

## Article

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# Comparative Exercise Physiology

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

--Manuscript--

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<b>Abstract:</b>	<p>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 <math>23.11 \pm 5.01</math> years, height <math>1.78 \pm 0.10</math> cm and body mass <math>77.13 \pm 7.89</math> kg) ran at <math>4.0</math> m.s<sup>-1</sup> 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 (<math>5.97 \pm 1.38</math> BW) compared to maximalist (<math>5.07 \pm 1.42</math> BW). In addition it was revealed that ATF per mile was significantly larger in minimalist (<math>492.31 \pm 157.72</math> BW) in comparison to both maximalist (<math>377.31 \pm 148.06</math> BW) and conventional (<math>402.71 \pm 125.51</math> 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.</p>



## 21 **Abstract**

22 The current investigation aimed to comparatively examine the effects of minimalist,  
23 maximalist and conventional footwear on Achilles tendon forces (ATF) during running.  
24 Twelve male runners (age  $23.11 \pm 5.01$  years, height  $1.78 \pm 0.10$  cm and body mass  $77.13 \pm$   
25  $7.89$  kg) ran at  $4.0 \text{ m}\cdot\text{s}^{-1}$  in the three footwear conditions. ATF's were calculated using  
26 Opensim software allowing the magnitudal and temporal aspects of the ATF to be quantified.  
27 Differences between footwear were examined using one-way repeated measures ANOVA.  
28 The results showed the peak ATF was significantly larger in minimalist footwear ( $5.97 \pm 1.38$   
29 BW) compared to maximalist ( $5.07 \pm 1.42$  BW). In addition it was revealed that ATF per  
30 mile was significantly larger in minimalist ( $492.31 \pm 157.72$  BW) in comparison to both  
31 maximalist ( $377.31 \pm 148.06$  BW) and conventional ( $402.71 \pm 125.51$  BW) footwear. Given  
32 the relationship between high ATF and Achilles tendon degradation, the current investigation  
33 indicated that minimalist footwear may increase runners risk for Achilles tendon injury.

34

## 35 **Introduction**

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

43

44 The Achilles tendon has been shown to be a common injury site in runners with an  
45 occurrence rate around 14.5 % (Mahieu *et al.*, 2006). The Achilles tendon represents a  
46 confluence of the gastrocnemius and soleus muscles. The tendon is inserted on the posterior  
47 surface of the calcaneus distal to the posterior-superior calcaneal tuberosity (Maffulli *et al.*,  
48 2004). The main function of the tendon is to transfer forces from these muscles to the  
49 calcaneus (Moore, 2006). The mechanism by which chronic Achilles tendon pathologies are  
50 initiated has not been fully clarified scientifically; however a key pathological stimulus for  
51 those involved in dynamic activities such as running is excessive loading of the tendon itself  
52 (Selvanetti *et al.*, 1997). Collagenous materials such as tendons are able to respond positively  
53 to applied loads provided that sufficient rest is allowed between training sessions (Magnusson  
54 *et al.*, 2010). However, when high loads are applied to the tendon too frequently this results  
55 in rates of collagen degradation that overtake the rate of collagen synthesis (Selvanetti *et al.*,  
56 1997). Overtime this creates micro tears in the collagenous fibres of the tendon leading to a  
57 condition known as tendinosis (Kirkendall & Garrett, 1997).

58

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

68 feature an oversized midsole designed to provide additional cushioning and shock attenuation  
69 in comparison to conventional running shoes.

70

71 There has been limited research investigating the effects of different footwear on the loads  
72 experienced by the Achilles tendon. However the limited work in this area has shown that  
73 footwear can influence the loads experienced by the Achilles tendon during running. Sinclair  
74 (2014) investigated the effects of barefoot and minimalist footwear on the loads experienced  
75 by the Achilles tendon during running. They showed that minimalist footwear were  
76 associated with significantly greater Achilles tendon loads compared to conventional  
77 footwear. Sinclair *et al.* (2015) investigated the effects of cross-trainers, running trainers and  
78 a traditional army boot on the forces experienced by the Achilles tendon. It was demonstrated  
79 that Achilles tendon loads were greater in the military boot compared to the cross-trainers and  
80 running trainers. Sobhani *et al.*, (2015) examined the effects of rocker soles on the forces  
81 experienced by the tendon in comparison to conventional running shoes. Their findings  
82 indicated that rocker soles significantly reduced the forces experienced by the Achilles  
83 tendon. Currently no published scientific investigations exist however regarding the effects of  
84 maximalist footwear on the loads experienced by the Achilles tendon.

85

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

91 minimalist footwear will be associated with increased Achilles tendon loads in relation to the  
92 conventional and maximalist condition.

93

## 94 **Methods**

### 95 *Participants*

96 Twelve male runners who had not previously experienced an Achilles tendon injury,  
97 volunteered to take part in this study. All were identified as recreational runners who trained  
98 a minimum of 3 times/week completing a minimum of 35 km. In addition each runner  
99 exhibited a rearfoot strike pattern as they exhibited an impact peak in their vertical ground  
100 reaction force curve. All runners were free from musculoskeletal pathology at the time of  
101 data collection and were not currently taking any medications. The participants provided  
102 written informed consent in accordance with the principles outlined in the Declaration of  
103 Helsinki. The mean characteristics of the participants were; age  $23.11 \pm 5.01$  years, height  
104  $1.78 \pm 0.10$  cm and body mass  $77.13 \pm 7.89$  kg. The procedure utilized for this investigation  
105 was approved by the University of Central Lancashire, Science, Technology, Engineering and  
106 Mathematics, ethical committee.

107

### 108 *Procedure*

109 Participants ran at  $4.0 \text{ m}\cdot\text{s}^{-1}$  ( $\pm 5\%$ ), striking an embedded piezoelectric force platform  
110 (Kistler, Kistler Instruments Ltd., Alton, Hampshire) with their right foot (Sinclair *et al.*,  
111 2014). Running velocity was monitored using infrared timing gates (Newtest, Oy Koulukatu,  
112 Finland). The stance phase was delineated as the duration over which 20 N or greater of  
113 vertical force was applied to the force platform (Sinclair *et al.*, 2011). Runners completed a

114 minimum of five successful trials in each footwear condition. The order that participants ran  
115 in each footwear condition was randomized. Kinematics and ground reaction forces data were  
116 synchronously collected. Kinematic data was captured at 250 Hz via an eight camera motion  
117 analysis system (Qualisys Medical AB, Goteburg, Sweden). Dynamic calibration of the  
118 motion capture system was performed before each data collection session.

119

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

132

### 133 *Footwear*

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



137

138 *Processing*

139 Dynamic trials were digitized using Qualisys Track Manager in order to identify anatomical  
140 and tracking markers then exported as C3D files to Visual 3D (C-Motion, Germantown, MD,  
141 USA). Ground reaction force and kinematic data were smoothed using cut-off frequencies of  
142 25 and 12 Hz with a low-pass Butterworth 4th order zero lag filter (Sinclair *et al.*, 2015).

143

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

149

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

158

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

165

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

175

#### 176 *Statistical analyses*

177 Means, standard deviations and 95 % confidence intervals were calculated for each outcome  
178 measure for all footwear conditions. Differences in ATF parameters between footwear were  
179 examined using one-way repeated measures ANOVAs, with significance accepted at the  
180  $p \leq 0.05$  level (Sinclair *et al.*, 2013c). Effect sizes were calculated using partial  $\eta^2$  ( $\eta^2$ ).  
181 Post-hoc pairwise comparisons were conducted on all significant main effects. In addition to  
182 this percentage differences were also calculated for all statistically significant effects. The

183 data was screened for normality using a Shapiro-Wilk which confirmed that the normality  
184 assumption was met. All statistical actions were conducted using SPSS v22.0 (SPSS Inc.,  
185 Chicago, USA).

186

## 187 **Results**

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

190

191 **@@@ Figure 1 near here @@@**

192 **@@@ Table 1 near here @@@**

193 **@@@ Table 2 near here @@@**

194

195 A main effect ( $P < 0.05$ ,  $\eta^2 = 0.31$ ) was shown for the magnitude of ATF. Post-hoc analyses  
196 showed that ATF was significantly greater in the minimalist compared to the maximalist ( $P =$   
197  $0.017$ ; 23.83 %) footwear (Table 1; figure 1a). In addition a main effect ( $P < 0.05$ ,  $\eta^2 = 0.43$ )  
198 was found for the time to ATF. Post-hoc analysis showed that time to ATF was significantly  
199 greater in the conventional ( $P = 0.025$ ; 7.79 %) and maximalist ( $P = 0.007$ ; 9.25 %) compared  
200 to the minimalist footwear (Table 1). A main effect ( $P < 0.05$ ,  $\eta^2 = 0.44$ ) was also observed for  
201 ATF average loading rate. Post-hoc analysis showed that ATF average loading rate was  
202 significantly greater in the minimalist compared to the conventional ( $P = 0.021$ ; 16.77 %) and  
203 maximalist ( $P = 0.007$ ; 23.35 %) footwear (Table 1). Finally a main effect ( $P < 0.05$ ,  $\eta^2 =$   
204  $0.63$ ) was found for ATF instantaneous loading rate. Post-hoc analysis showed that ATF

205 instantaneous loading rate was significantly greater in the minimalist compared to the  
206 conventional ( $P = 0.004$ ; 22.05 %) and maximalist ( $P = 0.00004$ ; 37.64 %) footwear (Table  
207 1).

208

209 A main effect ( $P < 0.05$ ,  $p\eta^2 = 0.26$ ) was observed for stance time. Post-hoc analysis showed  
210 that stance time was significantly greater in the conventional ( $P = 0.034$ ; 4.63 %) and  
211 maximalist ( $P = 0.03$ ; 4.68 %) compared to the minimalist footwear (Table 2). In addition a  
212 main effect ( $P < 0.05$ ,  $p\eta^2 = 0.28$ ) was noted for step length. Post-hoc analysis showed that step  
213 length was significantly greater in the conventional ( $P = 0.027$ ; 4.18 %) and maximalist ( $P =$   
214 1.3 ; 4.24 %) compared to the minimalist footwear (Table 2). Finally a main effect ( $P < 0.05$ ,  
215  $p\eta^2 = 0.28$ ) was shown for the number of steps per mile. Post-hoc analysis showed that steps  
216 per mile were significantly greater minimalist compared to the conventional ( $P = 0.03$ ; 4.64  
217 %) and maximalist ( $P = 0.03$ ; 4.66 %) footwear (Table 2).

218

219 A main effect ( $P < 0.05$ ,  $p\eta^2 = 0.37$ ) was noted for ATF impulse. Post-hoc analysis showed that  
220 ATF impulse was significantly greater in the minimalist compared to the conventional ( $P =$   
221 1.4 ; 19.26 %) and maximalist ( $P = 0.01$ ; 25.95 %) footwear (Table 2). Finally a main effect  
222 ( $P < 0.05$ ,  $p\eta^2 = 0.49$ ) was found for the ATF per mile. Post-hoc analysis showed that ATF per  
223 mile was significantly greater in the minimalist compared to the conventional ( $P = 0.02$ ;  
224 20.02 %) and maximalist ( $P = 0.003$ ; 26.46 %) footwear (Table 2).

225

226 **Discussion**

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

231

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

244

245 Previous work investigating the loads imposed on the musculoskeletal system when running  
246 in different footwear has habitually examined only the forces experienced per step. Therefore  
247 the potential effects that alterations in stride length/ frequency may have on the cumulative  
248 loads experienced by the body are not considered. The findings from the current investigation  
249 can be further contextualized taking into account the increased number of steps required to  
250 complete one mile when using minimalist footwear, an observation that concurs with the

251 findings of (Hollander *et al.*, 2014; Sinclair *et al.*, 2013ab). This led to further increases in  
252 ATF experienced per mile, over and above those reported per step when participants ran in  
253 the minimalist footwear. This therefore further supports the notion that running in minimalist  
254 footwear may increase the likelihood of experiencing an Achilles tendon injury.

255

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

267

268 In conclusion, although differences in ATF's as a function of different footwear have been  
269 examined previously, the current knowledge regarding the effects of both minimalist and  
270 maximalist footwear on ATF's is limited. The present investigation therefore adds to the  
271 current knowledge by providing a comprehensive evaluation of ATF parameters when  
272 running in minimalist, maximalist and conventional footwear. On the basis ATF and ATF per  
273 mile were shown to be significantly greater when running in minimalist footwear, the  
274 findings from the current investigation indicate that utilization of minimalist footwear may

275 place runners at increases risk from Achilles tendon pathology in comparison to conventional  
276 and maximalist conditions.

277

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337

338 **Figure labels**

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

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

	Maximalist			Conventional			Minimalist		
	<i>Mean</i>	<i>SD</i>	<i>95 % CI</i>	<i>Mean</i>	<i>SD</i>	<i>95 % CI</i>	<i>Mean</i>	<i>SD</i>	<i>95 % CI</i>
<b>Peak ATF (BW)</b>	5.07	1.42	4.17 – 5.97	5.37	1.05	4.17 – 6.03	5.97	1.38	5.10 – 6.85
<b>Time to peak ATF (s)</b>	0.14	0.02	0.12 – 0.15	0.14	0.02	0.12 – 0.15	0.13	0.02	0.11 – 0.14
<b>ATF average loading rate (BW/s)</b>	39.42	18.17	27.88 – 50.97	42.13	15.42	32.33 – 51.92	49.84	15.83	39.78 – 59.89
<b>ATF instantaneous loading rate (BW/s)</b>	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 2: Temporal factors as a function of footwear.

	Maximalist			Conventional			Minimalist		
	<i>Mean</i>	<i>SD</i>	<i>95 % CI</i>	<i>Mean</i>	<i>SD</i>	<i>95 % CI</i>	<i>Mean</i>	<i>SD</i>	<i>95 % CI</i>
<b>Stance time (s)</b>	0.22	0.02	0.21 – 0.23	0.22	0.02	0.21 – 0.23	0.21	0.02	0.20 – 0.22
<b>Step length (m)</b>	1.25	0.12	1.18 – 1.33	1.25	0.13	1.17 – 1.33	1.20	0.12	1.12 – 1.29
<b>Steps per mile</b>	648.60	62.04	609.18 – 688.02	650.46	67.28	607.71 – 693.20	674.57	63.80	634.04 – 715.11
<b>Impulse (BW.s)</b>	0.57	0.17	0.46 – 0.68	0.61	0.16	0.52 – 0.71	0.74	0.24	0.59 – 0.89
<b>ATF per mile (BW)</b>	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

