Journal of Biomechanics 89 (2019) 65–71

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Ultrasound elastographic assessment of plantar fascia in runners using rearfoot strike and forefoot strike

Tony Lin-Wei Chen [a,b], Cristine E. Agresta [b], David B. Lipps [c,d], Seraphina G. Provenzano [b], Jocelyn F. Hafer [b], Duo Wai-Chi Wong [a,f], Ming Zhang [f,a,*], Ronald F. Zernicke [b,d,e,*]

[a] Department of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[b] Michigan Performance Research Laboratory, School of Kinesiology, University of Michigan, Ann Arbor, MI, USA
[c] Musculoskeletal Biomechanics & Imaging Laboratory, School of Kinesiology, University of Michigan, Ann Arbor, MI, USA
[d] Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI, USA
[e] Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, MI, USA
[f] The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen, Guangdong, China

ARTICLE INFO

Article history:
Accepted 9 April 2019

Keywords:
Shear wave elastography
Plantar fascia
Foot strike patterns
Running

ABSTRACT

Forefoot strike is increasingly being adopted by runners because it can better attenuate impact than rearfoot strike. However, forefoot strike may overload the plantar fascia and alter the plantar fascia elasticity. This study aimed to use ultrasound elastography to investigate and compare shear wave elasticity of the plantar fascia between rearfoot strikers and forefoot strikers. A total of 35 participants (21 rearfoot strikers and 14 forefoot strikers), who were free of lower limb injuries and diseases, were recruited from a local running club. Individual foot strike patterns were identified through the measured plantar pressure during treadmill running. The B-Mode ultrasound images and shear wave elastographic images of the plantar fascia were collected from each runner. Two independent investigators reviewed the images and examined the plantar fascia qualitatively and quantitatively. The results demonstrated an overall good agreement between the investigators in the image review outcomes (ICC:0.96–0.98, κ: 0.89). There were no significant differences in the fascial thickness ($p = 0.50$) and hypoechogenicity on the gray-scale images ($p = 0.54$) between the two groups. Shear wave elastography showed that forefoot strikers exhibited reduced plantar fascia elasticity compared to rearfoot strikers ($p = 0.01$, Cohen's $d = 0.91$). A less elastic fascial tissue was more easily strained under loading. Tissue overstrain is frequently related to the incidence of plantar fasciitis. While further study is needed for firm conclusions, runners using forefoot strike were encouraged to enhance their foot strength for better protection of the plantar fascia.

1. Introduction

Overuse injuries are common in recreational runners, with an estimated 39–85% of runners becoming injured each year (van Gent et al., 2007). While the cause of injury is multifactorial, the rate of loading for the vertical ground reaction force (vGRF) immediately following impact is thought to be a significant contributor (van der Worp et al., 2016; Zadpoor and Nikooyan, 2011). As a result, running mechanics associated with high vGRF, as well as mechanics that increase knee joint loading, are typically targeted for gait retraining in runners that are at risk or currently injured (Agresta et al., 2018). These mechanics include increasing step frequency, reducing foot inclination angle at initial contact and heel-to-trunk distance (Wille et al., 2014), and, most notably, retraining rearfoot strike patterns (Cheung and Davis, 2011). Transitioning to a forefoot strike pattern has received the most attention and is frequently targeted, because it has the potential of reducing the vGRF impact peak and eliminating other potential contributors to running-related injuries (Crowell and Davis, 2011; Shih et al., 2013; Williams et al., 2012).

Despite the positive findings related to vGRF and its widespread popularity, adoption of a forefoot strike pattern may have negative consequences for runners in terms of changing the loading status of the plantar fascia (Lieberman et al., 2010). Forefoot strike pro-

* Corresponding authors at: Department of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong, China (M. Zhang). Michigan Performance Research Laboratory, School of Kinesiology, University of Michigan, Ann Arbor, MI, USA (R. Zernicke).

E-mail addresses: ming.zhang@polyu.edu.hk (M. Zhang), zernicke@umich.edu (R.F. Zernicke).

https://doi.org/10.1016/j.jbiomech.2019.04.013
0021-9290/

duced larger ankle plantarflexion moments compared to rearfoot strike (Rice and Patel, 2017) and, therefore, increased Achilles tendon tension and posterior calf muscle activity requirements (Knorz et al., 2017; Landreneau et al., 2014; Yong et al., 2014). Because of the strong myofascial connectivity among the plantar fascia, Achilles tendon, and posterior calf musculature (Carlson et al., 2000; Cheung et al., 2006), these biomechanical changes, along with the burden of body weight and the forward-shifted vGRF upon the forefoot (Kernozek et al., 2016), were speculated to impose a bending strain to the longitudinal foot arch and overstretch the plantar connective tissues (Arangio et al., 1998; Huang et al., 1993). Research using computational simulations has shown that forefoot strike can induce a higher tensile force on the plantar fascia than rearfoot strike (Chen et al., 2019). Repeated overload has been commonly considered as the primary cause of microtears in fascia and a contributor to plantar fasciitis (Wearing et al., 2006).

Ultrasound imaging is an effective tool to examine the plantar fascia and has been widely used to assist diagnosis of plantar fasciitis. Histologically, plantar fasciitis is a composite result of fiber microtears, collagen degeneration, chronic inflammation, and calcification caused by repetitive overstrain (Wearing et al., 2006), which underlies the typical appearances of plantar fasciitis on the conventional B-Mode ultrasound images: thickened plantar fascia and a diffuse hypoechoic area within the fascia band (McMillan et al., 2009). Hypoechoic change in the plantar fascia usually presents as a loss of the normal fibrillar pattern on the gray-scale images (Kim et al., 2016). However, research showed that not all patients with plantar fasciitis exhibited these changes in tissue morphology and hypoechogenicity (Kapoor et al., 2010; Wu et al., 2012). Recently, ultrasound shear wave elastography has emerged as a novel imaging technique that can detect early-stage plantar fasciitis through the assessment of tissue elasticity (Sabir et al., 2005). Shear wave elastography can autogenerate and track the transient shear waves propagating in the tissues, whereby the shear wave velocity (SWV) is proportional to the tissue elasticity (Nowicki and Dobruch-Sobczak, 2016). Reduced elasticity was frequently related to tissue rupture caused by repeated loading (Eby et al., 2013; Zhang and Fu, 2013) and subsequent plantar fasciitis (Wu et al., 2011). The use of elastography may help identify signs of negative adaptation to forefoot striking via a loss of elasticity in the fascial band. Together with the already available fascial thickness and hypoechogenicity measurements, this information could be valuable for the runners to better understand their foot health.

Therefore, the purpose of this study was to utilize the ultrasound shear wave elastography to document plantar fascia elasticity in runners using forefoot strike patterns. Since the majority of recreational runners are rearfoot strikers (de Almeida et al., 2015; Larson et al., 2011), we used this group as controls. We hypothesized that forefoot strikers would exhibit increased fascial thickness, increased hypoechogenicity, and reduced plantar fascia elasticity compared to rearfoot strikers. The results of this study may provide greater insights of whether there were altered material properties of the plantar fascia involved in forefoot strike running and help to guide training programming, given that tissue strength could influence its injury risk.

2. Methods

2.1. Participants

A total of 35 recreational runners (21 rearfoot strikers and 14 forefoot strikers) were recruited for the study. The ratio of rearfoot-to-forefoot-striker was approximately 3:2 based on their availability in the local running community. The sample size was calculated upon on a pilot study using the mean SWV of the plantar fascia (with the statistical power of $\alpha = 0.05$, $\beta = 0.2$, and an assumed effect size of 0.54) as our primary outcome variable. Runners' foot strike patterns were later confirmed by undergoing a treadmill session in the study. The experimental protocol was approved by the University Institutional Review Board (IRB NO.: HUM00149062). Participants were recruited from the local running community via recruitment flyers and word of mouth. Inclusion criteria were: (i) aged between 18 and 35 yr; (ii) currently had a weekly mileage of at least 15 km; (iii) had a running experience of at least 2 years prior to the experiment; (iv) originally rearfoot striker at the beginning of her/his running career; (v) had no ongoing symptoms or injuries of the lower limbs at the time of entry, and (vi) had no musculoskeletal diseases, such as rheumatoid disorders. Runners were excluded if they: (i) had an abnormal foot arch (i.e., pes planus or pes cavus), which was later confirmed by measures of foot arch index in the study (Cavanagh and Rodgers, 1987); (ii) modified foot strike pattern within the 6 months prior to the experiments; (iii) currently used orthotics, prosthetic devices, or footwear with motion control function; (iv) received lower limb surgeries in the past 6 months prior to the experiments; or (v) habitually ran barefoot. Runners with a foot arch index ≥ 0.26 (pes planus) or ≤ 0.21 (pes cavus) were excluded from the study (Wong et al., 2012). All participants were fully informed of the research procedures and provided informed consent prior to participation. Each participant also completed a questionnaire that collected information regarding basic anthropometry and running regime.

2.2. Experimental procedure

The study consisted of two sessions with a 5-minute rest interval: a shear wave elastography session and a treadmill session. The purpose of the treadmill session was to confirm foot arch type and foot strike pattern for the participants. To minimize the influences of physical activities on imaging quality (Skou et al., 2012), we performed the shear wave elastographic measurements to the participants prior to the treadmill session.

2.2.1. Shear wave elastography session

Shear wave elastography was performed using the Aixplorer ultrasonic scanner (Supersonic Imagine, Aix-en-Provence, France; software version 5). The participants laid prone with the knee fully extended, foot suspended at the bedside, and the ankle slightly plantarflexed in a resting position. The position for examination was kept consistent across all participants in the study. Gentle compression was applied to the heel with a linear array transducer (7–14 MHz). In the longitudinal view, the color-coded image of the shear wave (a rectangle 2 cm $\times$ 4 cm) was superimposed over the B-Mode ultrasound image obtained simultaneously (Wu et al., 2015). The following parameters were set and kept consistent throughout the measurements: "Muscle" probe mode, "Penetration," "High Definition," "Contrast" = 65%, and "Gain" = 100%. The region of interest was initially positioned at the anterior edge of the inferior calcaneal border (Lee et al., 2014) and slightly moved towards the toe direction if shear wave signals were difficult to acquire. Ten images were collected for each participant. All ultrasonic measurements were performed by the same investigator (TLC). The primary variable was the mean SWV of the plantar fascia, which represented the degree of tissue elasticity. The fascial thickness and hypoechogenicity on the gray-scale images were also examined as secondary outcomes.

The ultrasound images were analyzed qualitatively and quantitatively by two investigators (SGP and DWW), who were blinded to the grouping results. Plantar fascia thickness was measured as the vertical distance between the anterior edge of the inferior calcaneal border and the inferior border of the plantar fascia (Ríos-Díaz et al., 2015) (Fig. 1A). The hypoechogenicity of the plantar fascia was assessed based on a grading scheme (Archambault et al., 1998): grade I: normal appearance (parallel margins, homogeneous echogenicity); grade II: enlarged structure (bowed margins, homogeneous echogenicity); and grade III: hypo-echoic area with or without enlargement.

Shear wave elastography images were analyzed using an established algorithm (Lee et al., 2015; Leonardis et al., 2017). The algorithm provides quality control to ensure the elastography measurement only includes pixels with sufficient quality in the final calculation of SWV. A customized Matlab (R2014a, MathWorks, Natick, MA) code extracted both SWV and quality map from the elastography images. The quality map, which was provided by Supersonic Imaging, reflects the manufacturer's calculation regarding the cross-correlation of shear waves propagating in the tissue. In the map, each pixel of the image is assigned with a number that denotes the accuracy of the SWV measures. The number ranges from 0 to 1, with 1 representing the best quality and 0 representing the worse. To start with the algorithm, we manually cropped the region of interest corresponding to the plantar fascia band from the elastography image (Fig. 1B). The region of interest was approximately 2 cm in length along the fascial band (kept consistent for all participants), and its size could vary slightly to accommodate the individual variations in fascial thickness. Our algorithm computed the mean SWV of pixels with a quality number > 0.7 from the cropped image (Leonardis et al., 2017). On average, the percentage of qualified pixels within the cropped images was 45.8% for rearfoot strikers and 45.7% for forefoot strikers. We found no evidence of data saturation in any of the images. SWV was averaged across 10 images for each participant.

2.2.2. Treadmill session

Participants stood barefoot on a pressure-sensing treadmill (h/p cosmos Quasar Medical treadmill, h/p cosmos, Nussdorf-Traunstein, Germany) and performed a 6-second single leg stance on right and then left leg. After the standing trial, participants performed a 1-min walking trial at a set speed (4 km/h). Following the walking trial, participants ran on the treadmill for 3 min using a self-selected speed in their own running shoes. No instruction on specific running form (e.g., specific foot strike pattern) was given to the participants.

Foot arch type was quantified using the foot arch index (Cavanagh and Rodgers, 1987). Briefly, the measured foot pressure map was equally divided into three sections along its longitudinal axis (i.e., line intersecting the heel center and second toe), which represented the heel, midfoot, and forefoot regions. Foot arch index was calculated as the percentage of the midfoot area to the total footprint area. A mean foot arch index was averaged through the 6-s standing trial. Runners with an arch index of 0.21–0.26 were considered having the normal foot arch type (Wong et al., 2012).

Foot strike patterns were quantified by the strike index as modified by Graf et al. (Graf et al., 2013). Strike index was defined as

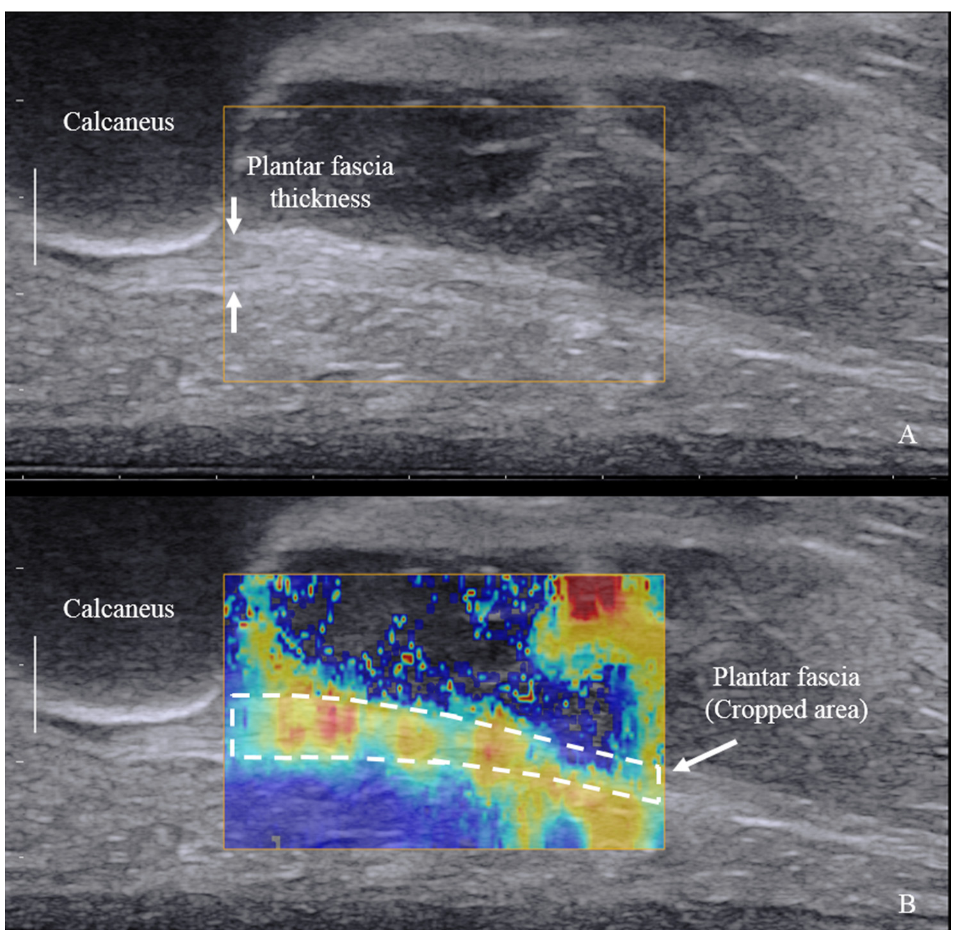

Fig. 1. The ultrasound images of one representative participant. A: the longitudinal B-Mode image, B: the color-coded shear wave elastographic image superimposed on the B-Mode image. The fascia thickness and hypoechogenicity were examined on the B-Mode image. The mean value of shear wave velocity was calculated from the manually cropped region (the dotted circle) on the shear wave elastographic image.

the percentile location of the plantar pressure center relative to the full footprint length. The toe region of the footprint was excluded as this modification has been shown to increase the validity of identifying a forefoot strike pattern (Graf et al., 2013). A strike index of 0–33.3% was classified as a rearfoot strike pattern while 66.6–100% was classified as forefoot strike pattern (Lieberman et al., 2010). Because forefoot strikers might produce incomplete footprints during running, the actual footprint of each participant was contoured from the walking trial based on the fact that all of them used a heel-to-toe walking gait, regardless of foot strike patterns used during running. The actual full footprints were then input and re-located in the running trial by aligning to the front edge of the foot pressure profile along the belt, assuming that, for either rearfoot strike or forefoot strike, the foot's tip always touched the ground at push-off and did not drift during the stance phase (Santuz et al., 2016). For each participant, strike index was averaged across the first, middle, and last 10 strides of the running trials.

For the treadmill session, plantar pressure was recorded using the proprietary software (myoRESEARCH MR3.12, Noraxon, Scottsdale, USA) at a sampling rate of 120 Hz. Raw data were exported and processed by a custom-code (Matlab R2014a, MathWorks, Natick, MA).

2.3. Statistics

Statistics utilized SPSS (V16.0, SPSS, Inc., Chicago, Illinois, USA) with alpha set at 0.05. Data were assessed for distribution normality (i.e., Kolmogorov-Smirnov test) and homogeneity of variance (i.e., Levene's test). Numerical outcome variables were compared between the rearfoot strike and forefoot strike groups using the independent Student's *t*-test or the Mann-Whitney *U* test—if the assumptions of normal distribution or homogeneity of variance were violated. An effect size (Cohen's *d* for the independent Student's *t*-test and Cohen's *r* for the Mann-Whitney *U* test) was demonstrated for each comparison pair (Cohen, 1988). A chi-square (X^2) test was used to compare the grade distribution of plantar fascia hypoechogenicity. The effect size (Cramer's V) was also reported (Cohen, 1988).

Intra-subject and inter-subject variabilities of plantar fascia SWV were expressed as coefficient of variation percentage (CV%) (standard deviation/mean $\times$ 100). Intraclass correlation coefficients (ICC) and Kappa value (κ) were calculated to determine the inter-rater agreement in the outcomes of plantar fascia thickness/SWE and hypoechogenicity grading, respectively. Both ICC and κ values were reported along with the associated 95% confidence interval. The level of agreement was categorized as: poor, 0 to 0.20; fair, 0.21 to 0.40; moderate, 0.41 to 0.60; substantial, 0.61 to 0.80; and almost perfect, 0.81 to 1.00 (Shrout and Fleiss, 1979).

3. Results

Except for the strike index, there were no differences in anthropometries and running regimen between forefoot strikers and rearfoot strikers at baseline (Table 1). Analysis of the B-Mode images showed that the majority (65.7%) of the participants had Grade I plantar fascia, while only 3 cases of Grade III plantar fascia presented (Table 2). There were no significant differences in grading ($p = 0.54$, Cramer's V = 0.19) and plantar fascia thickness ($p = 0.50$, $r = 0.10$) between the two groups. Forefoot strikers exhibited significantly lower plantar fascia SWV compared to the rearfoot strikers ($p = 0.01$, Cohen's $d = 0.91$).

A low intra-subject variability was observed in the measurements of plantar fascia SWV, with CV for all recruited participants ranging from 2.2% to 13.5%. Tests of inter-subject variability also reported congruent results for the rearfoot strike group (CV: 9.0%) and forefoot strike group (CV: 10.8%). There were overall good inter-rater agreements in the results of plantar fascia thickness (ICC: 0.96, 95% CI: 0.91, 0.98), plantar fascia SWV (ICC: 0.98, 95% CI: 0.95, 0.99), and hypoechogenicity grading (κ: 0.89, 95% CI: 0.74, 1.04).

4. Discussion

This study performed elastographic measurements of the plantar fascia to compare the results between runners using rearfoot strike and forefoot strike patterns. In partial support of our hypothesis, forefoot strikers produced significantly lower plantar fascia elasticity than rearfoot strikers. However, the fascial thickness and hypoechogenicity grade were similar between the two conditions.

Our results echoed previous findings that the outcomes of conventional ultrasound imaging and elastographic measurement to the same plantar fascia can vary due to their different sensitivity in identifying minor intrafascial changes (Kapoor et al., 2010). Generally, a plantar fascia more than 4 mm in the thickness is considered to relate to plantar fasciitis (Chen et al., 2013). Previous studies reported a fascia thickness of 2.6–3.2 mm for the healthy controls and 3.9–5.0 mm for patients with plantar fasciitis (Abdel-Wahab et al., 2008; Chen et al., 2013; Ríos-Díaz et al., 2015; Wu et al., 2015). Our measurements showed that most runners, regardless of foot strike pattern, had a fascia thickness that fell within the normal range. In addition, most runners had the grade I plantar fascia in hypoechogenicity. While three cases of grade III were identified, these participants reported no symptoms during participation and could continue training without complaints. The contrast in outcomes between conventional ultrasound imaging and elastography supported a statement that, shear wave elastography had the potential to identify the "preclinical" cases—individuals who are exhibiting biological tissue changes but have yet to report positive symptoms (De Zordo et al., 2009), though further study is required to determine the cut-off value for differentiating injured persons from the healthy.

Previously, our image processing algorithm demonstrated a good inter-rater reliability for muscle tissue evaluation (Leonardis et al., 2017). Similar strong inter-rater reliability was found with the plantar fascia. Previous studies using strain elastography to examine the plantar fascia commonly adopted a qualitative method to analyze the images (Lee et al., 2014; Ríos-Díaz et al., 2015; Wu et al., 2015) (i.e., comparing the different color distributions in the histograms). Those methods could not reflect the fascia elasticity quantitatively or facilitate between-study comparisons. Our measurements were quantitative, and the results supported the statement that the plantar fascia possessed an elasticity similar to human tendon and ligament (Ryu and Jeong, 2017; Wearing et al., 2006). Our measured SWE values (6.20–6.67 m/s) were slightly higher than those of Zhang's study (approximately 5.52 m/s) (Zhang et al., 2014) but lower than Shiotani's results (8.0–9.5 m/s) (Shiotani et al., 2019). The differences may be attributed to the variances in experimental setups. Zhang et al. (Zhang et al., 2014) did not control the imaging quality in their elastographic measurements. Including pixels with poor SWV measures would underestimate tissue elasticity due to the substantial noise in the echo (Barr and Zhang, 2015). Shiotani and coworkers (Shiotani et al., 2019) only recruited physical-inactive persons, and they likely acquired the tissue elasticity from a more tightened plantar fascia since the ankle was fixed at the neutral position for examination.

Table 1
Anthropometries and running regimen of the participants (mean ± standard deviation).

	Rearfoot strikers	Forefoot strikers	p value	Effect size
Age (years)[a]	25.14 ± 4.64	26.85 ± 4.50	0.29	0.36
Height (m)[b]	1.71 ± 0.08	1.74 ± 0.13	0.38	0.14
Body Mass (kg)[b]	65.65 ± 9.70	65.57 ± 9.53	0.85	0.03
Body Mass Index (%)[a]	22.32 ± 2.31	21.42 ± 1.29	0.20	0.44
Shoes' size (US)[b]	9.17 ± 1.19	9.61 ± 1.80	0.58	0.08
Running experience (years)[b]	11.00 ± 5.72	10.39 ± 6.86	0.73	0.05
Weekly running days[a]	4.43 ± 1.43	4.21 ± 1.22	0.65	0.15
Single-run mileage (km)[b]	9.83 ± 3.61	9.89 ± 3.52	0.99	0.01
Weekly mileage (km)[b]	44.58 ± 24.53	43.95 ± 25.73	0.93	0.01
Usual running speed (m/s)[a]	11.45 ± 1.54	11.87 ± 1.25	0.41	0.28
Foot arch index[a]	0.23 ± 0.01	0.23 ± 0.01	0.71	0.13
Strike index (%)[b]	26.38 ± 7.45	86.79 ± 8.57	**<0.001**	7.12

[a] tested by the Student-t test, effect size: Cohen's d;
[b] tested by the Mann-Whitney U test, effect size: Cohen's r.

Table 2
Outcomes of the ultrasound measurements (mean ± standard deviation).

		Rearfoot Strikers	Forefoot Strikers	p value	Effect size
Hypoechogenicity [c]	Grade I	15	8	0.54	0.19
	Grade II	5	4		
	Grade III	1	2		
Plantar fascia thickness (10^{-3} m)[b]		3.08 ± 0.35	3.41 ± 0.89	0.50	0.10
Plantar fascia SWV[*] (m/s)[a]		6.67 ± 0.48	6.20 ± 0.56	**0.01**	0.91

[*] SWV: shear wave velocity;
[a] Tested by the Student-t test, effect size: Cohen's d;
[b] Tested by the Mann-Whitney U test, effect size: Cohen's r;
[c] Tested by the chi-square test, effect size: Cramer's V.

The present study showed that the plantar fascia SWV was 6.46% lower in forefoot strikers compared to rearfoot strikers. Though that degree of reduction may not be clinically significant because the runners had no symptoms, it suggested that forefoot strikers had a less elastic plantar fascia than rearfoot strikers. Many mechanical factors in running can cause elasticity alterations of the plantar fascia. Most frequently they are associated with sports-related overuse (Abdel-Wahab et al., 2008). Since the baseline characteristics and running regimens were similar between the two groups, the reduced fascial elasticity in forefoot strikers may have resulted from their different running biomechanics. As reported, the most influential changes in forefoot strike may be the increased cadence (loading frequency) (Baggaley et al., 2017; Goss and Gross, 2013; Kulmala et al., 2013) and larger plantar fascia loading (Chen et al., 2019; McDonald et al., 2016). In addition, a great number of forefoot strikers could not recall the precise date on which they transitioned from rearfoot strike to forefoot strike. As a result, their running experiences with forefoot strike were likely less than the total running years as they reported, which may underestimate the effects of forefoot strike on the fascial elasticity and the subsequent differences in comparison to rearfoot strikers. All these factors, in combination, could play a role in the outcomes of the elastographic measurements. Due to the retrospective nature of the current study, it is not possible to conclude a causal link between forefoot strike and reduced plantar fascia elasticity, and the underlying mechanism for the elasticity difference. For more definitive insights, a prospective, controlled study must be conducted in those who plan to modify their foot strike patterns (Hamill and Gruber, 2017).

The present study may provide valuable information for the runner community. A plantar fascia with reduced elasticity is less resistant to strain and may render the runners to injuries caused by tissue overstretch (e.g., plantar fasciitis). It is currently not possible to determine the extent to which the loss of fascial elasticity in forefoot strikers would affect their running biomechanics or their foot health, unless a longitudinal follow-up study is conducted. Nonetheless, results from the current study suggest that forefoot strikers may focus on strengthening their foot for better protection of the plantar fascia, which has also been advocated by others (Chen et al., 2016; Lynn et al., 2012). Research has found that forefoot strike running could induce a higher loading on the foot arch and increasingly tensioned the plantar connective tissues (Kelly et al., 2018; McDonald et al., 2016). As a part of the loading-sharing system of the foot arch (Kirby, 2017), intrinsic foot muscles can shield the total arch loading for the plantar fascia during running. Habitual rearfoot strikers who tended to adopt forefoot strike are suggested to train on their foot muscle strength (Huffer et al., 2017), to take the strain off the plantar fascia. This may also be advisable for runners already using forefoot strike but showing signs of less elastic plantar fascia as presented in the current study.

This study has several limitations. First, the percentage of qualified pixels within the cropped image was relatively low. The plantar fascia is a deep structure overlaid by other soft tissues, and its visualization is usually not ideal on elastography (Ríos-Díaz et al., 2015). This is a problem commonly faced by research applying ultrasound-based modality. Second, since we did not measure foot muscle strength for the runners, the actual causes of the reduced elasticity in forefoot strikers remain unclear. Finally, the relation between SWV and tendinous elasticity (e.g., plantar fascia) is not fully understood. The plantar fascia is unidirectionally fibrous, and its varied thickness on the transverse plane could be a confounding factor influencing shear wave propagation and the value of SWE read by elastography (Brum et al., 2014; Helfenstein-Didier et al., 2016). Further investigation including measurement on the fascial morphology and mechanical property in different directions would be necessary for a better understanding of the nature of the plantar fascia.

5. Conclusion

Shear wave elastography was applied to examine and compare the plantar fascia elasticity between runners using rearfoot strike and forefoot strike. The results demonstrated that the fascial thickness and hypoechogenicity on the gray-scale image were comparable between the two groups. Forefoot strikers had a significantly lower plantar fascia elasticity compared to rearfoot strikers. A plantar fascia with reduced elasticity is less resistant to strain. Overstrain could be the potential cause of plantar fasciitis. Although it is unknown whether the loss of elasticity would influence the injury risk, forefoot strikers may wish to strengthen their foot muscles to better protect the plantar fascia.

Acknowledgments

The study was financially supported by National Key R&D Program of China granted by the Ministry of Science and Technology of China, China (No.: 2018YFB1107000), General Research Fund granted by the Hong Kong Research Grant Council, Hong Kong, China (No.: PolyU152065/17E, PolyU152002/15E), NFSC granted by the National Natural Science Foundation of China, China (No.: 11732015), and Shenzhen Research Fund granted by the Shenzhen Science and Technology Innovation Committee, China (No.: JCYJ-20160531-18462-1718).

Appendix A. Supplementary material

The original data of this study are available at Mendeley Data (http://dx.doi.org/10.17632/4tgr77pzrk.2). Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.04.013.

References

Abdel-Wahab, N., Fathi, S., Al-Emadi, S., Mahdi, S., 2008. High-resolution ultrasonographic diagnosis of plantar fasciitis: a correlation of ultrasound and magnetic resonance imaging. Int. J. Rheum. Dis. 11, 279–286. https://doi.org/10.1111/j.1756-185X.2008.00363.x.

Agresta, C.E., Peacock, J., Housner, J., Zernicke, R.F., Zendler, J.D., 2018. Experience does not influence injury-related joint kinematics and kinetics in distance runners. Gait Posture 61, 13–18. https://doi.org/10.1016/j.gaitpost.2017.12.020.

Agresta, C.E., Peacock, J., Housner, J., Zernicke, R.F., Zendler, J.D., 2018. Experience does not influence injury-related joint kinematics and kinetics in distance runners. Gait Posture 61, 13–18. https://doi.org/10.1016/j.gaitpost.2017.12.020.

Arangio, G.A., Chen, C., Salathé, E.P., 1998. Effect of varying arch height with and without the plantar fascia on the mechanical properties of the foot. Foot Ankle Int. 19, 705–709. https://doi.org/10.1177/107110079801901010.

Archambault, J.M., Wiley, J.P., Bray, R.C., Verhoef, M., Wiseman, D.A., Elliott, P.D., 1998. Can sonography predict the outcome in patients with Achillodynia? J. Clin. Ultrasound 26, 335–339. 10.1002/(SICI)1097-0096(199809)26:7<335::AID-JCU1>3.0.CO;2-A.

Baggaley, M., Willy, R.W., Meardon, S.A., 2017. Primary and secondary effects of real-time feedback to reduce vertical loading rate during running. Scand. J. Med. Sci. Sports 27, 501–507. https://doi.org/10.1111/sms.12670.

Barr, R.G., Zhang, Z., 2015. Shear-wave elastography of the breast: value of a quality measure and comparison with strain elastography. Radiology 275, 45–53. https://doi.org/10.1148/radiol.14132404.

Brum, J., Bernal, M., Gennisson, J.L., Tanter, M., 2014. In vivo evaluation of the elastic anisotropy of the human Achilles tendon using shear wave dispersion analysis. Phys. Med. Biol. 59, 505–523. https://doi.org/10.1088/0031-9155/59/3/505.

Carlson, R.E., Fleming, L.L., Hutton, W.C., 2000. The biomechanical relationship between the tendoachilles, plantar fascia and metatarsophalangeal joint dorsiflexion angle. Foot Ankle Int. 21, 18–25.

Cavanagh, P.R., Rodgers, M.M., 1987. The arch index: a useful measure from footprints. J. Biomech. 20, 547–551. https://doi.org/10.1016/0021-9290(87)90255-7.

Chen, H., Ho, H.-M., Ying, M., Fu, S.N., 2013. Association between plantar fascia vascularity and morphology and foot dysfunction in individuals with chronic plantar fasciitis. J. Orthop. Sports Phys. Ther. 43, 727–734. https://doi.org/10.2519/jospt.2013.4774.

Chen, T.L.-W., Sze, L.K.Y., Davis, I.S., Cheung, R.T.H., 2016. Effects of training in minimalist shoes on the intrinsic and extrinsic foot muscle volume. Clin. Biomech. 36, 8–13. https://doi.org/10.1016/j.clinbiomech.2016.05.010.

Chen, T.L.-W., Wong, D.W.-C., Wang, Y., Lin, J., Zhang, M., 2019. Foot arch deformation and plantar fascia loading during running with rearfoot strike and forefoot strike: a dynamic finite element analysis. J. Biomech. 83, 260–272. https://doi.org/10.1016/j.jbiomech.2018.12.007.

Cheung, J.T.-M., Zhang, M., An, K.-N., 2006. Effect of Achilles tendon loading on plantar fascia tension in the standing foot. Clin. Biomech. 21, 194–203. https://doi.org/10.1016/j.clinbiomech.2005.09.016.

Cheung, R.T.H., Davis, I.S., 2011. Landing pattern modification to improve patellofemoral pain in runners: a case series. J. Orthop. Sports Phys. Ther. 41, 914–919. https://doi.org/10.2519/jospt.2011.3771.

Crowell, H.P., Davis, I.S., 2011. Gait retraining to reduce lower extremity loading in runners. Clin. Biomech. 26, 78–83. https://doi.org/10.1016/j.clinbiomech.2010.09.003.

de Almeida, M.O., Saragiotto, B.T., Yamato, T.P., Lopes, A.D., 2015. Is the rearfoot pattern the most frequently foot strike pattern among recreational shod distance runners? Phys. Ther. Sport 16, 29–33. https://doi.org/10.1016/j.ptsp.2014.02.005.

De Zordo, T., Fink, C., Feuchtner, G.M., Smekal, V., Reindl, M., Klauser, A.S., 2009. Real-time sonoelastography findings in healthy Achilles tendons. Am. J. Roentgenol. 193, W134–W138. https://doi.org/10.2214/AJR.08.1843.

Eby, S.F., Song, P., Chen, S., Chen, Q., Greenleaf, J.F., An, K.-N., 2013. Validation of shear wave elastography in skeletal muscle. J. Biomech. 46, 2381–2387. https://doi.org/10.1016/j.jbiomech.2013.07.033.

Goss, D.L., Gross, M.T., 2013. A comparison of negative joint work and vertical ground reaction force loading rates in chi runners and rearfoot-striking runners. J. Orthop. Sports Phys. Ther. 43, 685–692. https://doi.org/10.2519/jospt.2013.4542.

Graf, E.S., Rainbow, M.J., Samaan, C.D., Davis, I.S., 2013. A modified strike index for detection of foot strike pattern in barefoot running. Presented at the 37th Annual Meeting of the American Society of Biomechanics, 1–3.

Hamill, J., Gruber, A.H., 2017. Is changing footstrike pattern beneficial to runners? J. Sport Health Sci. 6, 146–153. https://doi.org/10.1016/j.jshs.2017.02.004.

Helfenstein-Didier, C., Andrade, R.J., Brum, J., Hug, F., Tanter, M., Nordez, A., Gennisson, J.-L., 2016. In vivo quantification of the shear modulus of the human Achilles tendon during passive loading using shear wave dispersion analysis. Phys. Med. Biol. 61, 2485–2496. https://doi.org/10.1088/0031-9155/61/6/2485.

Huang, C.K., Kitaoka, H.B., An, K.N., Chao, E.Y., 1993. Biomechanical evaluation of longitudinal arch stability. Foot Ankle 14, 353–357. https://doi.org/10.1177/107110079301400609.

Huffer, D., Hing, W., Newton, R., Clair, M., 2017. Strength training for plantar fasciitis and the intrinsic foot musculature: A systematic review. Physical Therapy in Sport 24, 44–52. https://doi.org/10.1016/j.ptsp.2016.08.008.

Kapoor, Atul, Sandhu, H.S., Sandhu, P.S., Kapoor, Aprajita, Mahajan, G., Kumar, A., 2010. Realtime elastography in plantar fasciitis: comparison with ultrasonography and MRI: Current Orthopaedic. Practice 21, 600–608. https://doi.org/10.1097/BCO.0b013e3181f4a8d9.

Kelly, L.A., Farris, D.J., Lichtwark, G.A., Cresswell, A.G., 2018. The influence of foot-strike technique on the neuromechanical function of the foot. Med. Sci. Sports Exerc. 50, 98–108. https://doi.org/10.1249/MSS.0000000000001420.

Kernozek, T.W., Vannatta, C.N., Gheidi, N., Kraus, S., Aminaka, N., 2016. Plantar loading changes with alterations in foot strike patterns during a single session in habitual rear foot strike female runners. Phys. Therapy Sport 18, 32–37. https://doi.org/10.1016/j.ptsp.2015.05.004.

Kim, M., Choi, Y.S., You, M.-W., Kim, J.S., Young, K.W., 2016. Sonoelastography in the evaluation of plantar fasciitis treatment: 3-month follow-up after collagen injection. Ultrasound Quarterly 32, 327–332. https://doi.org/10.1097/RUQ.0000000000000233.

Kirby, K.A., 2017. Longitudinal arch load-sharing system of the foot. Revista Española de Podología 28, e18–e26. https://doi.org/10.1016/j.repod.2017.03.003.

Knorz, S., Kluge, F., Gelse, K., Schulz-Drost, S., Hotfiel, T., Lochmann, M., Eskofier, B., Krinner, S., 2017. Three-dimensional biomechanical analysis of rearfoot and forefoot running. Orthop. J. Sports Med. 5, 1–10. https://doi.org/10.1177/2325967117719065.

Kulmala, J.-P., Avela, J., Pasanen, K., Parkkari, J., 2013. Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers. Med. Sci. Sports Exerc. 45, 2306–2313. https://doi.org/10.1249/MSS.0b013e31829efcf7.

Landreneau, L.L., Watts, K., Heitzman, J.E., Childers, W.L., 2014. Lower limb muscle activity during forefoot and rearfoot strike running techniques. Int J Sports Phys Ther 9, 888–897.

Larson, P., Higgins, E., Kaminski, J., Decker, T., Preble, J., Lyons, D., McIntyre, K., Normile, A., 2011. Foot strike patterns of recreational and sub-elite runners in a long-distance road race. J. Sports Sci. 29, 1665–1673. https://doi.org/10.1080/02640414.2011.610347.

Lee, S.S.M., Spear, S., Rymer, W.Z., 2015. Quantifying changes in material properties of stroke-impaired muscle. Clin. Biomech. 30, 269–275. https://doi.org/10.1016/j.clinbiomech.2015.01.004.

Lee, S.-Y., Park, H.J., Kwag, H.J., Hong, H.-P., Park, H.-W., Lee, Y.-R., Yoon, K.J., Lee, Y.-T., 2014. Ultrasound elastography in the early diagnosis of plantar fasciitis. Clin. Imag. 38, 715–718. https://doi.org/10.1016/j.clinimag.2012.12.004.

Leonardis, J.M., Desmet, D.M., Lipps, D.B., 2017. Quantifying differences in the material properties of the fiber regions of the pectoralis major using ultrasound shear wave elastography. J. Biomech. 63, 41–46. https://doi.org/10.1016/j.jbiomech.2017.07.031.

Lieberman, D.E., Venkadesan, M., Werbel, W.A., Daoud, A.I., D'Andrea, S., Davis, I.S., Mang'eni, R.O., Pitsiladis, Y., 2010. Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature 463, 531–535. https://doi.org/10.1038/nature08723.

Lynn, S.K., Padilla, R.A., Tsang, K.K.W., 2012. Differences in static- and dynamic-balance task performance after 4 weeks of intrinsic-foot-muscle training: the

short-foot exercise versus the towel-curl exercise. J. Sport Rehabilitation 21, 327–333. https://doi.org/10.1123/jsr.21.4.327.
McDonald, K.A., Stearne, S.M., Alderson, J.A., North, I., Pires, N.J., Rubenson, J., 2016. The role of arch compression and metatarsophalangeal joint dynamics in modulating plantar fascia strain in running. PLoS ONE 11. https://doi.org/10.1371/journal.pone.0152602.
McMillan, A.M., Landorf, K.B., Barrett, J.T., Menz, H.B., Bird, A.R., 2009. Diagnostic imaging for chronic plantar heel pain: a systematic review and meta-analysis. J. Foot Ankle Res. 2, 32. https://doi.org/10.1186/1757-1146-2-32.
Nowicki, A., Dobruch-Sobczak, K., 2016. Introduction to ultrasound elastography. J. Ultrason. 16, 113–124. https://doi.org/10.15557/JoU.2016.0013.
Rice, H., Patel, M., 2017. Manipulation of foot strike and footwear increases Achilles tendon loading during running. Am. J. Sports Medi. 45, 2411–2417. https://doi.org/10.1177/0363546517704429.
Ríos-Díaz, J., Martínez-Payá, J.J., del Baño-Aledo, M.E., de Groot-Ferrando, A., Botía-Castillo, P., Fernández-Rodríguez, D., 2015. Sonoelastography of plantar fascia: reproducibility and pattern description in healthy subjects and symptomatic subjects. Ultrasound Med. Biol. 41, 2605–2613. https://doi.org/10.1016/j.ultrasmedbio.2015.05.024.
Ryu, J., Jeong, W.K., 2017. Current status of musculoskeletal application of shear wave elastography. Ultrasonography 36, 185–197. https://doi.org/10.14366/usg.16053.
Sabir, N., Demirlenk, S., Yagci, B., Karabulut, N., Cubukcu, S., 2005. Clinical utility of sonography in diagnosing plantar fasciitis. J. Ultrasound Med. 24, 1041–1048.
Santuz, A., Ekizos, A., Arampatzis, A., 2016. A pressure plate-based method for the automatic assessment of foot strike patterns during running. Ann. Biomed. Eng. 44, 1646–1655. https://doi.org/10.1007/s10439-015-1484-3.
Shih, Y., Lin, K.-L., Shiang, T.-Y., 2013. Is the foot striking pattern more important than barefoot or shod conditions in running? Gait Posture 38, 490–494. https://doi.org/10.1016/j.gaitpost.2013.01.030.
Shiotani, H., Yamashita, R., Mizokuchi, T., Naito, M., Kawakami, Y., 2019. Site- and sex-differences in morphological and mechanical properties of the plantar fascia: a supersonic shear imaging study. J. Biomech. 85, 198–203. https://doi.org/10.1016/j.jbiomech.2019.01.014.
Shrout, P.E., Fleiss, J.L., 1979. Intraclass correlations: uses in assessing rater reliability. Psychol Bull 86, 420–428.
Skou, S.T., Rathleff, M.S., Moelgaard, C.M., Rasmussen, S., Olesen, J.L., 2012. The influence of time-of-day variation and loading on the aponeurosis plantaris pedis: an ultrasonographic study. J. Sports Med. Phys. Fitness 52, 506–512.
van der Worp, H., Vrielink, J.W., Bredeweg, S.W., 2016. Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis. Br. J. Sports Med. 50, 450–457. https://doi.org/10.1136/bjsports-2015-094924.
van Gent, R.N., Siem, D., van Middelkoop, M., van Os, A.G., Bierma-Zeinstra, S.M.A., Koes, B.W., 2007. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. Br. J. Sports Med. 41, 469–480. https://doi.org/10.1136/bjsm.2006.033548. discussion 480.
Wearing, S.C., Smeathers, J.E., Urry, S.R., Hennig, E.M., Hills, A.P., 2006. The pathomechanics of plantar fasciitis. Sports Med. 36, 585–611.
Wille, C., Lenhart, R., Wang, S., Thelen, D., Heiderscheit, B., 2014. Ability of sagittal kinematic variables to estimate ground reaction forces and joint kinetics in running. J. Orthop. Sports Phys. Ther. 44, 825–830. https://doi.org/10.2519/jospt.2014.5367.
Williams, D.S.B., Green, D.H., Wurzinger, B., 2012. Changes in lower extremity movement and power absorption during forefoot striking and barefoot running. Int. J. Sports Phys. Ther. 7, 525–532.
Wong, C.K., Weil, R., de Boer, E., 2012. Standardizing foot-type classification using arch index values. Physiotherapy Canada 64, 280–283. https://doi.org/10.3138/ptc.2011-40.
Wu, C.-H., Chang, K.-V., Mio, S., Chen, W.-S., Wang, T.-G., 2011. Sonoelastography of the Plantar Fascia. Radiology 259, 502–507. https://doi.org/10.1148/radiol.11101665.
Wu, C.-H., Chen, W.-S., Wang, T.-G., 2015. Plantar fascia softening in plantar fasciitis with normal B-mode sonography. Skeletal Radiol. 44, 1603–1607. https://doi.org/10.1007/s00256-015-2215-4.
Wu, C.-H., Chen, W.-S., Wang, T.-G., Lew, H.L., 2012. Can sonoelastography detect plantar fasciitis earlier than traditional B-mode ultrasonography? Am. J. Phys. Med. Rehabil. 91, 185. https://doi.org/10.1097/PHM.0b013e31822de9ab.
Yong, J.R., Silder, A., Delp, S.L., 2014. Differences in muscle activity between natural forefoot and rearfoot strikers during running. J. Biomech. 47, 3593–3597. https://doi.org/10.1016/j.jbiomech.2014.10.015.
Zadpoor, A.A., Nikooyan, A.A., 2011. The relationship between lower-extremity stress fractures and the ground reaction force: a systematic review. Clin. Biomech. 26, 23–28. https://doi.org/10.1016/j.clinbiomech.2010.08.005.
Zhang, Lining, Wan, W., Zhang, Lihai, Xiao, H., Luo, Y., Fei, X., Zheng, Z., Tang, P., 2014. Assessment of plantar fasciitis using shear wave elastography. J. South Med. Univ. 34, 206–209.
Zhang, Z.J., Fu, S.N., 2013. Shear elastic modulus on patellar tendon captured from supersonic shear imaging: correlation with tangent traction modulus computed from material testing system and test–retest reliability. PLoS ONE 8, 1–9. https://doi.org/10.1371/journal.pone.0068216.