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Loading Force in Recreational Runners and its Effect on Achilles Tendon Biomechanical Properties

Joshua K. Sponbeck

A dissertation submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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Abstract

Loading Force in Recreational Runners and its Effect on Achilles Tendon Biomechanical Properties

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Background: Achilles tendinopathy is a common debilitating running related injury. Achilles tendon loading force has been hypothesized as a contributor to Achilles tendinopathy. Loading force through the Achilles tendon during running is impacted many factors such as footwear and foot strike pattern. Achilles tendon biomechanical (Achilles tendon cross-sectional area, thickness, echogenicity, stiffness, and T2*) responses to loading forces are variable and measurable in vivo. These responses impact physiologic function of the tendon.

Aims: 1) To evaluate baseline Achilles tendon biomechanical characteristics associated with a runner’s habitual foot strike pattern. 2) To evaluate single running bout Achilles tendon biomechanical changes to varied forces in runners while maintaining their habitual foot strike pattern. This will be accomplished using minimalist and cushioned running shoes.

Methods: 29 recreational runners were recruited. Runners completed two separate 5.3 km running sessions wearing alternating shoe types (cushioned and minimalist) at a pace of 3.15 m/s. Prior to running each day, participants had 32 retroreflective markers placed upon them for motion analysis collection. Additionally, participants had their Achilles tendon imaged via ultrasound pre and post run. On a separate day 24 of the participants underwent an ultrashort echo time (UTE) MRI imaging session of their Achilles tendon.

Results: Achilles tendon stiffness was 20% greater in non-rear foot strike runners when compared with rear foot strike runners (p = 0.0166). Achilles tendon CSA, thickness, echogenicity, and T2* were not different between running groups (p > 0.05). Both foot strike pattern groups experienced significant Achilles tendon CSA and thickness decreases from pre to post run in minimalist and cushioned shoes (p < 0.05). Both running groups in cushioned shoes and the non-heel strike runners in minimalist shoes experienced significant increases in Achilles tendon echogenicity from pre to post run. Only non-rear foot strike runners had a significant increase in Achilles tendon stiffness while running in cushioned shoes (p = 0.03).

Conclusions: The Achilles tendons of non-rear foot strike runners were significantly stiffer than those of rear foot strike runners. This Achilles tendon characteristic may be attributable to differences in Achilles tendon loading force while running but needs further research. Both groups of runners experienced multiple single running bout Achilles tendon changes as measured via ultrasound. Although loading forces varied within groups in different shoes and between foot strike pattern groups, all Achilles tendon changes were similar regardless of loading forces from pre to post run.

Keywords: Achilles tendon, running, ultrasound, MRI
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Introduction

Recreational running is one of the most popular physical activities practiced throughout the world\(^1\). Running has numerous health benefits including improved musculoskeletal health, body composition, cardiovascular health, and psychological state\(^2\text{-}^4\). Unfortunately, one main drawback of running is a high rate of running related injury\(^5\text{-}^6\), which leads to running dropout\(^7\). Running related injuries offset health related benefits of running by decreasing or eliminating beneficial running activity\(^7\text{-}^8\).

One injury with high incidence and prevalence that stops running participation is Achilles tendinopathy\(^6\text{-}^9\text{-}^10\). Achilles tendinopathy is a devastating injury that is known to limit athletic participation and performance\(^11\). Additionally, resolution of the injury is slow, with recovery times up to one year, and once return to sport is achieved reinjury is common\(^11\text{-}^12\). Many research studies have been published concerning Achilles tendon adaptations and tendinopathy because of its debilitating nature\(^11\), high prevalence\(^13\), and increasing incidence\(^14\). However, its etiology is still not well understood\(^15\). A popular proposed mechanism for the development of Achilles tendinopathy in runners is the mechanical theory stating that excessive, repeated loading forces result in tendon fiber and extracellular matrix disruption causing dysfunction and pain\(^9\text{-}^16\).

Loading forces through the Achilles tendon during running vary highly, depending on various internal and external stimuli\(^17\text{-}^18\), such as habitual foot strike patterns and choice of footwear\(^19\). Non-rear foot strike runners experience greater Achilles tendon loading force during running when compared with rear foot strike runners\(^20\). Increased loading force in non-rear foot strike runners is associated with a larger internal plantarflexor moment arm at foot contact\(^21\text{-}^22\). One published study has indicated that non-rear foot strike runners experience higher frequency of Achilles tendinopathy which may be attributable to higher peak loading force during
running. Additionally, other factors such as eccentric loading and shock absorption in the Achilles tendon during running, both displayed more so by non-rear foot vs. rear foot strike runners, are also hypothesized to contribute to increased risk of injury besides loading force. Other researchers have reported that a non-rear foot strike pattern optimally loads the foot and ankle and provides the ideal biomechanical loading environment for tissues in this foot and ankle area, including the Achilles tendon. These authors contend that heel striking during running began with the evolution of cushioned shoes, and that having a non-rear foot strike pattern will lead to less injuries over time with appropriate time allocation for tissue adaptation.

Additionally, footwear alters the forces experienced by the Achilles tendon during running. Minimalist shoes have been shown to increase the magnitude of load and impulse experienced on the Achilles tendon during running. Minimalist shoes are also known to increase the loading rate on the Achilles tendon in runners with a non-rear foot strike and rear foot strike pattern.

In response to loading forces during running, the Achilles tendon experiences various biomechanical (Achilles tendon cross-sectional area, stiffness as measured via shear wave elastography and will simply be referred to as stiffness hereafter), echogenicity, and T2* value) tissue changes which improve running economy, improve maximal muscle power output and muscle efficiency, and allow the tendon to withstand increased forces over time. For example, long-term tendon tissue characteristics of greater stiffness and increased Achilles CSA have been found in people that run in minimalist running shoes consistently. While the Achilles tendon requires a certain amount of loading force for advantageous adaptations and to maintain tendon health, excessive forces potentially exceed the tendons inherent tensile strength, which is presumed to result in maladaptation of the tendon leading to tendinopathy. Understanding
the impact of loading forces on healthy Achilles tendon characteristics and changes may be helpful in the prevention of Achilles tendinopathy and further inform about its etiology\textsuperscript{19,34,35}. Ultrasound and magnetic resonance imaging (MRI) are imaging modalities that allow clinicians and researchers to visualize and evaluate in vivo Achilles tendon biomechanical changes\textsuperscript{36,37}. MRI is a widely used tool to assess tendon tissue properties\textsuperscript{38}. Further, MRI provides the ability to assess a T2* value of the tendon which is related to tendon collagen fiber orientation and water content\textsuperscript{39-43}. Due to long imaging times, T2* mapping is not a tool that is used to assess tendon single running bout changes\textsuperscript{44}, but can provide valuable insight into Achilles tendon baseline characteristics that occur due to habitual foot strike patterns. Ultrasound allows for reliable dynamic and static assessment of soft tissue\textsuperscript{45-47}. Using ultrasound clinicians and researchers can record high resolution video clips, known as Cine-loops, of the Achilles tendon giving insight into its CSA, thickness, stiffness, and water content (echogenicity)\textsuperscript{46}. These inherent properties of tendon can be measured and used to evaluate both baseline characteristics, and single running bout changes in real time\textsuperscript{36,48,49}. Using MRI to obtain T2* values and diagnostic ultrasound to obtain CSA, thickness, echogenicity, and stiffness, in conjunction allows for more complete evaluation of the health of the Achilles tendon.

Research on biomechanical characteristics and changes of the Achilles tendon in response to loading forces, via foot strike or footwear, is limited at this time. Three studies\textsuperscript{20,50,51} have found no baseline Achilles tendon CSA characteristics differences between non-rear foot strike runners and rear foot strike runners. One of those studies also included tendon thickness as an outcome variable and found no differences between habitual foot strike pattern groups\textsuperscript{50}. To our knowledge there have been no investigations into the baseline Achilles tendon characteristics of echogenicity, stiffness, or T2* value based upon foot strike pattern groups. Additionally, we
have no knowledge of previous investigations on any single running bout Achilles tendon changes to force. Understanding healthy Achilles tendon changes to force incurred during a single running bout and baseline tendon characteristics may help clinicians and researchers detect Achilles tendinopathy earlier and inform about its etiology.

Therefore, the aims of this study were to: 1) Evaluate baseline Achilles tendon biomechanical characteristics associated with a runner’s habitual foot strike pattern. 2) Evaluate single running bout Achilles tendon biomechanical changes in runners with habitual foot strike patterns that have experienced varying Achilles tendon loading forces during a run via footwear. We hypothesize that non-rear foot strike runners will display baseline tendon characteristics, that display a healthy tendon tissue adapted to increased force, namely increased Achilles CSA, thickness, and stiffness in conjunction with decreased tendon echogenicity and T2* values. Additionally, we hypothesize that during a single running bout in minimalist shoes both groups of foot strike runners will display exacerbated Achilles tendon biomechanical tissue changes of decreased Achilles CSA, and thickness, with increases in stiffness and echogenicity when compared with cushioned shoes.

Methods

Design

Baseline Achilles tendon characteristics associated with foot strike pattern groups – Aim 1

An analysis of covariance was utilized to answer aim 1 of this study. The dependent variables chosen were Achilles tendon CSA, thickness, echogenicity, and stiffness as measured by diagnostic ultrasound and T2* value as measured via MRI. The main effect of foot strike pattern was used to determine groups. Other independent variables included as covariates in the
analysis were age, height, weight, weekly running mileage, and hydration status over the previous 24 hours.

Acute Achilles tendon changes to force – Aim 2

A 2 x 2 x 2 (time, foot strike pattern, and foot wear) factorial design was utilized to understand the acute Achilles tendon changes in response to force changes. The first independent variable was time (2 levels – pretest and posttest separated by 3 miles of running), the second independent variable was foot strike pattern (2 levels – rear foot strike pattern and non-rear foot strike pattern) and the third independent variable was foot wear (2 levels – inov-8 (minimalist) and Nike Pegasus (cushion) shoe). The cushion shoe was chosen to represent a common regular training shoe in recreational runners and the minimalist running shoes were chosen as they have been shown to increase force through the Achilles tendon during running in comparison with a cushion shoe. The dependent variables used to measure acute Achilles tendon changes to force were Achilles tendon CSA, thickness, echogenicity, and stiffness as measured by diagnostic ultrasound.

Population

33 recreational runners, (15 heel strike runners, age = 22 ± 1.7 years, height = 179.5 ± 5.543 cm, weight = 72.27 ± 8.742 kg, 14 non-heel strike runners, age = 23 ± 3.4 years, height = 178.3 ± 8.512 cm, weight 70.51 ± 6.829 kg) were recruited for participation in this study. Four recruited participants data were not used during single running bout data analysis. The reasons for unused runner data were: two runners had varying foot strike patterns between feet with the left foot showing a heel strike pattern, and the right foot showing a non-heel strike pattern. One participant did not participate in both running sessions. The last unused participant changed foot strike patterns between the cushioned and minimalist shoes from heel strike to a non-heel strike
pattern. Of these 33 participants, 24 runners (12 heel strike, age = 22 ± 1.8 years, height = 179.2 ± 5.74 cm, weight = 72.2 ± 7.80 kg, 12 non-heel strike, age = 23 ± 3.8 years, height = 178.6 ± 7.68 cm, weight = 69.7 ± 7.03 kg) were asked to participate in the MRI portion of this study.

Participants for this study were recruited from the campus community at Brigham Young University and surrounding areas using fliers. Only male participants were recruited as higher estrogen levels found in females is known to have effects on collagen synthesis and tendon structure\textsuperscript{53-55}. Study participants were recreational runners not currently using minimalist running shoes between the ages of 18-35. For this study recreational runners running at least three times per week and able to run 5000 meters in less than 24:00 minutes were recruited. The exclusion criteria chosen for this study were 1) anyone who has experienced any injury that has kept them from running in the last 3 months, and 2) any Achilles tendon injury within the last 6 months. For the MRI portion of this study additional exclusion criteria were contraindications for undergoing MRI (pacemakers, loose metal in the body, or ferrous metal implants, etc.). No significant differences in participants’ demographics and descriptive data were found between groups as shown in table 1.

Study procedures

Participants reported to the Hunter running lab (SFH 196) on the campus of Brigham Young University. Upon arrival participants were screened according to the inclusion and exclusion criteria of the study. After determining eligibility participants read and signed an informed consent. This study was approved by the institutional review board at BYU (IRB2022-091).
Running Sessions to answer Aim 2

On two separate days participants reported to the running lab (SFH 196) on the campus of Brigham Young University separated by a minimum of 24 hours. Participants were instructed before coming to wear regular running clothes. Upon arrival participants were given a pre-participation worksheet. Following completion of the pre-participation questionnaire participants underwent ultrasound imaging of their Achilles tendon followed by a three-minute warm up period where they ran on an instrumented treadmill (Bertec Force Sensing Tandem Treadmill, Columbus, Ohio) at a pace of 2.98 m/s. After three minutes upon a signal from the treadmill operator the treadmill speed was moved to a rate of 3.15 m/s for three miles. Total running time including warm up was 28 minutes and 30 s. After completion of three miles at a pace of 3.15 m/s the treadmill was stopped, and study participants had their Achilles tendon re-imaged. During one visit participants ran in cushioned running shoes (Nike Pegasus), and on the other visit participants ran in minimalist footwear (inov-8) for the duration of the run. The order of foot wear was switch ordered and randomized so the same number of participants started in the same type of shoe.

Motion data and force data collection

Prior to the Achilles tendon imaging session on both days participants were prepared for 3D motion analysis collection. 30 retro-reflective markers were placed on various anatomical landmarks according to the Vicon Plugin Gait Model (Vicon Cord, Oxford, UK). Markers were placed bilaterally using double-sided adhesive tape on the lower extremity over the following anatomical landmarks: anterior and posterior superior iliac spines, mid-lateral thigh, lateral femoral condyle, mid-lateral shank, posterior heel on the superior, medial and lateral calcaneus, and over the second toe. Ten cameras were used during recording sampling at 250 Hz, with
instrumented treadmill (Bertec Force Sensing Tandem Treadmill, Columbus, Ohio) force plates sampling at 1000 Hz. During the running session runners were filmed with the treadmill moving at a rate of 3.15 m/s.

Foot strike pattern determination

During the motion and force data collection periods of running participants were filmed using a high-speed camera (Sony A7S, frame rate = 120 Hz) for use in determining foot strike patterns at initial contact. Foot strike was classified subjectively using this video. Rear foot strike was classified as initial ground contact with heel or rear 1/3 of shoe, non-rear foot strike was classified as initial ground contact with any part of the foot besides the heel (figure 1).

Ultrasound Imaging

Prior to the running protocol, all participants participated in ultrasound imaging. During Achilles tendon ultrasound imaging the participant lay prone on a treatment table with their ankle resting in a comfortable position. While participants rested foot dominance was determined by asking the study participant with which foot, they would most likely kick a soccer ball. Additionally, during this period a mark was placed in a straight line between the apex of the medial and lateral malleolus for use during ultrasound imaging. Following the rest period study participants were positioned with their feet flat on a fixed flat surface (a wall) during imaging. The fixed flat surface was used to maintain a 90-degree ankle position and constant pronation and supination position during imaging. Ultrasound (GE Logic E, GE Healthcare, Little Chalfont, United Kingdom) images were taken of the participants left and right Achilles tendons. Achilles tendon CSA, thickness and elastography images were taken at the mark made between the level of the medial and lateral malleolus (figure 2). Cross sectional area and thickness ultrasound images were taken using a li8-18 “hockey stick” probe, while stiffness images were
acquired using a 9L probe with capability for elastography. Cine-loop images consisting of multiple frames were taken for use in tendon CSA, thickness, and echogenicity calculations. A continuous cine loop image consisting of at least three separate frames was collected of elastography data for use in determining Achilles tendon stiffness.

**US Reliability**

Data for this study showed excellent reliability. The intraclass correlation coefficients (ICC\(_{3,1}\)) values, standard error of the mean (SEM) with associated 95% confidence intervals, and minimum detectable difference (MDD) for Achilles tendon measurements of CSA, thickness, echogenicity, and stiffness can be seen in table 2. The formulas used for calculations are as follows:

\[
\text{SEM} = \text{SD} \times \sqrt{1 - r_{ICC}}
\]

\[
95\% \ CI\ \text{SEM} = \text{tendon mean} \pm (1.96 \times \text{SEM})
\]

\[
\text{MDD} = \text{SEM} \times 1.96 \times \sqrt{2}
\]

**MRI Session to answer Aim 1**

As part of a different data collection session on a different day participants reported to the MRI facility located on the campus of Brigham Young University. Participants were instructed to not participate in exercise before their MRI session. Prior to entering the MRI machine, participants completed an MRI safety screening in the waiting room. Once completed and MRI eligibility was ensured participants entered the MRI room and were positioned on the MRI table. A 3 Tesla magnet (TIM-Trio 3.0 T MRI, Siemens, Erlangen, Germany) was used to scan the dominant foot Achilles tendon. Participants lay supine on the MRI table and were placed feet first into the magnet. An initial localizer scan was used to center the Achilles tendon at the level of the medial and lateral malleolus. T2 weighted MRI images were acquired using a custom cones sequence\(^{56}\), with an acquisition time of 53 minutes. The
resolution was 0.4 x 1.1 x 0.4 mm with a slice thickness of 0.44 mm, and a distance between slices of 1 mm. The resolution matrix was 220x220x220. An 8-channel foot and ankle coil was used to obtain a total of 10 images at each location. Repetition Time (TR)=10 ms and ultra short Echo Times (TE)= 0.25 ms, 0.5 ms, 0.75 ms, 1 ms, 2 ms, and 5 ms.

Data Processing

Motion analysis data, collected from the locations of the reflective markers, were reconstructed into three-dimensional coordinates using VICON Nexus software (VICON Motion Technologies, Centennial, CO, USA). During the 30 second run the instrumented treadmill recorded peak vertical ground reaction forces at 1200 Hz. A static trial was obtained before running, where the participant stood on the treadmill for at least two seconds in anatomical position but with palms facing medially. Force data were smoothed with a 50--Hz low-pass Butterworth filter. Motion data were filtered with a 20--Hz low pass Butterworth filter. Motion data were collected about 4 minutes into the running protocol. Obtaining motion data following the warm-up protocol ensured that subjects were warm and accustomed to the treadmill and conditions of the lab. Motion data were used to calculate peak force experienced by the Achilles tendon in the different shoes using the ground reaction force, and ankle plantar flexor moment arms. Ankle plantar flexor moments were generated by use of Newton-Euler inverse dynamics. Achilles tendon force (ATF) was calculated using the following equation:

\[
\text{ATF} = \frac{\text{Internal ankle plantar flexor moment}}{\text{Achilles tendon moment arm throughout stance}}
\]

Achilles tendon moment arm was estimated using a previously published regression equation:

\[
\text{Achilles tendon moment arm} = -0.5910 + 0.08297x - 0.0002606x^2
\]

In this equation x was equal to the sagittal plane ankle angle. Cumulative force data was calculated using the following equation:
Cumulative Force = Achilles Tendon Force × Strides per Mile × 3 miles

Achilles tendon CSA, thickness, and stiffness were analyzed using internal software on the ultrasound machine. To analyze CSA the Achilles tendon border was outlined manually for both the left and the right leg. The tendon was outlined twice (once on each cine loop) for each the right and the left leg and the average used for statistical analysis. During analysis for Achilles tendon thickness the tendon was measured from the superficial to the deep border of the tendon on two frames. The measurement occurred at the midpoint of the ultrasound screen, as this point corresponded to the malleolar line. Echogenicity was obtained by utilizing the region of interest from Achilles tendon CSA measurements in a custom Matlab (Mathworks, Natick, MA) software. The software is based upon a grey scale profile ranging from 0 – 150. Both Achilles tendon CSA images were analyzed and the average of the two was used for statistical analysis. Achilles tendon elastography was analyzed across two frames using three circles per frame. The average of the six data points was used for statistical analysis (figure 2). Where possible the circles inside a frame spanned from the superficial side of the tendon to the deep side of the tendon. This was not always possible due to voids during elastography imaging. In the event of voids the largest circles possible were used. T2* value analysis was obtained following MRI image acquisition. MRI files were loaded through a custom Matlab program in order to obtain T2* maps. Anatomy scans were used to obtain a region of interest that was in the Achilles tendon at the level of the medial and lateral malleoli. An average T2* value was obtained at this level using a constant region of interest across three slices.

Statistical Analysis

Power analysis indicated that to understand aim 1 of this study 28 participants (14 rear foot strikers, and 14 non-rear foot strikers) were needed for sufficient study power.
Power analysis was calculated using a clinical difference of 4% and a standard deviation of 0.0378 which was obtained from preliminary data.

Power analysis indicated that 24 participants (12 rear foot strike pattern runners, and 12 non-rear foot strike pattern runners) were needed to understand aim 2 of this study. Clinical difference values and standard deviation values were obtained using published data from Grosse et al.93

Achilles tendon baseline characteristics associated with foot strike pattern were assessed using an analysis of covariance. Fixed effects in this model were age, height, weight, miles ran this week, miles ran last week, and 5K time. Alpha was set at 0.05, and a backward stepwise approach was used to identify significant variables. Due to non-normalized data, analysis of T2* data was performed using a log transformation. Achilles tendon changes in response to force were analyzed using a mixed model analysis of covariance. Subject was utilized as a random effect, with all other variables being fixed effects in the model. Fixed effects included age, height, weight, miles ran this week, miles ran last week, and 5K time. Tukey HSD post hoc tests were used to determine differences among significant variables. All statistical analysis was performed using Statistical Analysis Software (JMP pro Version 16, SAS Institute, Inc. Cary, NC, USA)

Results

Baseline Achilles Tendon Characteristics associated with Foot Strike Pattern

Achilles tendon stiffness was 20% greater in non-rear foot strike runners when compared with rear foot strike runners (p = 0.02) (Figure 3). Achilles tendon CSA, thickness, echogenicity, and T2* were all not different between running groups (p > 0.05).
Single Running Bout Achilles Tendon Changes

Both running groups experienced significant Achilles tendon CSA and thickness decreases from pre to post run in minimalist and cushioned shoes \((p < 0.05)\) (Table 3). Both running groups experienced significant increases in Achilles tendon echogenicity from pre to post run in cushioned shoes and non-heel strike runners experienced a significant increase in echogenicity in minimalist shoes \((p < 0.05)\). Only non-rear foot strike runners experienced a significant increase in Achilles tendon stiffness while running in cushioned shoes from pre to post run \((p = 0.03)\) (Table 3).

There were no between running group or within running group differences in Achilles tendon CSA percent loss, Achilles thickness percent loss, Achilles echogenicity percent increase, or Achilles elastography percent change when comparing shoe wear within groups or foot strike patterns between groups \((p > 0.05)\) (Figure 4).

Achilles Tendon Force Data

Non-rear foot strike runners experienced statistically significantly more Achilles tendon force during running when compared with rear foot strike runners as seen in figure 5 and table 4 \((p < 0.01)\). Runners best five-kilometer race time was a significant fixed effect \((p = 0.01)\). When the rear foot strike runners were in minimalist shoes Achilles tendon peak force difference was statistically significant increased compared with cushioned shoes \((p < 0.01)\) as seen in figure 5.

There were no significant differences in stride rate per second between rear foot strike and non-rear foot strike runners during running \((p = 0.95)\). Both running groups experienced a statistically significant increase in stride rate per second when running in minimalist shoes when compared with cushion shoes \((p = 0.046)\). The average footsteps per mile had no significant difference between the running groups, or within a running group when comparing the different shoes \((p > 0.05)\). During a mile the non-rear foot strike runners took on average five additional
strides while wearing minimalist shoes and 8 additional strides in cushion shoes when compared with rear foot strike runners (Table 4).

Accumulating Achilles tendon force over the run was statistically different between non-rear strike runners and rear strike runners (p < 0.01) with non-rear foot strike runners experiencing higher cumulative Achilles tendon force. The difference in total Achilles tendon force between non-rear foot strike and rear foot strike runners was 1,535 and 1,922 body weights, in minimalist shoes and cushioned shoes respectively. Both groups of runners experienced statistically significantly higher total force (p < 0.01) when running in minimalist shoes compared with cushioned shoes over the run. The rear foot strikers experienced the largest change in Achilles tendon force when running in the minimalist shoes, just over 900 body weights of force on average (table 4).

Achilles tendon loading rate showed no statistical difference when comparing non-rear foot strike runners and rear foot strike runners (p = 0.09). Both groups of runners experienced a statistically significant increase in Achilles tendon loading rate when running in minimalist shoes (p < 0.01).

Discussion

The aims of this study were:

1. To evaluate baseline Achilles tendon biomechanical characteristics associated with foot strike pattern. We hypothesized that Achilles tendons of non-rear foot strike runners would be increased in CSA, thickness, elastography, and T2*, and decreased in echogenicity, compared with rear foot strike runners.

2. To evaluate single running bout Achilles tendon biomechanical changes in response to force. We hypothesized that running in minimalist shoes would exacerbate Achilles tendon
CSA and thickness size decreases, and increases in echogenicity and Achilles tendon elastography when compared with cushioned shoes from pre to post run.

One hypothesis from aim 1 of this study was supported by the results of our data, which indicate that non-rear foot strike runners Achilles tendons are significantly stiffer as measured by shear wave elastography when compared with rear foot strike runners. No other Achilles tendon baseline characteristics differences were seen, contrary to our hypothesis of aim 1. No hypotheses from aim 2 were supported by the results of this study, as no statistical Achilles tendon biomechanical differences were found when comparing minimalist to cushioned shoes.

The Achilles tendon stiffness of non-rear foot strike runners was significantly greater than rear foot strike runners when comparing baseline tendon characteristics based on habituated foot strike pattern. During functional movements, such as walking, or running, the Achilles tendon experiences extreme load up to nearly 8 times body weights of force\textsuperscript{58}. A stiff tendon is healthy and ready to absorb high loading force that occurs during functional activity\textsuperscript{59}. A pathologic tendon loses stiffness, and becomes painful\textsuperscript{16}. A loss of stiffness during tendon pathology is likely the result of microscopic or macroscopic damage degenerating tendon extracellular matrix structure\textsuperscript{16}. A tendon that is pathologic is not ready to withstand the high loading forces that occur during functional movements. Recent evidence indicates that Achilles tendon stiffness is a continuous adaptation that increases due to physical activity and sport level\textsuperscript{60-62}. The differences in Achilles tendon stiffness in this study may be associated with the high Achilles tendon peak force experienced by non-rear foot strike runners during running. This study provides supporting evidence that within healthy, active, populations, variation in Achilles tendon elastography occurs. Additional normative values of stiffness within physically active asymptomatic Achilles tendons will help to further establish what is considered an appropriate
tendon characteristic as measured by shear wave elastography. These values may help clinicians and researchers detect earlier Achilles tendon pathology in active individuals.

Achilles tendon CSA, thickness, echogenicity, and T2* were not statistically different between habituated non-rear foot strike and rear foot strike runners. To our knowledge, this is the first study to investigate differences in Achilles tendon thickness, echogenicity, and T2* between runners with a non-rear foot strike pattern and a rear foot strike pattern. The results of this investigation are in agreement with three previous studies comparing foot strike patterns and Achilles tendon CSA, where no statistical differences were found. It has previously been shown that Achilles CSA hypertrophy occurs in athletes when compared with non-athletes. However, amongst already active populations Achilles CSA changes may not be the main adaptation to handle increased loading forces. Although the populations of foot strike runners in this study had significantly different loading forces during each loading cycle, the load experienced by each group was enough stimulus to cause similar Achilles tendon CSA in running groups. T2* values provide an additional measure of Achilles tendon health and will be discussed in the subsequent paragraph. These factors deserve further research and exploration.

T2* values are a non-invasive, useful measure of Achilles tendon collagen organization and water content that help researchers and clinicians understand the health of a tendon. It has previously been shown that individuals with Achilles tendon pathology have elevated T2* values reflective of collagen disorganization and increased water content. Additionally, one previously published study found T2* values differ by activity level within an active, healthy population such as runners. The T2* values found in the mentioned study are slightly higher than the rear foot strike runners in this study, and over two times the values of the non-heel strike runners. The majority of runners are rear foot strike runners and it is possible that some of
the runners in the Grosse study were rear foot strike runners. Additional data and a more complete understanding of normative T2* values amongst various running populations may be used as an important predictor of Achilles tendinopathy.

During a single running bout both groups of runners experienced acute Achilles tendon CSA, thickness, echogenicity, and stiffness changes, which were significantly different from pre to post run. Achilles tendon changes during activity are integral to increase efficiency of muscle output\(^{69}\), increase power output of a muscle\(^{70}\), and retain and release elastic energy during movement\(^{71}\). The Achilles tendon changes observed during a single running bout in this study were decreased Achilles tendon CSA and thickness, and increased echogenicity and stiffness. The results of this study agree with previous research displaying single running bout CSA tendon changes\(^{48, 49, 72}\). These observed changes are important to improve physiologic function or nutrition of the tendon.

Although Achilles tendon loading forces varied between foot strike pattern groups and within the rear foot strike running group between shoes, the Achilles tendon single running bout biomechanical changes were statistically not different regardless of running condition. Although Achilles tendinopathy has several proposed etiologic mechanisms\(^{9, 16}\) a commonly accepted hypothesis is the mechanical theory of Achilles tendinopathy as proposed by Burry et al in 1978\(^{73}\). It states that excessive mechanical stimulation via strain or compression leads to tendon degenerative changes. This study created variational loading forces via shoe wear in runners with different foot strike patterns and measured biomechanical tissue changes which then were compared to changes obtained from a lesser load. The results of this study show inducing an additional 913 body weights in heel strike runners in minimalist shoes vs. cushion shoes over three miles did not result in larger single running bout biomechanical changes in the tendon. It
should be noted that under normal healthy tendon regulation, early tendon extracellular matrix
disruption starts an effective healing process, and that tendinopathy may only result from
accumulated matrix damage over time\textsuperscript{74}. Since imaging in this study occurred directly after
running, and the running stimulus occurred only once, runners may have had initial micro
damage within the extracellular matrix due to increased force that initiated early healing that was
not discernable on a whole tissue level. Further investigation needs to be conducted into the
accumulation of matrix damage in vivo and how that relates to tissue wide biomechanical
changes.

Non-rear foot strike runners experienced statistically significantly higher force in both
shoe types when compared with rear foot strike runners. These data agree with one previously
published study that demonstrated significantly larger Achilles tendon peak force in habitual
non-rear foot strike runners in cushioned running shoes\textsuperscript{22}. Additionally, this study agrees with a
study by Lyght et al which recruited habitual rear foot and non-rear foot strike runners and had
each runner perform several paces and types of foot strike while running and found significant
Achilles tendon peak force differences between non-rear foot and rear foot strike runners\textsuperscript{51}. Two
previous studies which only recruited rear foot strike runners\textsuperscript{19} or had runners non shod while
running\textsuperscript{52} showed no difference in Achilles tendon peak force between non-rear foot and rear
foot strike runners while running. Method differences between studies are potential reasons for
the discrepancies in results in comparison with this study and the study by Kulmala et al. In each
referenced study running protocols were performed on a raised platform with data collection
occurring on a force plate recording a single foot strike. Trials were performed at least 5 times
and then the average of 5 trials was averaged. The current study was performed on a treadmill,
where data collections were able to occur over a longer time with consistent running patterns.
The extended collection time period allowed for an average of 41 footsteps during data collection that were averaged and time normalized. The total averaged footsteps along with the habitual running patterns conducted as a part of this study adds an important component to the literature regarding Achilles tendon loading rate, and peak force, along with the calculation of Achilles tendon force per mile and three mile run.

Rear foot strike runners experienced significantly more Achilles tendon force when comparing minimalist shoes to cushioned shoes, while the non-rear foot strike runners did not. Previous investigations into the impact of footwear on Achilles tendon loading have shown differing results\textsuperscript{19, 28}. Similar to the results of this study Sinclair et al found a significant increase in Achilles tendon force while wearing minimalist shoes in rear-foot strike runners\textsuperscript{28}. In contrast with the results of this study and those of Sinclair et al, Rice et al found no statistical difference between shoe wear conditions in habitual rear foot strike runners\textsuperscript{19}. The Achilles tendon peak force of this study in minimalist shoes and cushioned shoes were similar to those found by Sinclair et al with averages close to 6 body weights per footstep. Each of these previous studies recruited only habitual heel strike runners. To our knowledge this is the first investigation on the impact of footwear on Achilles tendon peak force, and loading rate, in habitual non-rear foot strike and rear foot strike runners comparing shoe types.

Limitations

There are some possible limitations that should be noted as part of this study. One possible limitation was the impact of increased training or intensity on Achilles tendon biomechanical properties. Although all runners were able to at least run a 24:00 minute five-kilometer race, and participated in running at least three times each week, within each foot strike pattern group, runners varied in five-kilometer race times and weekly running mileage. However,
there were no significant between group differences found in this study. Training patterns may likely impact Achilles tendon biomechanical changes and need additional investigation.

An additional limitation of this study is variability in ultrasound imaging day to day. We did assess our reliability in ultrasound imaging as part of this study which we found to be excellent. Additionally, we assessed the minimum detectable difference as part of this study which was lower than the measured differences in our results. The authors feel confident that the results of this study were larger than day to day variability in ultrasound imaging.

Conclusions

The Achilles tendons of non-rear foot strike runners were significantly stiffer than those of rear foot strike runners when comparing baseline tendon characteristics by foot strike pattern. This Achilles tendon characteristic may be attributable to differences in Achilles tendon loading force while running but needs further research. A stiffer Achilles tendon is readily able to handle high loading forces during functional activities like running. Both groups of runners experienced multiple single running bout Achilles tendon changes as measured via ultrasound. Although loading forces varied within groups in different shoes and between foot strike pattern groups, all Achilles tendon changes were similar regardless of loading forces from pre to post run. Understanding baseline tendon characteristics and single running bout Achilles tendon changes to force is useful for clinicians and researchers to establish parameters of a healthy Achilles tendon amongst athletic individuals. In addition, these imaging measures may prove useful in predicting and diagnosing Achilles tendinopathy in the future.
References


Table 1. Participant Demographics and Descriptive Data by Running Group

<table>
<thead>
<tr>
<th></th>
<th>Heel Strike Runners</th>
<th>Non-Heel Strike Runners</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22 ± 1.7</td>
<td>23 ± 3.4</td>
<td>0.15</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.5 ± 5.54</td>
<td>178.3 ± 8.51</td>
<td>0.69</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>72.27 ± 8.74</td>
<td>70.51 ± 6.83</td>
<td>0.68</td>
</tr>
<tr>
<td>Miles Run Last week</td>
<td>21.6875 ± 15.56</td>
<td>23.375 ± 17.24</td>
<td>0.75</td>
</tr>
<tr>
<td>Miles Run this week</td>
<td>21.5 ± 14.0</td>
<td>25.1 ± 17.9</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Data are provided as means ± SD
Table 2. Ultrasound reliability data for Achilles CSA, thickness, echogenicity, and stiffness

<table>
<thead>
<tr>
<th></th>
<th>ICC value (95% CI)</th>
<th>SEM (95% CI)</th>
<th>MDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSA</td>
<td>0.993 (0.990-0.995)</td>
<td>0.006 (0.510-0.534)</td>
<td>0.017</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.990 (0.985-0.993)</td>
<td>0.004 (0.468-0.484)</td>
<td>0.011</td>
</tr>
<tr>
<td>Echogenicity</td>
<td>0.997 (0.996-0.998)</td>
<td>0.427 (56.45-58.13)</td>
<td>1.184</td>
</tr>
<tr>
<td>Stiffness</td>
<td>0.997 (0.987-0.999)</td>
<td>1.47 (117.43-123.19)</td>
<td>4.075</td>
</tr>
</tbody>
</table>
Table 3. Single Running Bout Achilles Tendon Changes

<table>
<thead>
<tr>
<th>Achilles Tendon Cross Sectional Area (cm²)</th>
<th>Achilles Tendon Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimalist Shoes</td>
</tr>
<tr>
<td></td>
<td>RFS</td>
</tr>
<tr>
<td>Pre Run Value</td>
<td>0.51 ± 0.07</td>
</tr>
<tr>
<td>Post Run Value</td>
<td>0.49 ± 0.06</td>
</tr>
<tr>
<td>% Change</td>
<td>5.54 ± 3.82</td>
</tr>
<tr>
<td>Pre to Post run P Value</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cohen’s D Effect Size</td>
<td>0.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Achilles Tendon Echogenicity (1)</th>
<th>Achilles Tendon Stiffness (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimalist Shoes</td>
<td>Cushion Shoes</td>
</tr>
<tr>
<td>RFS</td>
<td>NRFS</td>
</tr>
<tr>
<td>Pre Run Value</td>
<td>55.79 ± 7.97</td>
</tr>
<tr>
<td>Post Run Value</td>
<td>58.61 ± 6.15</td>
</tr>
<tr>
<td>% Change</td>
<td>5.89 ± 8.50</td>
</tr>
<tr>
<td>Pre to Post run P Value</td>
<td>0.06</td>
</tr>
<tr>
<td>Cohen’s D Effect Size</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Single running bout Achilles tendon changes as measured by diagnostic ultrasound. Values are provided as means and standard deviations. Significant effects are in bold. RFS, rear-foot strike; NRFS, non-rear foot strike.
Table 4. Achilles Tendon Force Data by Shoe Type and Foot Strike Pattern Group

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimalist Shoes</th>
<th></th>
<th></th>
<th>Cushion Shoes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RFS</td>
<td>NRFS</td>
<td>RFS</td>
<td>NRFS</td>
<td></td>
</tr>
<tr>
<td>ATF (BW)</td>
<td>6.10 (0.60)†</td>
<td>6.73 (0.62)*</td>
<td>5.78 (0.50)</td>
<td>6.55 (0.41)*</td>
<td></td>
</tr>
<tr>
<td>Stride rate/s</td>
<td>1.40 (0.09) †</td>
<td>1.40 (0.07) †</td>
<td>1.38 (0.09)</td>
<td>1.39 (0.06)</td>
<td></td>
</tr>
<tr>
<td>Strides/mile</td>
<td>712.77 (48.05)</td>
<td>717.48 (34.09)</td>
<td>703.58 (48.52)</td>
<td>711.70 (30.82)</td>
<td></td>
</tr>
<tr>
<td>AT loading rate</td>
<td>54.48 (7.53)†</td>
<td>56.95 (7.85) †</td>
<td>47.95 (5.49)</td>
<td>53.51 (7.65)</td>
<td></td>
</tr>
<tr>
<td>ATF/ 3 miles (BW)</td>
<td>13885.52† (1297.52)</td>
<td>15420.01*† (1033.95)</td>
<td>12972.55 (1100.04)</td>
<td>14894.23* (727.89)</td>
<td></td>
</tr>
</tbody>
</table>

Data are provided as means (SD). * indicates a statistically significant difference between rear foot strike and non-rear foot strike runners (p < 0.05) † indicates a statistically significant difference between shoe wear conditions (p < 0.05) ATF, Achilles Tendon Force; BW, Body Weight; RFS, rear-foot strike; NRFS, non-rear foot strike
Figure 1. Foot strike pattern examples and shoe type examples. a) Non-heel strike in cushion shoes. b) Non-heel strike in minimalist shoes. c) Heel strike in cushion shoes d) Heel strike in minimalist shoes
Figure 2 Ultrasound tendon images and associated measurements a) Achilles tendon CSA. b) Achilles tendon thickness. c) Achilles tendon echogenicity. d) Achilles tendon stiffness
Figure 3. Baseline Achilles tendon characteristics associated with foot strike pattern groups. * indicates a significant difference of $p = 0.02$
Figure 4. Achilles tendon single running bout changes within running groups and between foot strike pattern groups. No changes were significant within running groups by shoe type or between foot strike pattern groups (p > 0.05)
RFS, rear-foot strike; NRFS, non-rear foot strike
Figure 5. Time normalized Achilles tendon force for one foot step in body weights for both rear foot and non-rear foot strike runners. * indicates a statistically significant difference between rear foot strike and non-rear foot strike runners (p < 0.05). † indicates a statistically significant difference between shoe wear conditions (p < 0.05)