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Effects of minimalist and maximalist footwear on Achilles tendon load in recreational runners

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Effects of minimalist and maximalist footwear on Achilles tendon load in recreational runners

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Abstract

The current investigation aimed to comparatively examine the effects of minimalist, maximalist and conventional footwear on Achilles tendon forces (ATF) during running. Twelve male runners (age 23.11 ± 5.01 years, height 1.78 ± 0.10 cm and body mass 77.13 ± 7.89 kg) ran at 4.0 m.s^{-1} in the three footwear conditions. ATF's were calculated using Opensim software allowing the magnitudal and temporal aspects of the ATF to be quantified. Differences between footwear were examined using one-way repeated measures ANOVA. The results showed the peak ATF was significantly larger in minimalist footwear (5.97 ± 1.38 BW) compared to maximalist (5.07 ± 1.42 BW). In addition it was revealed that ATF per mile was significantly larger in minimalist (492.31 ± 157.72 BW) in comparison to both maximalist (377.31 ± 148.06 BW) and conventional (402.71 ± 125.51 BW) footwear. Given the relationship between high ATF and Achilles tendon degradation, the current investigation indicated that minimalist footwear may increase runners risk for Achilles tendon injury.

Introduction

Recreational running is a popular exercise modality. It has been projected that as many as 2 million people in the UK utilize running as a mode of exercise (Sport England, 2014). Running is known to provide a substantial number of physiological benefits (Lee *et al.*, 2014; Schnohr *et al*., 2015). However despite the physical benefits that running provides, running is also known to be associated with a high incidence of chronic injuries. Over the course of ane year up to 80 % of runners will experience a chronic musculoskeletal injury as a consequence of their training (Van Gent *et al*., 2007).

The Achilles tendon has been shown to be a common injury site in runners with an occurrence rate around 14.5 % (Mahieu *et al*., 2006). The Achilles tendon represents a confluence of the gastrocnemius and soleus muscles. The tendon is inserted on the posterior surface of the calcaneus distal to the posterior-superior calcaneal tuberosity (Maffulli *et al*., 2004). The main function of the tendon is to transfer forces from these muscles to the calcaneus (Moore, 2006). The mechanism by which chronic Achilles tendon pathologies are initiated has not been fully clarified scientifically; however a key pathological stimulus for those involved in dynamic activities such as running is excessive loading of the tendon itself (Selvanetti *et al*., 1997). Collagenous materials such as tendons are able to respond positively to applied loads provided that sufficient rest is allowed between training sessions (Magnusson *et al*., 2010). However, when high loads are applied to the tendon too frequently this results in rates of collagen degradation that overtake the rate of collagen synthesis (Selvanetti *et al*., 1997). Overtime this creates micro tears in the collagenous fibres of the tendon leading to a condition known as tendinosis (Kirkendall & Garrett, 1997).

Recently, it has been advocated that running conventional running shoes may place runners as a dis-advantage both in terms of their susceptibility to injury and their running performance (Liebermann *et al*., 2010). This led to a new proposal in footwear research that running barefoot or in minimalist footwear may be associated with a reduced incidence of chronic running injuries (Liebermann *et al*., 2010). Based on this hypothesis a number of runners are now choosing to run barefoot or in minimalist footwear (Sinclair *et al*., 2013a). Based on this increasing interest led footwear manufacturers to develop a large range of minimalist footwear. Even more recently however the opposite approach in maximalist footwear has been advocated and developed by shoe manufacturers. Maximalist footwear feature an oversized midsole designed to provide additional cushioning and shock attenuation in comparison to conventional running shoes.

There has been limited research investigating the effects of different footwear on the loads experienced by the Achilles tendon. However the limited work in this area has shown that footwear can influence the loads experienced by the Achilles tendon during running. Sinclair (2014) investigated the effects of barefoot and minimalist footwear on the loads experienced by the Achilles tendon during running. They showed that minimalist footwear were associated with significantly greater Achilles tendon loads compared to conventional footwear. Sinclair *et al.* (2015) investigated the effects of cross-trainers, running trainers and a traditional army boot on the forces experienced by the Achilles tendon. It was demonstrated that Achilles tendon loads were greater in the military boot compared to the cross-trainers and running trainers. Sobhani *et al*., (2015) examined the effects of rocker soles on the forces experienced by the tendon in comparison to conventional running shoes. Their findings indicated that rocker soles significantly reduced the forces experienced by the Achilles tendon. Currently no published scientific investigations exist however regarding the effects of maximalist footwear on the loads experienced by the Achilles tendon.

Therefore the aim of the current investigation was to comparatively examine the effects of minimalist, maximalist and conventional footwear on the loads experienced by the Achilles tendon during running. Given the high incidence of Achilles tendon pathologies in runners a study of this nature may provide important clinical information to runners regarding the selection of appropriate footwear. The current investigation tests the hypothesis that minimalist footwear will be associated with increased Achilles tendon loads in relation to the conventional and maximalist condition.

Methods

Participants

Twelve male runners who had not previously experienced an Achilles tendon injury, volunteered to take part in this study. All were identified as recreational runners who trained a minimum of 3 times/week completing a minimum of 35 km. In addition each runner exhibited a rearfoot strike pattern as they exhibited an impact peak in their vertical ground reaction force curve. All runners were free from musculoskeletal pathology at the time of data collection and were not currently taking any medications. The participants provided written informed consent in accordance with the principles outlined in the Declaration of Helsinki. The mean characteristics of the participants were; age 23.11 ± 5.01 years, height 1.78 ± 0.10 cm and body mass 77.13 ± 7.89 kg. The procedure utilized for this investigation was approved by the University of Central Lancashire, Science, Technology, Engineering and Mathematics, ethical committee.

Procedure

Participants ran at 4.0 $m.s^{-1}$ (±5%), striking an embedded piezoelectric force platform (Kistler, Kistler Instruments Ltd., Alton, Hampshire) with their right foot (Sinclair *et al*., 2014). Running velocity was monitored using infrared timing gates (Newtest, Oy Koulukatu, Finland). The stance phase was delineated as the duration over which 20 N or greater of vertical force was applied to the force platform (Sinclair *et al*., 2011). Runners completed a minimum of five successful trials in each footwear condition. The order that participants ran in each footwear condition was randomized. Kinematics and ground reaction forces data were synchronously collected. Kinematic data was captured at 250 Hz via an eight camera motion analysis system (Qualisys Medical AB, Goteburg, Sweden). Dynamic calibration of the motion capture system was performed before each data collection session.

To define the anatomical frames of the thorax, pelvis, thighs, shanks and feet retroreflective markers were placed at the C7, T12 and xiphoid process landmarks and also positioned bilaterally onto the acromion process, iliac crest, anterior superior iliac spine, posterior super iliac spine, medial and lateral malleoli, medial and lateral femoral epicondyles and greater trochanter. Carbon-fibre tracking clusters comprising of four non-linear retroreflective markers were positioned onto the thigh and shank segments. Static calibration trials were obtained with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters/markers. A static trial was conducted with the participant in the anatomical position in order for the anatomical positions to be referenced in relation to the tracking markers, following which those not required for dynamic data were removed. All markers were positioned by the lead author. The mean temperature of the laboratory throughout data collection was 21.07 ± 1.08 °C.

Footwear

The footwear used during this study consisted of conventional footwear (New Balance 1260 v2), minimalist (Vibram five-fingers, ELX) and maximalist (Hoka One-One) footwear, (shoe size 8–10 in UK men’s sizes).

Processing

Dynamic trials were digitized using Qualisys Track Manager in order to identify anatomical and tracking markers then exported as C3D files to Visual 3D (C-Motion, Germantown, MD, USA). Ground reaction force and kinematic data were smoothed using cut-off frequencies of 25 and 12 Hz with a low-pass Butterworth 4th order zero lag filter (Sinclair *et al*., 2015).

Data during the stance phase of running were exported from Visual 3D into OpenSim software (Simtk.org), which was used give to simulations of muscles forces. Simulations of muscle forces were obtained using the standard gait2392 model within Opensim v3.2. This model corresponds to the eight segments that were exported from Visual 3D and features 19 total degrees of freedom and 92 muscle-tendon actuators.

We firstly performed a residual reduction algorithm (RRA) within OpenSim, this utilizes the inverse kinematics and ground reaction forces that were exported from Visual 3D. The RRA calculates the joint torques required to re-create the dynamic motion. The RRA calculations produced route mean squared errors <2°, which correspond with the recommendations for good quality data. Following the RRA, the computed muscle control (CMC) procedure was then employed to estimate a set of muscle force patterns allowing the model to replicate the required kinematics (Thelen *et al*., 2003). The CMC procedure works by estimating the required muscle forces to produce the net joint torques.

Achilles tendon force (ATF) was estimated in accordance with the protocol of Almonroeder *et al*. (2013) by summing the muscle forces of the medial gastrocnemius, lateral, gastrocnemius, and soleus muscles. Average Achilles tendon load rate was quantified as the peak ATF divided by the time to peak ATF. Instantaneous Achilles tendon load rate was also determined as the peak increase in ATF adjacent data points. All Achilles tendon load parameters were normalized by dividing the net values by body weight (BW).

Minimalist footwear has been shown to alter the step length/ stance time during running, which may affect the number of steps used to complete a set distance (Hollander *et al*., 2014; Sinclair *et al*, 2013ab). We therefore firstly calculated the total ATF impulse (BW x s) during running by multiplying the ATF estimated during the stance phase by the stance time. In addition to this we also estimated the total ATF impulse per mile (BW x s) by multiplying the ATF impulse by the number of steps required to run a mile. The number of steps required to complete one mile was quantified using the step length (m). Step length was determined by taking the difference in the horizontal position of the foot centre of mass between the right and left legs at footstrike (Almonroeder *et al*., 2013).

Statistical analyses

Means, standard deviations and 95 % confidence intervals were calculated for each outcome measure for all footwear conditions. Differences in ATF parameters between footwear were examined using one-way repeated measures ANOVAs, with significance accepted at the $p \leq 0.05$ level (Sinclair *et al*., 2013c). Effect sizes were calculated using partial eta^2 ($p\eta^2$). Post-hoc pairwise comparisons were conducted on all significant main effects. In addition to this percentage differences were also calculated for all statistically significant effects. The data was screened for normality using a Shapiro-Wilk which confirmed that the normality assumption was met. All statistical actions were conducted using SPSS v22.0 (SPSS Inc., Chicago, USA).

Results

Figure 1 and tables 1-2 and present the footwear differences in ATF parameters. The results indicate that the experimental footwear significantly influenced ATF measures.

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@@@ Table 1 near here @@@

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A main effect ($P<0.05$, $p\eta^2 = 0.31$) was shown for the magnitude of ATF. Post-hoc analyses showed that ATF was significantly greater in the minimalist compared to the maximalist ($P = 0.017$; 23.83 %) footwear (Table 1; figure 1a). In addition a main effect ($P<0.05$, $p\eta^2 = 0.43$) was found for the time to ATF. Post-hoc analysis showed that time to ATF was significantly greater in the conventional ($P = 0.025$; 7.79 %) and maximalist ($P = 0.007$; 9.25 %) compared to the minimalist footwear (Table 1). A main effect ($P<0.05$, $p\eta^2 = 0.44$) was also observed for ATF average loading rate. Post-hoc analysis showed that ATF average loading rate was significantly greater in the minimalist compared to the conventional ($P = 0.021$; 16.77 %) and maximalist ($P = 0.007$; 23.35 %) footwear (Table 1). Finally a main effect ($P<0.05$, $p\eta^2 = 0.63$) was found for ATF instantaneous loading rate. Post-hoc analysis showed that ATF instantaneous loading rate was significantly greater in the minimalist compared to the conventional (P = 0.004; 22.05 %) and maximalist (P = 0.00004; 37.64 %) footwear (Table 1).

A main effect ($P<0.05$, $p\eta^2 = 0.26$) was observed for stance time. Post-hoc analysis showed that stance time was significantly greater in the conventional (P = 0.034; 4.63 %) and maximalist (P = 0.03; 4.68 %) compared to the minimalist footwear (Table 2). In addition a main effect ($P<0.05$, $p\eta^2 = 0.28$) was noted for step length. Post-hoc analysis showed that step length was significantly greater in the conventional (P = 0.027; 4.18 %) and maximalist (P = 1.3 ; 4.24 %) compared to the minimalist footwear (Table 2). Finally a main effect ($P<0.05$, $p\eta^2 = 0.28$) was shown for the number of steps per mile. Post-hoc analysis showed that steps per mile were significantly greater minimalist compared to the conventional (P = 0.03; 4.64 %) and maximalist (P = 0.03; 4.66 %) footwear (Table 2).

A main effect ($P<0.05$, $p\eta^2 = 0.37$) was noted for ATF impulse. Post-hoc analysis showed that ATF impulse was significantly greater in the minimalist compared to the conventional (P = 1.4 ; 19.26 %) and maximalist (P = 0.01; 25.95 %) footwear (Table 2). Finally a main effect ($P<0.05$, $p\eta^2 = 0.49$) was found for the ATF per mile. Post-hoc analysis showed that ATF per mile was significantly greater in the minimalist compared to the conventional (P = 0.02; 20.02 %) and maximalist (P = 0.003; 26.46 %) footwear (Table 2).

Discussion

The aim of the current investigation was to examine the effects of minimalist and maximalist footwear on the loads experienced by the Achilles tendon. To the authors knowledge this represents the first comparative examination of Achilles tendon kinetics when running in these footwear.

The first important observation from this work is that ATF parameters were shown to be significantly larger in the minimalist footwear in comparison to the conventional and maximalist conditions. This observation concurs with our hypothesis and the findings of Sinclair (2014) who showed that minimalist footwear were associated with significant increases in ATF. This observation is important clinically regarding the aetiology of Achilles tendon pathologies in runners and appears to refute the notion that minimalist footwear may unanimously reduce the incidence of chronic injuries. The mechanical stimulus for the initiation of Achilles tendinosis is believed to be repeated high loads imposed too frequently to the tendon itself (Selvanetti *et al*., 1997). Tendon loads that exceed the physiological threshold for collagen synthesis initiate collagen degradation which ultimately leads to injury (Kirkendall & Garrett, 1997). Therefore the findings from the current investigation indicate that minimalist footwear may place runners at a greater risk from Achilles tendon pathology.

Previous work investigating the loads imposed on the musculoskeletal system when running in different footwear has habitually examined only the forces experienced per step. Therefore the potential effects that alterations in stride length/ frequency may have on the cumulative loads experienced by the body are not considered. The findings from the current investigation can be further contextualized taking into account the increased number of steps required to complete one mile when using minimalist footwear, an observation that concurs with the findings of (Hollander *et al*., 2014; Sinclair *et al*, 2013ab). This led to further increases in ATF experienced per mile, over and above those reported per step when participants ran in the minimalist footwear. This therefore further supports the notion that running in minimalist footwear may increase the likelihood of experiencing an Achilles tendon injury.

Of further interest to both runners and also the biomechanics community is the finding that the maximalist footwear did not differ in ATF parameters from the conventional running shoes. Although the majority of ATF measures were larger in the conventional footwear compared to the maximalist condition the differences did not reach statistical significance. This indicates that maximalist footwear despite their substantiality larger midsole did not provide any further benefits in the context of reductions in ATF's. The aforementioned link between overloading of the Achilles tendon and the aetiology of tendon pathology (Selvanetti *et al*., 1997), leads to the preliminary conclusion that maximalist footwear does not provide any additional benefits in comparison in terms of protection from Achilles tendon injuries. Although it is recommended that further prospective work be conducted, before the potential benefits of maximalist footwear can be dismissed.

In conclusion, although differences in ATF's as a function of different footwear have been examined previously, the current knowledge regarding the effects of both minimalist and maximalist footwear on ATF's is limited. The present investigation therefore adds to the current knowledge by providing a comprehensive evaluation of ATF parameters when running in minimalist, maximalist and conventional footwear. On the basis ATF and ATF per mile were shown to be significantly greater when running in minimalist footwear, the findings from the current investigation indicate that utilization of minimalist footwear may place runners at increases risk from Achilles tendon pathology in comparison to conventional and maximalist conditions.

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Figure labels

Figure 1: Achilles tendon loads as a function of footwear (Black = minimalist, grey = conventional, dash = maximalist).

Table

Table 1: Achilles tendon magnitudes as a function of footwear.

	Maximalist			Conventional			Minimalist		
	Mean	***SD***	***95 % CI***	***Mean***	***SD***	***95 % CI***	***Mean***	***SD***	***95 % CI***
Peak ATF (BW)	5.07	1.42	4.17 – 5.97	5.37	1.05	4.17 – 6.03	5.97	1.38	5.10 – 6.85
Time to peak ATF (s)	0.14	0.02	0.12 – 0.15	0.14	0.02	0.12 – 0.15	0.13	0.02	0.11 – 0.14
ATF average loading rate (BW/s)	39.42	18.17	27.88 – 50.97	42.13	15.42	32.33 – 51.92	49.84	15.83	39.78 – 59.89
ATF instantaneous loading rate (BW/s)	125.16	64.83	83.97 – 166.35	146.81	62.70	106.97 – 186.64	183.19	69.37	139.11 – 227.27

Table

Table 2: Temporal factors as a function of footwear.

	Maximalist			**Conventional**			**Minimalist**		
	Mean	***SD***	***95 % CI***	***Mean***	***SD***	***95 % CI***	***Mean***	***SD***	***95 % CI***
Stance time (s)	0.22	0.02	0.21 – 0.23	0.22	0.02	0.21 – 0.23	0.21	0.02	0.20 – 0.22
Step length (m)	1.25	0.12	1.18 – 1.33	1.25	0.13	1.17 – 1.33	1.20	0.12	1.12 – 1.29
Steps per mile	648.60	62.04	609.18 – 688.02	650.46	67.28	607.71 – 693.20	674.57	63.80	634.04 – 715.11
Impulse (BW.s)	0.57	0.17	0.46 – 0.68	0.61	0.16	0.52 – 0.71	0.74	0.24	0.59 – 0.89
ATF per mile (BW)	377.31	148.06	283.24 – 471.38	402.71	125.51	322.97 – 482.46	492.31	157.72	392.10 – 592.52

Figure