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RESEARCH ARTICLE

Achilles tendon structure differs between competitive distance runners and nonrunners despite no clinical signs or symptoms of midsubstance tendinopathy

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Hullfish TJ, Hagan KL, Casey E, Baxter JR. Achilles tendon structure differs between competitive distance runners and nonrunners despite no clinical signs or symptoms of midsubstance tendinopathy. *J Appl Physiol* 125: 453–458, 2018. First published May 17, 2018; doi:10.1152/japplphysiol.00012.2018.—Achilles tendinopathy affects many running athletes and often leads to chronic pain and functional deficits. Although changes in tendon structure have been linked with tendinopathy, the effects of distance running on tendon structure are not well understood. Therefore, the purpose of this study was to characterize structural differences in the Achilles tendons in healthy young adults and competitive distance runners using quantitative ultrasound analyses. We hypothesized that competitive distance runners with no clinical signs or symptoms of tendinopathy would have quantitative signs of tendon damage, characterized by decreased collagen alignment and echogenicity, in addition to previous reports of thicker tendons. Longitudinal ultrasound images of the right Achilles tendon midsubstance were acquired in competitive distance runners and recreationally active adults. Collagen organization, mean echogenicity, and tendon thickness were quantified using image processing techniques. Clinical assessments confirmed that runners had no signs or symptoms of tendinopathy, and controls were only included if they had no history of Achilles tendon pain or injuries. Runner tendons were 40% less organized, 48% thicker, and 41% less echogenic compared with the control tendons ($P < 0.001$). Young adults engaged in competitive distance running have structurally different tendons than recreationally active young adults.

NEW & NOTEWORTHY In this study, we quantified the Achilles tendon substructure in distance runners, and a control group of young adults, to determine whether distance running elicits structural adaptations of the tendon. We found that competitive distance runners have structurally compromised Achilles tendons despite not showing any clinical signs or symptoms of tendon injury. These findings suggest that distance running may stimulate structural changes as a protective mechanism against tendon pain and dysfunction.

Achilles tendon; collagen alignment; running; tendinopathy; ultrasound

INTRODUCTION

Midsubstance Achilles tendinopathy is among the most commonly reported injuries in running athletes (24). Repetitive tendon loading as high as 12 times body weight (10) is thought to elicit structural changes observed in tendinopathy development. This overuse injury presents with pain and swelling of the tendon 4–6 cm proximal to the calcaneal insertion, which leads to upward of a 50% decrease in the elastic modulus of the tendon (4). Qualitative ultrasonography is often used to confirm this diagnosis using subjective grading scales of tendon structure and echogenicity (18, 30, 41). Once symptomatic, Achilles tendinopathy can be challenging to treat and may result in suboptimal clinical outcomes (31); therefore, it is essential to develop sensitive predictors of presymptomatic tendinopathy. While structural changes elicited by tendinopathy, in both human and animal tendon, have been characterized using histological and imaging techniques (39), these invasive measurements are not practical to employ in clinical settings.

In vivo measurements of tendon structure have been linked to tendon damage in both human and small animal studies. Magnetic resonance imaging has highlighted tendon hypertrophy in response to tendon loading during running in elite and recreational athletes (7, 28); however, these observations have only characterized the cross-sectional area of the tendon—not the underlying structure. Micromorphological analyses of symptomatic Achilles tendons are correlated with decreased tendon mechanics (20) but have not quantified structural differences in individuals at increased risks of developing tendinopathy. Differences in tendon mechanics observed between healthy and diseased tendons have been correlated with mean echogenicity in animals (9), suggesting a relationship between tendon structure and echogenicity. Crossed polarizer imaging (21, 34) and an ultrasonography analog (11, 13, 34) detect structural changes, characterized by decreased collagen alignment, in response to acute tendon damage and the healing response in small animal models. However, the sequence of structural changes and symptomatic tendinopathy have not yet been clarified. The first step to elucidating this structure-symptom relationship is to quantify tendon structure in a cohort of individuals that are at an elevated risk of developing tendinopathic symptoms (27).

The purpose of this study was to quantify Achilles tendon structure in recreationally active adults and competitive distance runners using a repeatable and reliable ultrasound measurement of collagen organization. We hypothesized that competitive distance runners would show quantitative signs of tendon damage, characterized by decreased echogenicity (9)

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and collagen alignment (21, 34) and have thicker Achilles tendons (28) compared with recreationally active adults, despite no reports or clinical signs of tendinopathy symptoms. Studying trained distance runners that have no recent tendon injuries provides a unique opportunity to assess the structure in tendon that is habituated to repetitive loading. A secondary aim of this study was to determine whether sex, body mass index (BMI), foot strike pattern, or years running affect collagen organization and echogenicity in competitive distance runners.

METHODS

Study design. Twenty-two competitive-collegiate distance runners (12 men/10 women; age: 19 ± 1.5, BMI: 20.3 ± 1.6) and twelve healthy controls (5 men/7 women; age: 25 ± 2; BMI: 23.8 ± 2.4) participated in this institutional review board-approved study (Table 1). All subjects provided informed written consent before participation. All subjects met several inclusion criteria: no Achilles tendon pain at or 3 mo before the initial evaluation, no history of partial or complete tendon rupture, and ability to perform single-leg hops on both sides, which is commonly used as a clinical screening tool for diagnosing Achilles tendon maladies. Age, sex, height, and weight were collected from all subjects. In addition to demographics, other information was collected from the runner group: a clinical outcome questionnaire (VISA-A) (35), self-reported running foot-strike pattern, lower-extremity injury history, and years of participation in competitive-distance running. All competitive-distance runners participated on an NCAA cross-country team, and images were acquired during a single session before the start of the competitive season. The runners did not participate in heavy-resistance training. Individuals with clinical signs of tendinopathy, identified through qualitative ultrasonography assessments and self-reported clinical outcomes, were excluded from analysis.

Image acquisition. Longitudinal B-mode ultrasound images of the right Achilles tendon were acquired while subjects lay prone on a treatment table with the knee fully extended, the anterior aspect of the shank resting on the table, and the foot hanging off the table. We choose to acquire images in this resting ankle position because it controlled the amount of tension in the tendon across subjects (38). Images of the runner group were acquired on the rest day of a light training week, and the control subjects reported no physical activity 24 h before completing this protocol. These images were acquired at the midsubstance of the Achilles tendon, ~4 cm proximal to the calcaneal insertion, using an 18-MHz transducer (L18-10L30H-4, SmartUs; TELEMED, Vilnius, Lithuania) with a scanning width of 3 cm (scan parameters: dynamic range: 72 dB; gain: 47 dB). Longitudinal Doppler images were acquired in the runner group as part of the clinical evaluation to quantify the level of neovascularization of the tendon (41). All images were acquired by a single investigator, saved as videos, and evaluated by a fellowship-trained sports medicine physician who was blinded to all other subject data. Tendon structure and neovascularization were both graded (41) on a scale from 0 to 3: ranging from normal (0) to severe symptoms (3). Recreationally active adults served as the control group in this study and reported no history of Achilles tendon pain or injuries, and, therefore, they were not evaluated using a clinical grading system (41).

Table 1. *Subject demographics*

	Sex, Women/Men (total)	Age, yr	Height, cm	Weight, kg
Runners	9/10 (19)	19 ± 1.5	172 ± 7	60.4 ± 8
Controls	7/5 (12)	25 ± 2*	175 ± 7	73 ± 9*

Values are expressed as means ± SD; total *n* appears in parentheses. *$P < 0.05$, significantly different from control group.

Table 2. *Runner information and tendon clinical grading*

Footstrike Pattern (FF/MF/RF)	Years Running	VISA-A, %	Clinical Grading: Structure, 0–3	Clinical Grading: Neovascularity, 0–3
3/11/2 (16)	6.4 ± 2.5	93.4 ± 8	0 ± 0	0.05 ± 0.21

Values are expressed as means ± SD; total *n* appears in parentheses.

Image analysis. Collagen organization was quantified in the longitudinal B-mode ultrasound images using custom-written software that has been described in detail elsewhere (34). Briefly, a computational analog for crossed polarizer imaging was used to quantify collagen fascicle alignment of the midsubstance of the Achilles tendon. Fascicles are hyperechoic compared with the hypoechoic extracellular matrix, which gives the tendon a banded appearance. The orientations of these bands were determined, and the distribution was calculated as a circular standard deviation (CSD). Lower CSD values represent more aligned—or organized—collagen fascicles; conversely, higher CSD values indicate less organized fascicles. This computational analog for crossed polarizer imaging has characterized tendon damage in small animal studies (13, 34) and has strong intrarater reliability in human tendon [$0.77 < r < 0.94$ (17)].

Tendon thickness and echogenicity were calculated using established quantitative methods (9, 37, 41). The longitudinal thickness of the tendon was measured as the point-to-point distance between the deep and superficial edges of the tendon. These measurements were made by a single investigator using an open-source image analysis tool (ImageJ, version 1.51k) (37). Previous work has shown measurements of longitudinal thickness to be highly reliable between investigators ($r > 0.96$) (41). Average echogenicity was calculated for the same tendon regions of interest that were used to calculate CSD, by averaging each pixel grayscale value (9).

Statistical analysis. To test our hypothesis that the Achilles tendons of competitive-distance runners differed structurally without presentation of tendinopathic symptoms than their recreationally active peers, we compared measurements of collagen organization, tendon thickness, and echogenicity between the two groups using one-way unpaired *t*-tests. This study was powered to detect an expected difference in CSD of 25% ($\beta = 0.80$, $n = 12$). The a priori significance level of 0.05 was adjusted to account for multiple comparisons using a Bonferroni correction ($\alpha = 0.05/3 = 0.017$). Secondary analyses were performed to determine whether other runner characteristics, sex, BMI, self-reported foot-strike pattern (forefoot, midfoot, and rearfoot), and years running at the collegiate level explained measurements of collagen organization. Unpaired two-way *t*-tests were performed to test differences explained by sex and foot-strike pattern. Univariate linear regression was performed to test the relationship between the continuous variables of BMI and years running with collagen alignment.

RESULTS

Runners had high VISA-A scores (93.4 ± 8.05, $n = 19$) and no signs of neovascularization in the tendon (Table 2). Three runners did not complete the VISA-A score and were excluded in further analyses despite meeting our inclusion criteria, which included no current or recent Achilles tendon pain. Some runners had reported dealing with running-related pain either at the time of the study or previously; however, these reported events did not originate in the Achilles tendon. All runner tendons were qualitatively graded as having "normal structure," and only one of the Doppler scans showed "mild neovascularization," while the remaining subjects in the runner cohort showed no signs of neovascularization.

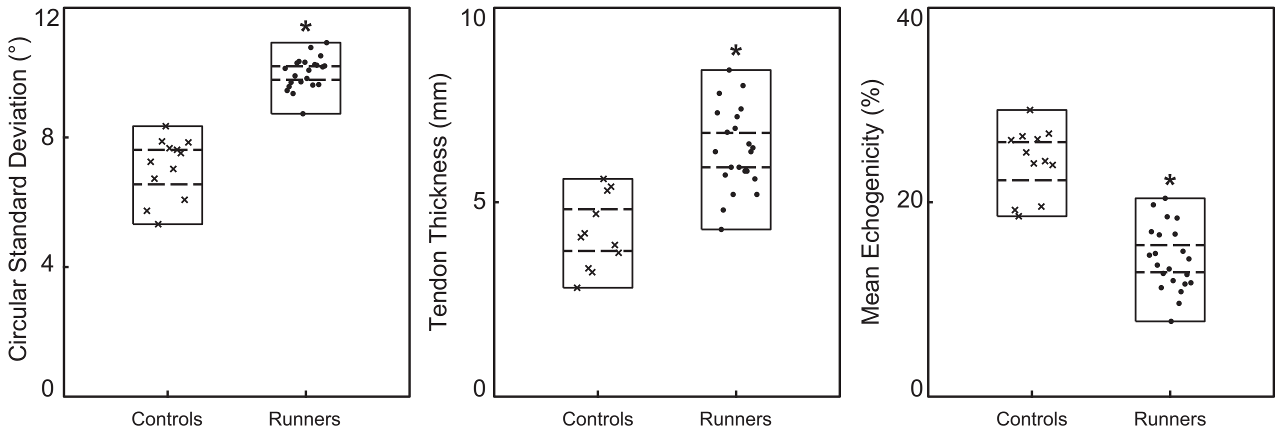

Fig. 1. Measures of circular SD (*left*), tendon thickness (*middle*), and mean echogenicity (*right*) are plotted for runners (dots; $n = 19$) and controls (crosses; $n = 12$). The measurement ranges (solid lines) and 95% confidence intervals (dashed lines) for each group are plotted as well. Runners had 40% less organized, 48% thicker, and 41% less echogenic tendons compared with controls ($^*P < 0.001$).

Collagen alignment (CSD) was 40% less organized in the runners compared with controls (95% confidence interval, 9.7–10.1° and 6.5–7.6°, respectively; $P < 0.001$; Fig. 1). Additionally, collagen alignment measures in the runners were 64% less variable, quantified as the coefficient of variation (standard deviation/mean), than those in the controls. Sex, BMI, self-reported foot-strike pattern, and years running at the collegiate level had no effect on measurements of collagen alignment in the competitive runners ($P > 0.1$). Ultrasound images of runner tendon demonstrated darker and thicker tendon midsubstances compared with the control subjects (Fig. 2). Images of the runner tendons were 41% less echogenic (95% confidence interval, 12.5–15.2 and 21.7–25.6%, respectively; $P < 0.001$; Fig. 1) compared with control scans. Mean echogenicity (Fig. 3) was negatively correlated with collagen alignment in the runner group ($R^2 = 0.24$, $P = 0.03$) but not among the control subjects ($R^2 = 0.02$, $P = 0.68$). Measurements of tendon midsubstance thickness were 48% greater in runners than controls (95% confidence interval, 5.9–6.8 and 3.7–4.8 mm, respectively; $P < 0.001$; Fig. 1). However, there were no signs of fusiform swelling of the tendon midsubstance, which characterizes tendinopathy.

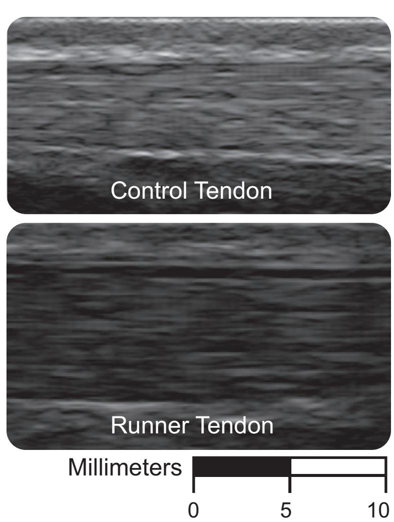

Fig. 2. Major differences between the runner and control group can be seen when comparing these tendons under ultrasound. Runner tendon appears visibly thicker and less echogenic than control tendon.

DISCUSSION

Achilles tendon structure differs in competitive-distance runners compared with recreationally active young adults despite no clinical presentation of midsubstance tendinopathy or pain. Specifically, ultrasound analyses of the Achilles tendon midsubstance highlights reduced collagen alignment and echogenicity and increased tendon thickness in competitive-distance runners. Compromised tendon material properties are partly mitigated by tendon thickening in individuals with Achilles tendinopathy (4), suggesting a compensatory response to maintain tendon strain during high-stress activities. These differences in tendon structure are not explained with risk factors commonly associated with tendon loading and musculoskeletal pain (43), such as sex, BMI, or foot-strike pattern ($R^2 < 0.01$). Additionally, less-variable tendon structure in runners compared with controls suggests that these structural changes may be highly dependent on the biomechanical demands placed on the tendon, which is similar among distance runners on the same team (6).

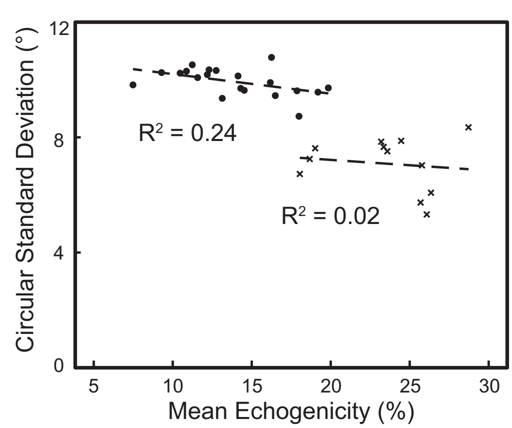

Fig. 3. Mean echogenicity was compared with circular standard deviation for the runners (dots; $n = 19$) and controls (crosses; $n = 12$). There was a negative correlation between mean echogenicity and circular standard deviation for the runners ($P = 0.03$) but not for the controls ($P = 0.68$).

Differences in Achilles tendon structure observed in this study agree with prior reports of Achilles tendinopathy development and progression and contribute new insights into the differences that exist between populations. This cross-sectional study quantified tendon structure of competitive-distance runners at a single time point just before the start of a competitive season. Although distance runners are at a 10-fold risk of developing tendinopathy (27), the majority of runners never report symptoms or pain (44). Therefore, we propose two divergent structural responses to the biomechanical rigors of distance running: habituated tendon and symptomatic tendon. Our results suggest that cyclic tendon loads elicit structural changes in the tendon, which have been linked with decreased tendon stiffness, Young's modulus, and maximal stress and strain (9, 12). Tendon hypertrophy appears to mitigate decreases in tendon material properties as large as 51% (4). However, it remains unclear as to what sustained biomechanical environment results in symptomatic or habituated and pain-free tendons. Training and exercise have been shown to increase tendon thickness (7, 28, 40), and elevated levels of peritendinous collagen synthesis are responses to short-term (23) and long-term (22) exercise. In contrast to our cohort of competitive distance runners, training does not appear to elicit tendon hypertrophy in naïve tendon, which may be explained by insufficient loading stimuli (16). Thus, targeted interventions that improve healing responses and beneficial remodeling may mitigate the risks of developing tendinopathy during high-risk activities, such as distance running.

Our findings suggest that cyclic tendon loading, experienced during distance running, drives changes in tendon structure without leading to symptoms of tendinopathy. This is highlighted by the low coefficient of variability in collagen alignment of runners (Fig. 1), which may be a normal response to the cyclic loading experienced during distance running. Achilles tendon stiffness also scales with plantarflexor strength (1, 3, 29), suggesting that the tendon undergoes remodeling as a protective mechanism against excessive strain to maintain good health. In addition, the absence of painful symptoms, neovascularization, and perceived functional deficits in the runners indicates a lack of pathology (41).

Reliable and noninvasive techniques that quantify tendon collagen organization provide opportunities to develop imaging biomarkers that could forecast the development of symptomatic tendinopathy. Currently, tendinopathy is difficult to predict and is only detected after symptoms manifest, at which point, treating the condition is not always successful (14, 19, 25, 26). Shear-wave elastography detects changes in the mechanical properties of an affected tendon (42) but requires specialized imaging equipment not available in all clinical settings. Other techniques correlate tendon tension with the speed at which sound travels through the tendon, but these measures do not directly assess structural changes (8, 33). In contrast, quantifying collagen alignment using ultrasonography only requires a B-mode ultrasound image that any sonographer or physician could acquire without additional training or specialized equipment available in most sports medicine practices.

There are some key limitations to consider for this study. The competitive runners were collegiate athletes and, therefore, did not vary greatly in age, BMI, or years running at the collegiate level. While previous work has shown that these factors are not correlated with the development of tendinopathy (24), the lack of correlation between these factors and the CSD observed in this study could be partially attributed to the low variability. This cross-sectional study design cannot confirm that prolonged training elicited the measured tendon structure. Foot-strike pattern was self-reported through a multiple choice question and not independently evaluated by investigators. While self-reported foot-strike patterns have been shown to be inconsistent with video analysis one-third of the time (15) and higher rates of loading have been observed in rear-foot vs. non-rear-foot patterns (2), foot-strike pattern has not been correlated with increased risk of tendinopathy among runners (24). Measurements of tendon thickness using ultrasonography may underapproximate tendon thickness compared with magnetic resonance imaging, but these measurements are strongly correlated (5). Further, Doppler imaging may lack the resolution needed to detect changes in microvasculature in the tendon compared with contrast-based imaging (32). Images were acquired in all of the runners in the same afternoon scanning session, but control subjects participated in both morning and afternoon scan sessions. The groups compared in this study differed significantly in both age and weight ($P < 0.05$); however, these small differences in demographics have not been shown to elicit changes in tendon structure. Achilles tendon function was not quantitatively assessed; instead, we collected VISA-A scores (35) in the competitive runners and clinically analyzed ultrasound images (41) to confirm that no underlying tendinopathy was present. A functional task such as a single-leg heel raise or a maximal plantarflexion contraction normalized between subjects could be more sensitive to changes in function than a qualitative questionnaire, but the time constraints of this study prevented more thorough biomechanical assessments. However, asymptomatic tendinopathy has not been linked to losses in plantarflexor function, and good clinical outcomes reported by the runners suggest that these structural changes did not lead to a perceived loss in functional ability.

In conclusion, young adults who participate in competitive-distance running have structurally different tendons than recreationally active young adults. These differences do not appear to be correlated with age, sex, BMI, self-reported foot-strike pattern, or years running at the collegiate level. It remains unclear whether these measurements of decreased tendon organization predict tendinopathy symptoms; however, trained runners are at a 10-times increased risk of Achilles tendon injuries (27, 36). The noninvasive imaging technique used to quantify tendon structure can be used to track changes in tendon structure and better characterize the progression of tendinopathy. Prospectively quantifying tendon structure throughout a training season of distance running may identify imaging biomarkers that can predict painful tendinopathy before symptoms manifest.

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GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

K.L.H., E.C., and J.R.B. conceived and designed research; T.J.H., E.C., and J.R.B. performed experiments; T.J.H., E.C., and J.R.B. analyzed data; T.J.H., K.L.H., E.C., and J.R.B. interpreted results of experiments; T.J.H. and J.R.B. prepared figures; T.J.H. and J.R.B. drafted manuscript; T.J.H., K.L.H., E.C., and J.R.B. edited and revised manuscript; T.J.H., K.L.H., E.C., and J.R.B. approved final version of manuscript.

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