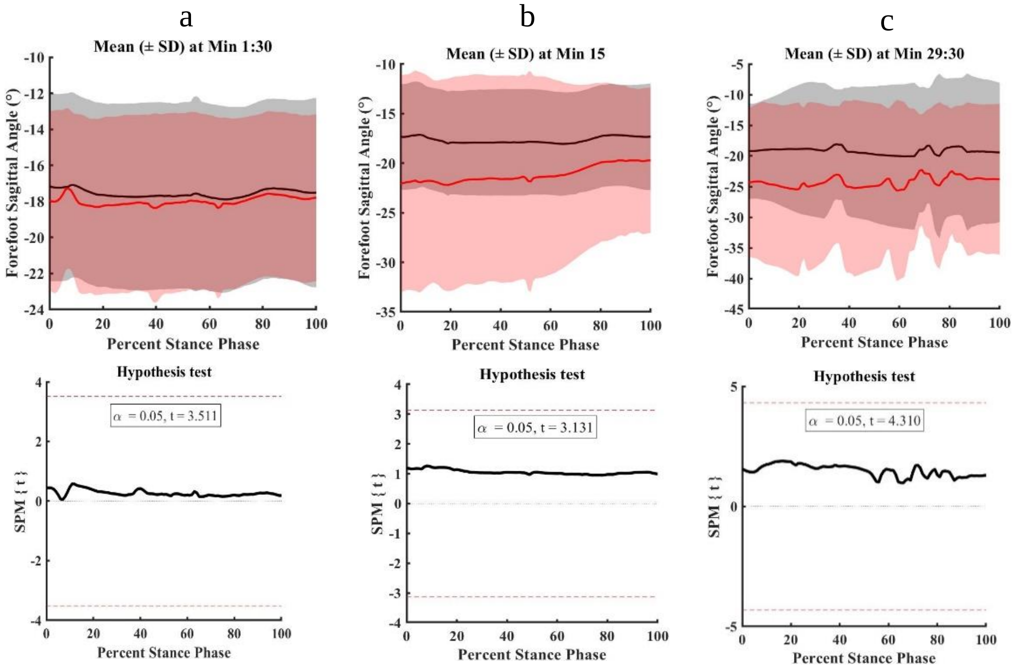

Figure 5. Means (lines) and SD (shaded region) for forefoot sagittal plane angle at minute 1:30 (a), 15 (b), and 29:30 (c). The dashed red lines indicate the threshold for significant differences. RPF (red) and NPF (black) showed no differences at all time points.

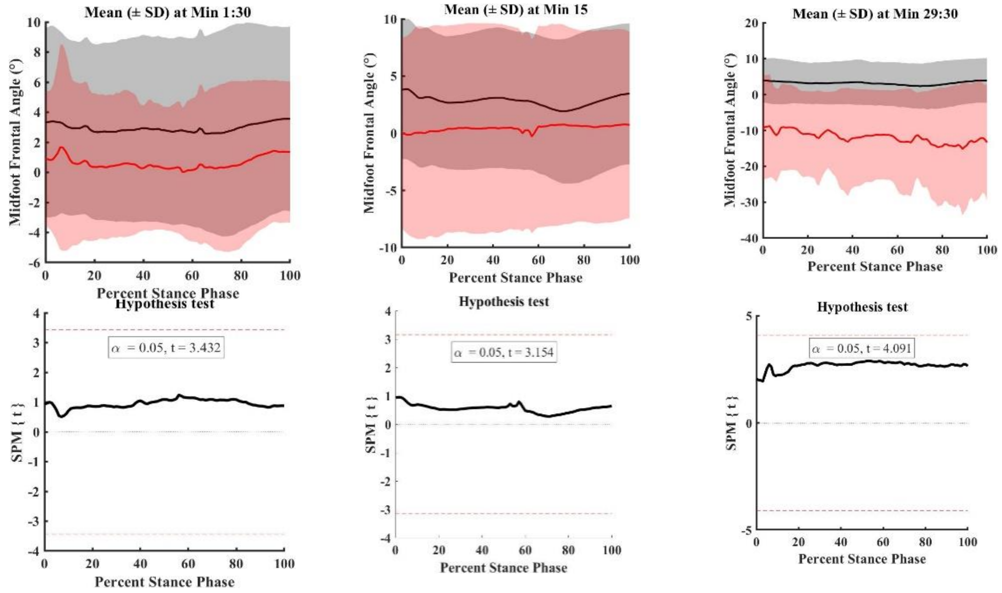

Figure 6. Means (lines) and SD (shaded region) for midfoot frontal plane angle at minute 1:30 (a), 15 (b), and 29:30 (c). The dashed red lines indicate the threshold for significant differences. RPF (red) and NPF (black) showed no differences at all time points.

The SPM analysis revealed a significant main effect of group for midfoot sagittal angles, yet no effect of time. No interaction was found (Figure 7).

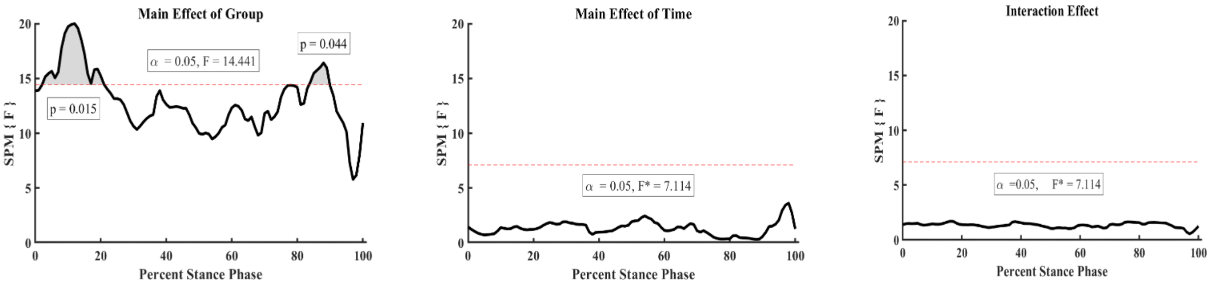

Figure 7. SPM repeated measures ANOVA outcome for midfoot sagittal plane angle. The dashed red lines indicate the threshold for significant differences. RPF and NPF group showed significant differences twice during the stance phase throughout the 30-minute

Post-hoc pairwise comparisons revealed that the RPF and NPF group showed significant differences for midfoot sagittal angles at the 15-minute measurement only. No significant differences were found at the 1:30-minute, and 29:30-minute measurement (Figure 8).

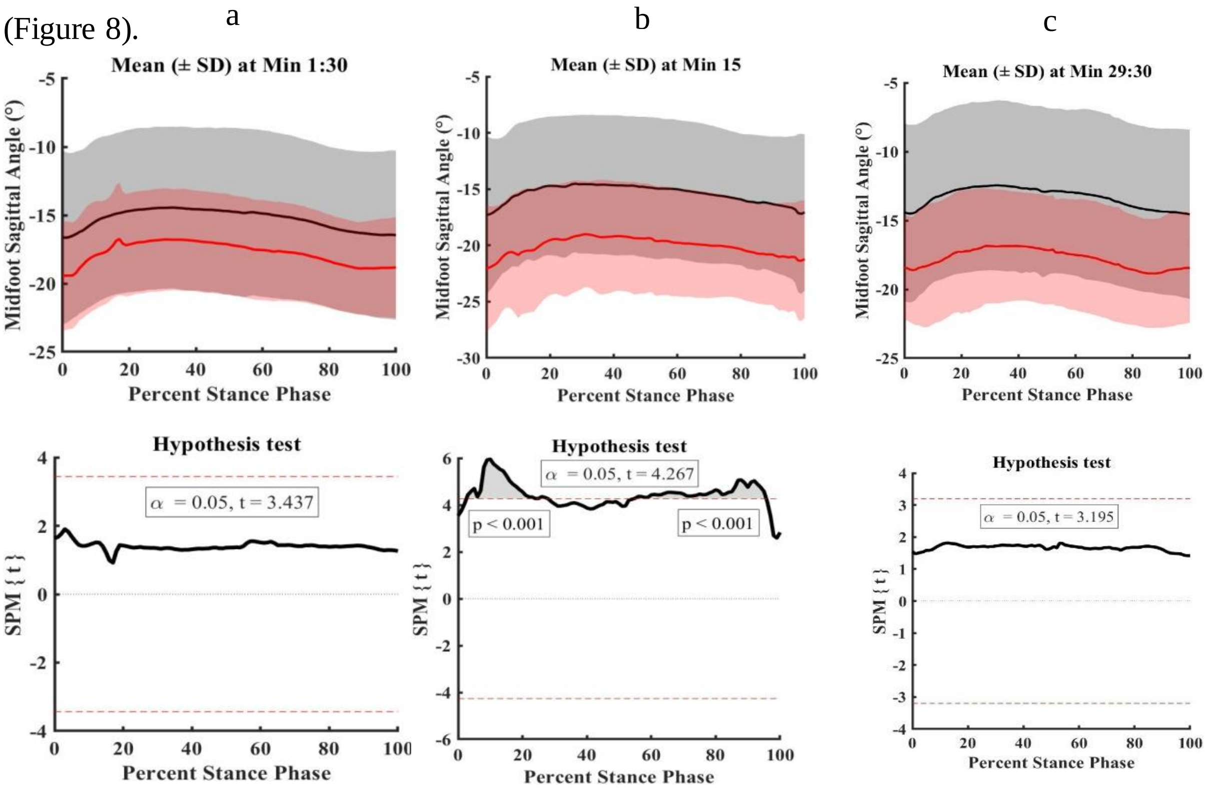

Figure 8. SPM post-hoc pairwise comparisons of means (lines) and SD (shaded region) for midfoot angle in the sagittal plane at minute 1:30 (a), 15 (b), and 29:30 (c). The dashed red lines indicate the threshold for significant differences. RPF (red) and NPF (black) group showed significant differences twice (p<0.001) during the stance phase at the 15-minute measurement.

Discussion

The purpose of the present study was to investigate the effects of treadmill running on plantar fascia properties and gait mechanics in individuals with resolved plantar fasciitis. To the knowledge of the authors, this is the first study to evaluate PF tissue response to submaximal running in individuals with resolved plantar fasciitis. The difference in PF thickness between the RPF and the NPF group at the pre-run measurement aligns with the initial hypothesis. Individuals with resolved plantar fasciitis displayed a significantly thicker tissue compared to their counterparts. Yet, PF stiffness was also greater in the RPF group, rejecting the initial hypothesis of a less stiff tissue in people with resolved plantar fasciitis. The decrease in PF thickness and stiffness from pre- to post-run measurements also partially align with the secondary hypothesis. It was hypothesized that both properties would decrease in the NPF group only, suggesting that previous plantar fasciitis would alter the tissue's viscoelastic response to running. However, it was found that the RPF group displayed the same decrease in thickness and stiffness at the post-run measurements. The acute decrease in both properties was followed by a gradual increase returning approximating baseline values.

PF thickness has been widely used as a clinical factor to diagnose plantar fasciitis (Buchbinder, 2004; Stecco et al., 2013). Individuals with plantar fasciitis generally display a tissue significantly thicker compared to their healthy counterparts (Gibbon & Long, 1999; Jariwala et al., 2011). Individuals with resolved plantar fasciitis showed a significantly thicker tissue compared to those who have never experienced said injury. Consistent with the literature is the mean thickness of approximately 4 mm in previously injured individuals of the present study, as that threshold or greater is considered consistent with plantar fasciitis (League, 2008). The PF thickness of participants with resolved plantar fasciitis falling just below 4 mm aligns with the evidence that a decrease in thickness over time after various treatment methods has been shown previously (Fabrikant & Park, 2011; Hansen et al., 2018; Mahowald et al., 2011). Plantar fasciitis symptomatic individuals experience a less stiff tissue compared to healthy individuals (Baur et al., 2021; Welk et al., 2015). The present findings do not concur, as people with resolved plantar fasciitis showed stiffer tissue compared to the healthy participants.

The decrease in thickness and stiffness in individuals without plantar fasciitis history after the submaximal 30-minute run was expected (Shiotani et al., 2013). Similarly, the recovery within 30 minutes post-run aligns with previous research (Shiotani et al., 2013), as well as what is generally understood about the behavior of biomechanical tissues in response to the removal of a mechanical load. The submaximal 30-minute run applied continuous mechanical loading to the tissue, inducing deformation of the PF because of the principle of tissue creep. However, due to the potential of scar tissue within the PF (Grant et al, 2012), it was unexpected to see a similar response in PF thickness and stiffness in people with resolved plantar fasciitis. Despite the increased thickness and stiffness at the pre-run measurement, the PF of previously injured participants displayed a similar pattern of decrease post-run, followed by a recovery approaching baseline values. These findings suggest that the properties of the PF of both non-injured and resolved plantar fasciitis individuals behave similarly in response to submaximal treadmill running stimuli. This indicates that previous plantar fasciitis alters the morphology of the tissue long term, yet its viscoelastic properties and responses to mechanical loading maintain. However, as this is a retrospective study, tissue behavior of the RPF group prior to their injury history was not determined.

The discrepancy in thickness and stiffness may be due to the formation of scar tissue, which can alter the tissue behavior by changing the composition and mechanical properties (Grant et al., 2012). Scar tissue has been shown to display stiffer behavior and decrease capability to dissipate energy (Grant et al., 2012). This is important as individuals with resolved plantar fasciitis may have remnants of scar tissue explaining the increased thickness of the tissue. However, it appears the mechanical loading response of the PF in individuals with resolved plantar fasciitis behaves similar to healthy tissue, despite any potential changes to tissue composition. This may be due to several factors, including the ability of the tissue to remodel and adapt in response to mechanical stimuli, and the effectiveness of rehabilitation and recovery programs in restoring the tissue's mechanical properties (Hildebrand et al., 2005).

It is important to note that while the mechanical loading response may be similar between the groups, the tissue’s thickening may still have implications for tissue function and overall mechanical performance. These changes can affect the tissue's ability to dissipate stored elastic energy, absorb shock, and resist deformation, and may increase the risk of re-injury or damage in the future (Grant et al., 2012). Leg and vertical stiffness are two variables frequently referred to as measures to evaluate the body’s capacity to store for utilizing stored elastic energy and shock absorption by the lower extremities. The spring-mass model is commonly utilized as a representation of the leg's spring-like compression caused by the weight of the body. It illustrates the mechanisms by which the lower extremities, comprising joints, muscles, tendons, ligaments, and bones work together to manage an external force and transfer elastic potential energy (Grant et al., 2012). In the present study, leg and vertical stiffness did not change throughout the submaximal effort 30-minute run. This was expected as both leg and vertical stiffness are strongly correlated to running speed (Morin et al., 2005), and the present protocol was conducted at a constant speed. Furthermore, no change in these variables throughout the 30-minute run may also indicate the run did not produce fatigue, as leg and vertical stiffness have been shown to decrease with fatigue (García-Pinillos et al., 2020; Morin et al., 2006). While the findings for leg and vertical stiffness were not statistically different between the RPF and NPF group, participants in the RPF group had consistently lower leg and vertical stiffness throughout the 30-minute run. Increased leg and vertical stiffness are suggested to improve the ability of the lower extremities to utilize stored elastic energy and recruit the stretch-shortening cycle for a more efficient running economy (Brazier et al., 2019). A trend toward lower leg and vertical stiffness of the RPF group proposes that previous plantar fasciitis may diminish the ability to transmit potential elastic energy.

As leg and vertical stiffness can have an impact on run mechanics, medial longitudinal arch lowering and lengthening during the stance phase have been found to improve walking and running gait efficiency (Erdemir et al., 2004; Kelly et al., 2015). Regularly termed as *Windlass Mechanism*, the PF coils around the metatarsals and allows the medial longitudinal arch to lower during the stance phase to absorb the external force applied. The present study found a difference in midfoot sagittal angles during stance phase between the RPF and NPF groups. The NPF group displayed greater midfoot dorsiflexion, compared to the RPF group. No differences were found in forefoot sagittal and midfoot frontal angles between groups, or throughout the 30-minute run. This suggests that forefoot dorsiflexion and midfoot eversion were not impacted in individuals with resolved plantar fasciitis. However, the run conducted on a treadmill at submaximal effort may explain these unchanged running and foot mechanics and warrant further investigations at greater intensities to increase structural demands.

A greater midfoot dorsiflexion aligns with a more pronounced lowering of the medial longitudinal arch (MLA) (Kelly et al., 2015; Wearing et al., 2004). This was specifically visible at the 15-minute measurement, where the NPF group had greater midfoot dorsiflexion after initial contact and prior to toe off. Based on this finding, a lower MLA arch during these periods of the stance phase can be inferred in the NPF group. Further investigation is necessary to determine the reasoning behind a significant difference halfway through the run, but not at the beginning or the end. A potential explanation can be found in the large standard deviation found at the 29:30-minute mark of the run (Figure 8c). Not statistically different, but evident in the SPM analysis visually, is the decrease in midfoot dorsiflexion from the beginning to the end of the run in the NPF group (Figure 8 a,b,c). Midfoot dorsiflexion of the RPF group appears unchanged (Figure 8 a,b,c). Overall, midfoot dorsiflexion angles ranged from 9.3º to 18.9º. The values found for midfoot sagittal angles align with previous literature which applied a modified Leardini foot segment model (Wiegand et al., 2022).

Diminished MLA lowering has been found in people with plantar fasciitis and is suggested to decrease the foot’s capacity to return stored potential kinetic energy (Wearing et al., 2004). The present results indicate that resolved plantar fasciitis may similarly alter midfoot sagittal angles throughout the stance phase, as presented by a decreased ability of MLA lowering. One of the potential mechanisms behind the decreased capability to lower the MLA might be the morphological and mechanical differences of the PF between the RPF and the NPF group. Increased thickness, possibly due to scar tissue, may affect the PF’s viscoelasticity (Grant et al., 2012), while increased stiffness of the PF may prevent the tissue from lengthening and engaging in the Windlass Mechanism. This potential relationship warrants further investigation in regard to a lasting effect of resolved plantar fasciitis on MLA extensibility and flexibility.

The findings of the present study should be interpreted with the following limitations and delimitations in mind. While the theory regarding a thicker PF in people with resolved plantar fasciitis suggests accumulation of scar tissue, the presence of scar tissue within the PF was not assessed or measured. Additionally, the missing information regarding PF tissue properties prior to or during plantar fasciitis of the RPF group, as well as a group presenting with current plantar fasciitis are two additional limitations. It cannot be concluded that the occurrence of plantar fasciitis yields long term thickening of the tissue after injury is resolved, as no prior knowledge of this population was collected. Another limitation of the present study is the application of the foot segment model on the footwear of participants, rather than the anatomical structures directly. During shod conditions, the foot and shoe behave independently depending on the tightness and composition of the shoe (Wiegand et al., 2022). Therefore, it cannot be stated with certainty that the presented foot mechanics depict true foot motion. However, the present study aimed to replicate common shod running behavior for recreational runners.

Conclusion

The present study provides insights into the effects of running on PF properties and running mechanics in individuals with resolved plantar fasciitis. The findings suggest that previous plantar fasciitis may alter properties of the plantar fascia, as seen by the increased thickness and stiffness, but does not affect its acute response to mechanical loading. The findings demonstrate that although both groups exhibited similar responses to submaximal treadmill running in terms of PF properties, there were differences in midfoot sagittal angles during the stance phase of gait halfway through the run. Specifically, individuals in the RPF group displayed a decreased ability to lower the medial longitudinal arch compared to their NPF counterparts. Leg and vertical stiffness throughout the stance phase did not differ between groups and did not change throughout the run. The difference in PF thickness and stiffness between the two groups may have implications for the rehabilitation and recovery programs of individuals with plantar fasciitis. Further research is needed to explore the potential long-term consequences of these alterations in tissue properties and gait mechanics on running economy, injury risk, and overall performance. Future studies may also investigate the effectiveness of programs aimed at restoring mechanical properties of the PF and improving gait efficiency in individuals with resolved plantar fasciitis.

References

Arampatzis, A., Brüggemann, G. P., & Metzler, V. (1999). The effect of speed on leg stiffness and joint kinetics in human running. *Journal of Biomechanics*, *32*(12), 1349-1353.

Baur, D., Schwabl, C., Kremser, C., Taljanovic, M. S., Widmann, G., Sconfienza, L. M., ... & Klauser, A. S. (2021). Shear wave elastography of the plantar fascia: Comparison between patients with plantar fasciitis and healthy control subjects. *Journal of Clinical Medicine*, *10*(11), 2351.

Brazier, J., Maloney, S., Bishop, C., Read, P. J., & Turner, A. N. (2019). Lower extremity stiffness: considerations for testing, performance enhancement, and injury risk. *The Journal of Strength & Conditioning Research*, *33*(4), 1156-1166.

Buchbinder, R. (2004). Plantar fasciitis. *New England Journal of Medicine*, *350*(21), 2159-2166.

Corr, D. T., Gallant-Behm, C. L., Shrive, N. G., & Hart, D. A. (2009). Biomechanical behavior of scar tissue and uninjured skin in a porcine model. *Wound Repair and Regeneration*, *17*(2), 250-259.

Corr, D. T., & Hart, D. A. (2013). Biomechanics of scar tissue and uninjured skin. *Advances in Wound Care*, *2*(2), 37-43.

Crary, J. L., Hollis, J. M., & Manoli, A. (2003). The Effect of Plantar Fascia Release on Strain in the Spring and Long Plantar Ligaments. Foot & Ankle International, 24(3), 245–250.

Davis IV, J. J., & Gruber, A. H. (2021). Leg stiffness, joint stiffness, and running-related injury: Evidence from a prospective cohort study. *Orthopaedic Journal of Sports Medicine*, *9*(5).

Edwards, W. B., Gillette, J. C., Thomas, J. M., & Derrick, T. R. (2008). Internal femoral forces and moments during running: Implications for stress fracture development. *Clinical Biomechanics, 23*(10), 1269-1278.

Elsangedy, H. M., Krinski, K., Costa, E. C., Haile, L., Fonteles, A. I., da Silva Timossi, L., & da Silva, S. G. (2013). The rating of perceived exertion is not different at the ventilatory threshold in sedentary women with different body mass indices. *Journal of Exercise Science & Fitness*, *11*(2), 102-106.

Erdemir, A., Hamel, A. J., Fauth, A. R., Piazza, S. J., & Sharkey, N. A. (2004). Dynamic loading of the plantar aponeurosis in walking. *JBJS*, *86*(3), 546-552.

Fabrikant, J. M., & Park, T. S. (2011). Plantar fasciitis (fasciosis) treatment outcome study: plantar fascia thickness measured by ultrasound and correlated with patient self-reported improvement. *The Foot*, *21*(2), 79-83.

Frost, H. M. (1990). Skeletal structural adaptations to mechanical usage (SATMU): 4. Mechanical influences on intact fibrous tissues. The Anatomical Record, 226(4), 433-439.

García-Pinillos, F., Cartón-Llorente, A., Jaén-Carrillo, D., Delgado-Floody, P., Carrasco-Alarcón, V., Martínez, C., & Roche-Seruendo, L. E. (2020). Does fatigue alter step characteristics and stiffness during running?. *Gait & Posture*, *76*, 259-263.

Gefen, A. (2003). The in vivo elastic properties of the plantar fascia during the contact phase of walking. *Foot & Ankle International*, *24*(3), 238-244.

Gibbon, W. W., & Long, G. (1999). Ultrasound of the plantar aponeurosis (fascia). *Skeletal Radiology*, *28*, 21-26.

Goff, J. D., & Crawford, R. (2011). Diagnosis and treatment of plantar fasciitis. *American Family Physician*, *84*(6), 676-682.

Grant, C. A., Twigg, P. C., & Tobin, D. J. (2012). Static and dynamic nanomechanical properties of human skin tissue using atomic force microscopy: effect of scarring in the upper dermis. *Acta Biomaterialia*, *8*(11), 4123-4129.

Hansen, L., Krogh, T. P., Ellingsen, T., Bolvig, L., & Fredberg, U. (2018). Long-term prognosis of plantar fasciitis: a 5-to 15-year follow-up study of 174 patients with ultrasound examination. *Orthopaedic Journal of Sports Medicine*, *6*(3).

Hildebrand, K. A., Gallant-Behm, C. L., Kydd, A. S., & Hart, D. A. (2005). The basics of soft tissue healing and general factors that influence such healing. *Sports Medicine and Arthroscopy Review*, *13*(3), 136-144.

Jariwala, A., Bruce, D., & Jain, A. (2011). A guide to the recognition and treatment of plantar fasciitis. *Primary Health Care*, *21*(7).

Johnson, C. D., Tenforde, A. S., Outerleys, J., Reilly, J., & Davis, I. S. (2020). Impact-related ground reaction forces are more strongly associated with some running injuries than others. *The American Journal of Sports Medicine*, *48*(12), 3072-3080.

Kelly, L. A., Lichtwark, G., & Cresswell, A. G. (2015). Active regulation of longitudinal arch compression and recoil during walking and running. *Journal of the Royal Society Interface*, *12*(102), 20141076.

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*, 863.

League, A. C. (2008). Current concepts review: plantar fasciitis. *Foot & Ankle International*, *29*(3), 358-366.

Leardini, A., Benedetti, M. G., Berti, L., Bettinelli, D., Nativo, R., & Giannini, S. (2007). Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait & posture*, *25*(3), 453-462.

Lin SC, Chen CPC, Tang SFT, Chen CW, Wang JJ, Hsu CC, et al. Stress distribution within the plantar aponeurosis during walking - a dynamic finite element analysis. J Mech Med Biol. 2014;14(04):1450053.

Mahowald, S., Legge, B. S., & Grady, J. F. (2011). The correlation between plantar fascia thickness and symptoms of plantar fasciitis. *Journal of the American Podiatric Medical Association*, *101*(5), 385-389.

McMahon, T. A., & Cheng, G. C. (1990). The mechanics of running: how does stiffness couple with speed?. *Journal of Biomechanics*, *23*, 65-78.

Moisan, G., Miramand, L., Younesian, H., Legrand, T., & Turcot, K. (2021). Assessment of biomechanical deficits in individuals with a trans-tibial amputation during level gait using one-dimensional statistical parametric mapping. *Gait & Posture*, *87*, 130-135.

Morin, J. B., Dalleau, G., Kyröläinen, H., Jeannin, T., & Belli, A. (2005). A simple method for measuring stiffness during running. *Journal of Applied Biomechanics*, *21*(2), 167-180.

Morin, J. B., Jeannin, T., Chevallier, B., & Belli, A. (2006). Spring-mass model characteristics during sprint running: Correlation with performance and fatigue-induced changes. *International Journal of Sports Medicine*, *27*(02), 158-165.

Shiotani, H., Mizokuchi, T., Yamashita, R., Naito, M., & Kawakami, Y. (2020). Acute effects of long-distance running on mechanical and morphological properties of the human plantar fascia. *Scandinavian Journal of Medicine & Science in Sports*, *30*(8), 1360-1368.

Skovdal Rathleff, M., Moelgaard, C., & Lykkegaard Olesen, J. (2011). Intra-and interobserver reliability of quantitative ultrasound measurement of the plantar fascia. *Journal of Clinical Ultrasound*, *39*(3), 128-134.

Stecco, C., Corradin, M., Macchi, V., Morra, A., Porzionato, A., Biz, C., & De Caro, R. (2013). Plantar fascia anatomy and its relationship with Achilles tendon and paratenon. *Journal of Anatomy*, *223*(6), 665-676.

Wearing, S. C., Smeathers, J. E., Yates, B., Sullivan, P. M., Urry, S. R., & Dubois, P. (2004). Sagittal movement of the medial longitudinal arch is unchanged in plantar fasciitis. *Medicine & Science in Sports & Exercise*, *36*(10), 1761-1767.

Welk, A. B., Haun, D. W., Clark, T. B., & Kettner, N. W. (2015). Use of high-resolution ultrasound to measure changes in plantar fascia thickness resulting from tissue creep in runners and walkers. *Journal of Manipulative and Physiological Therapeutics*, *38*(1), 81-85.

Wiegand, K., Tandy, R., & Silvernail, J. F. (2022). Plantar fasciitis injury status influences foot mechanics during running. *Clinical Biomechanics*, *97*, 105712.

Williams III, D. S., McClay, I. S., & Hamill, J. (2001). Arch structure and injury patterns in runners. *Clinical Biomechanics, 16*(4), 341-347.

Chapter 5

Overarching Dissertation Conclusion

By

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Conclusion

The purpose of this dissertation was to investigate the effects of different running intensities and volumes on the mechanical and morphological properties of the plantar fascia (PF). The potential relationship between PF tissue changes and onset of injury is unknown within an endurance running population. To address the specific purpose of this dissertation, three studies were designed and conducted. Each study focused on a different running demand to better understand the behavior of the PF in response to imposed running demands: (1) High intensity interval running, (2) maximal effort long distance running on consecutive days, (3) consistent submaximal velocity treadmill running.

While general research regarding the PF is concerned with treatment modalities of injuries such as plantar fasciitis, the overarching goal of this dissertation was to evaluate how the PF behaves in the absence of injury. Thus, the morphological (thickness) and mechanical (stiffness) properties of the PF were measured via ultrasonography before and after each running protocol to determine the acute changes to the tissue due to continuous loading. Each study also included a rest period of 30 minutes to visualize the potential recovery of the PF once stress and strain are removed.

The collective finding is that healthy PF tissue reacts to different running modalities with an acute decrease in thickness and stiffness but demonstrates an ability to recover after 30 minutes of rest. A single bout of high intensity interval running (400m) until fatigue caused the PF to become thinner and less stiff, with a reduced medial longitudinal arch height. The decrease in both the morphological and mechanical properties of the PF was expected as it aligned with the general characteristics of tissue mechanics for a viscoelastic material in response to the mechanical loading. The repetitive mechanical loading of the interval runs may have induced tissue creep which suggests that continuously applied stress induced steady strain of the tissue, leading to an acute decrease in thickness. What is unknown is the direction of the strain that caused this deformation.

The findings of the first manuscript provided evidence for the quantifiable changes the PF undergoes during exercise. As tissue thickness and stiffness are commonly used as symptomatic and diagnostic factors for plantar fasciitis, the need to further understand the response of healthy tissue to imposed demands may lead to a better understanding of the causative effect of these factors. Additionally, the changes in arch height between pre- and post-run measures suggest that a decrease in PF stiffness coincides with a potential loss of medial longitudinal arch control. The PF's function to coil around the toes during initial contact and push-off, the Windlass Mechanism, may be altered with a decrease in stiffness, as the foot could lose its tension to maintain proper structure and functioning.

The second manuscript evaluated the effects of repetitive high intensity long distance runs on PF thickness and stiffness. More specifically, this protocol included a total three 5-km runs completed over the course of three consecutive days. The purpose of this study was to investigate the effects of maximal effort 5 km running on three consecutive days on morphological and mechanical properties of the plantar fascia. PF thickness and stiffness responded to the 5km bouts of running in the same manner as the high intensity interval run. Both properties decreased immediately post-run and were able to recover following 30 minutes. A novel finding from this study was the increase in PF thickness at the pre-run measurement between days. The demands of the repetitive runs did not allow adequate time for the PF thickness to return to normal thickness values.

These findings suggest that three maximal effort 5k runs have a significant effect on PF thickness. More specifically, the increase in thickness found at the pre-run measurements indicates that the lack of rest between the high intensity 5k runs may play an important role in that tissue change. This finding advocates the need for rest days or a change of the intensity or frequency of running stimuli between sessions. PF stiffness and medial longitudinal arch height showed a similar pattern of decrease immediately post-run, indicating that repetitive mechanical loading may have an effect on the PF's ability to maintain proper arch support. However, no increase over the three days was found with stiffness. The increase in thickness may be the initial evidence of tissue inflammation leading up to plantar fasciitis. A theory behind the mechanism of plantar fasciitis development suggests that excess mechanical loading without providing sufficient rest and recovery would lead to microfractures, followed by inflammation, and then chronic pain.

Thus, the third manuscript aimed to investigate individuals with resolved plantar fasciitis. A retrospective analysis of people with resolved plantar fasciitis enables potential identification of differences in tissue following a pathological condition. The running-imposed demands were a 30-minute submaximal treadmill run at a constant relative treadmill speed. To assess mechanical changes during the run, motion capture trials were collected to evaluate whether previous PF mechanical changes affect gait mechanics.

Participants with a previously reported PF injury did not have a different mechanical response of the tissue than those with no history. Both the no history and resolved plantar fasciitis groups displayed decreases in PF thickness and stiffness immediately post-run, as well as a return approaching baseline following a 30-minute recovery period. However, people with resolved plantar fasciitis presented with a significantly thicker PF at baseline and throughout the measurement times. This suggests that even after plantar fasciitis recovery, the tissue remains thicker. This can be due to scar tissue build up, or continuing inflammation. Nevertheless, the increased thickness in the resolved plantar fasciitis group did not alter PF mechanics response to the imposed running demands. Stiffness displayed similar patterns, which was unexpected as people with plantar fasciitis have displayed a less stiff PF compared to their healthy counterparts.

In terms of foot mechanics, there were no differences in forefoot dorsiflexion/plantar flexion and midfoot inversion/eversion between the two groups. However, the NPF group showed significantly greater midfoot dorsiflexion compared to the individuals with resolved plantar fasciitis. In other words, individuals who had never experienced plantar fasciitis demonstrated more medial longitudinal arch flattening during the stance phase at the halfway mark of the 30-minute run. This can be attributed to the increased stiffness of PF diminishing the ability of the medial longitudinal arch to lengthen during foot contact. Longitudinal prospective investigations are necessary to determine whether previous plantar fasciitis may indeed induce permanent changes to foot mechanics during running, and why these differences were only seen halfway through the run, and not the beginning or end. This was especially interesting as no changes in leg or vertical stiffness were found between the groups, or throughout the 30-minute treadmill run.

The series of manuscripts within this dissertation illustrates that the PF responds to running-imposed mechanical loading by decreasing thickness and stiffness acutely. This response was seen in both over ground and treadmill running. The change of the morphological and mechanical properties was quantified via ultrasound, indicating the potential to utilize ultrasound to evaluate PF tissue changes, whether post-exercise or throughout a training cycle or competitive season. Furthermore, differences in midfoot dorsiflexion during the stance phase of running, between plantar fasciitis resolved individuals and those with no history of plantar fasciitis, suggest that a previous injury to the PF may impact foot mechanics beyond recovery. It is still not understood how plantar fasciitis comes about and why thickness and stiffness change when individuals experience said injury.