ACUTE EFFECTS OF FOOTWEAR AND FOOTSTRIKE PATTERN ON ACHILLES TENDON LOADING DURING RUNNING

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The study aimed to investigate the effect of footwear and foot strikes on Achilles tendon (AT) loading during running. Eleven male recreational runners with rearfoot strike pattern were recruited. The ground reaction force, kinematics, and kinetics of the ankle joint at 10 km/h were collected using an instrumented split-belt treadmill and a motion capture system. The morphological and mechanical characteristics of AT were recorded and calculated with a synchronous ultrasonic imaging instrument. The results showed a significantly greater peak AT force in minimalist shoes and forefoot strike pattern. The peak force and length change of the AT significantly increased when forefoot striking. It suggested that immediate use of minimalist shoes and/or transitioning to forefoot strike could provide higher tendon loading intensity to improve the loading characteristics of the AT.

KEYWORDS: Achilles tendon force, strain, running, strike pattern

INTRODUCTION: The Achilles tendon (AT) plays a crucial role in movements such as walking, running, and jumping by transmitting the strength of the triceps muscle in the lower leg (Benjamin, 2006). The rate of tendinopathy is as high as 2.35 per 1000 in adults (21–60 years) with a lifetime prevalence of up to 52 % for individual runners (de Vos RJ, 2010). Therefore, understanding the factors that contribute to AT loading during running is essential for both preventing injuries and optimizing performance.
The previous study has found that the runners who habitually wore minimalist shoes had greater AT cross-sectional area (CSA), stiffness, and Young's modulus than runners who habitually wore conventional shoes, which has been indicated the benefit of endurance runners for better running performance (Histen, 2017). Different shoe conditions were believed to influence the landing pattern. It is generally accepted that runners in conventional shoes prefer a rearfoot strike (RFS) pattern, while runners in minimalist shoes or barefoot running prefer a forefoot strike (FFS) pattern. However, evidence is currently limited regarding the combined influence of foot strikes and footwear on AT loading.
The purpose of this study was to investigate the effect of footwear and foot strikes on AT loading during running.

METHODS: Eleven male recreational runners (age: 33.7±8. years, height: 175.3±4.5 cm, body mass: 69.6±7.0 kg) were recruited for this study. All runners were used to running in cushioned shoes with an RFS pattern and had never tried minimalist shoes or running barefoot. All participants ran>20 km per week in the last 3 months and did not have any medical history of musculoskeletal injuries to the lower extremity in the previous six months.
At the beginning of the experiment, an ultrasound device (uSmart 3300, Terason, USA) was used to capture AT images with a 12L5A probe (12 MHz maximum frequency). The participants were asked to rest prone on a treatment bed with a dominant ankle in the neutral position (90◦). Ultrasound gel was applied at the head of the probe at 10 cm proximal to the calcaneal insertion to determine the CSA of AT (Lyght, 2016). The resting length of the AT was then obtained by placing the probe at the medial head of the gastrocnemius muscle at its junction with the AT and the insertion of the AT at the calcaneus, respectively.
After the AT test, participants were affixed with reflective markers, including 36 markers on bony landmarks of the lower limbs and 4 markers on the ultrasound probe. The ultrasound imaging probe was secured to the medial head of the gastrocnemius with an elastic band (Figure 1). At the beginning of the experiment, participants were instructed to randomly wear

minimalist shoes and conventional shoes. They started by running at a self-selected strike pattern of 10 km/h on an instrumented treadmill (Bertec FIT, Bertec), followed by changing to the other strike pattern. The trajectory of the markers was collected with a 10-camera infrared 3D motion capture system (Vicon T40, Oxford Metrics) at a sampling rate of 200 Hz. The ground reaction force was measured at a sampling rate of 1000 Hz. All tests were conducted after the participants adapted to the treadmill speed, and 10 seconds of valid data were collected. During the synchronized collection, signals such as the trajectory of reflective markers, ground reaction forces, and ultrasound images of the AT were recorded. The process was then repeated with a change in shoe conditions.

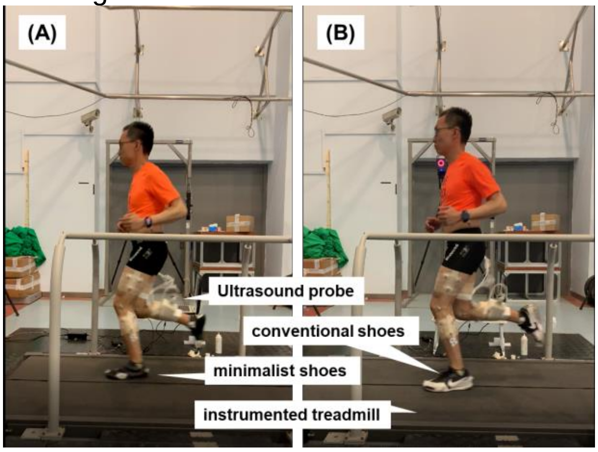

Figure 1: **Experimental setup.**

Clear ultrasound videos were extracted under five support phase phases and calculated to obtain the AT loading (e.g. peak AT force, peak AT elongation, peak AT strain, AT work, etc.). A 2 × 2 two-way analysis of variance was used to determine the effects of different running shoes (conventional shoes vs. minimalist shoes) and foot strike patterns (FFS vs. RFS) on the AT loading characteristics. The significance level, *α*, was set at 0.05. For results where there was an interaction, post hoc tests were validated using Bonferroni for multiple comparisons.

RESULTS: The peak AT loading rate showed a significant interaction effect ($p < 0.05$). Post-hoc tests revealed that the peak AT loading rate when wearing minimalist shoes with an RFS was significantly higher than when wearing cushioned shoes with an RFS. Additionally, the peak AT loading rate when wearing cushioned shoes with an FFS was significantly higher than when using an RFS.

There were no significant interaction effects for other AT loading characteristics ($p > 0.05$, Table 4-6). There were significant main effects of footwear factors on the AT moment arm ($p < 0.05$), with the AT moment arm significantly greater when immediately wearing conventional shoes compared to minimalist shoes. The peak AT force during running showed significant main effects of both footwear and foot strike ($p < 0.05$). Specifically, the peak AT force was significantly higher when immediately adopting an FFS compared to an RFS, and when wearing minimalist shoes compared to conventional shoes.

Average AT loading rate, AT impulse, peak AT stress, peak AT elongation, peak AT strain, and AT work exhibited significant main effects of foot strike ($p < 0.05$). Regardless of whether wearing cushioned shoes or minimalist shoes, immediately adopting an FFS resulted in a significantly higher average AT loading rate, AT impulse, peak AT stress, peak AT elongation, peak AT strain, and AT work compared to an RFS.

Table 1: Effect of different footwear and foot strike patterns on AT loading during running (mean ± SD).

Variables	Conventional Shoes (n=11)		Minimalist shoes (n=11)		*P*-value		
	FFS	RFS	FFS	RFS	FT	FS	Interaction
Peak ATF (BW)	6.6±0.7	5.8±0.8	7.5±0.7	6.1±0.6	0.02	＜0.001	0.391
Aver. AT LR (BW/s)	60.4±9.6	44.3±7.2	65.3±7.9	50.4±8.1	0.033	＜0.001	0.816
Peak AT LR (BW/s)	359.5±72.7	253.4±91.7#	319.7±55.3	362.3±91.4*	0.156	0.191	0.003
ATF impulse (BW·s)	0.8±0.1	0.7±0.1	0.9±0.1	0.7±0.1	0.052	＜0.001	0.150
AT stress (MPa)	74.4±12.4	68.2±8.6	81.9±15.4	69.9±13.2	0.232	0.022	0.453
AT elongation (mm)	9.7±2.8	7.4±1.4	10.0±2.9	8.6±2.0	0.382	0.005	0.469
AT strain (%)	4.7±1.2	3.7±1.1	5.0±1.8	4.3±1.4	0.429	0.005	0.549
AT work (J)	12.0±6.2	7.2±3.8	13.5±7.6	8.1±3.1	0.594	0.001	0.963

Abbreviations: ATF, Achilles tendon force; Aver., average; LR, loading rate; FFS, forefoot strike; RFS, rearfoot strike; FT, footwear; FS, footstrike pattern.

*Significant difference between conventional and minimalist shoes for the same foot strike pattern, $p < 0.05$.

#significant difference between the forefoot and rearfoot strike pattern for the same shoe condition, $p < 0.05$.

DISCUSSION: The purpose of this study was to investigate the changes in AT length and loading in runners who wore conventional shoes and minimalist shoes, with two different foot patterns, RFS and FFS, respectively. To evaluate the mechanical load and strain capacity of the AT during running, participants were asked to run on an instrumented split-belt treadmill. An ultrasound probe was securely fastened at the junction of the AT and the medial head of the gastrocnemius muscle using an elastic bandage. The conjunction was tracked through a sequence of ultrasound images, and its coordinates were converted to a three-dimensional laboratory coordinate system. This system was employed to calculate the real-time length change of the AT in vivo, considering its insertion position into the Achilles.

This calculation method, validated in studies by Waugh et al. (2017) and Suzuki et al. (2019), revealed two characteristic peaks, a maximum, and a minimum, in the AT length change curve during RFS running. The maxima of AT length change were comparable in FFS and RFS, both occurring in the middle of the support phase, near the beginning of the propulsion phase, aligning with peak centrifugal muscle movement. The AT rapidly shortened at contact during RFS, leading to a minimum, a phenomenon absent in FFS. Results indicated that peak AT strain was significantly higher during FFS than RFS, suggesting earlier activation of the calf triceps muscle and AT entering the stretch phase for energy storage during FFS. Despite this, no significant effect of shoe condition on AT strain was observed, consistent with Rice et al. 's (2017) speculation that running shoes do not independently influence AT strain.

Considering that low-intensity strains may not stimulate tendon adaptations, our results suggested that transition to FFS during running provided adequate tendon loading intensities to enhance AT mechanical properties compared to immediate shoe change conditions. The peak strain in the AT ranged from 3.7% to 5.0% when running at 10 km/h in both minimalist and conventional shoes, similar to Kharazi et al.'s findings (2021), supporting the potential benefits of FFS running in improving AT mechanical properties.

The results of this study revealed that the peak AT force during running ranged from 5.8 to 7.5 body weight (BW), a value similar to outcomes based on a musculoskeletal model. The model indicated a peak AT force range of 5 to 7 BW during running. Furthermore, in comparison to RFS running, the peak AT force during FFS landing was 14% higher when wearing conventional shoes and 23% higher when wearing minimalist shoes. This discrepancy is mainly attributed to the fact that runners exhibit a greater plantarflexion moment when adopting an FFS compared to an RFS. The present study confirmed this observation, showing an approximately 21% increase in peak plantarflexion moment when runners adopted an FFS compared to an RFS.

Moreover, FFS requires higher eccentric movement of the calf muscles to control the dorsiflexion velocity of the ankle joint, supported by the larger ankle joint negative work during forefoot landing. As the cross-sectional area of the subjects' ATs does not change immediately, the increased AT force associated with the immediate use of minimalist shoes or an immediate change in footstrike pattern also implied a significant increase in AT stress, i.e., force per unit area. If the increase in stress exceeds the load range that runners can tolerate, the risk of AT injury will rise, especially when stress does not gradually increase.

CONCLUSION: Compared to wearing conventional shoes, the peak AT force significantly increased when immediately wearing minimalist shoes. Additionally, in comparison to RFS running, the peak force and length change of the AT significantly increased, and more energy was released during contraction when immediately transitioning to FFS. This suggested that immediate use of minimalist shoes and/or transitioning to FFS during running could provide higher tendon loading intensity to improve the loading characteristics of the AT. However, when wearing minimalist shoes with RFS running, the higher AT loading rate also suggested that changing shoe conditions involved not just wearing a different pair of running shoes but enduring different mechanical loads. For runners wishing to enhance the mechanical properties of the AT, we recommend a gradual transition to forefoot landing mode, accompanied by strengthening exercises for the lower limb muscles.

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