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EFFECTS OF BAREFOOT AND MINIMALLY SHOD FOOTWEAR ON EFFECTIVE MASS – IMPLICATIONS FOR TRANSIENT MUSCULOSKELETAL LOADING

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Abstract:

The purpose of this investigation was to explore the effects of barefoot and minimally shod footwear on effective mass and determine the implications that this had for transient loading during running. Fifteen male runners ran at 4.0 m/s in five different footwear conditions (barefoot, running trainer, Nike-free, Inov-8 and Vibram five-fingers). Kinematics were collected using an 8 camera motion capture system and ground reaction forces (GRF) via an embedded force platform. Effective mass was examined using impulse-momentum modelling. Differences between types of footwear were examined using one-way repeated measures ANOVA and linear regression was used to determine the association between effective mass and instantaneous loading rate. The findings showed that effective mass was significantly larger in the barefoot (11.47 %BW), Nike-free (9.81 %BW), Inov-8 (12.10 %BW) and Vibram five-fingers (8.84 %BW) compared to the running trainer (6.86 %BW). Furthermore, instantaneous loading rate was significantly larger in the barefoot (347.55 BW/s), Nike-free (178.76 BW/s), Inov-8 (369.93 BW/s) and Vibram five-fingers (339.37 BW/s) compared to the running trainer (133.18 BW/s). It was also revealed that there were significant positive associations between effective mass and the instantaneous rate for each footwear: barefoot (R^2=0.60), Nike-free (R^2=0.53), Inov-8 (R^2=0.80), Vibram five-fingers (R^2=0.52) and running trainer (R^2=0.40). The findings from the current investigation indicate that effective mass has key implications for the generation of transient forces and also that running barefoot and in minimally shod footwear may place runners at increased risk from impact-related injuries compared to the traditional running shoes.

Key words: *biomechanics, footwear, effective mass, transient forces*

Introduction

Distance running is known to be associated with a plethora of physiological and psychological benefits (Schnohr, O'Keefe, Marott, Lange, & Jensen, 2015). However, running is highly renowned for being associated with a high frequency of chronic pathologies (Taunton, et al., 2002). Up to 79 % of runners will experience a running injury each year (Van Gent, et al., 2007). The most common chronic running pathologies include: patellofemoral pain (Taunton, et al., 2002), medial tibial stress syndrome (Hamstra-Wright, Huxel Bliven, & Bay, 2015), Achilles tendinopathy (Van Ginckel, et al., 2009) and stress fractures (Snyder, Koester, & Dunn, 2006).

During running, the human body experiences cyclic impact forces (Whittle, 1999), which manifest as high frequency peaks in the vertical ground reaction force (GRF) time curve. Impact forces are generated by inertial alterations of the lower extremities during the early stance phase (Addison & Liebermann, 2015). Because of their aetiological link to chronic running injuries, the attenuation of impact forces has received considerable research attention (Whittle, 1999).

The effects of running footwear have been extensively examined in the context of their ability to attenuate transient impact forces. The properties of running shoes have been proposed as a mechanism by which chronic injuries may be controlled (Shorten, 2000). Recently, the effects of running barefoot and in minimally shod footwear has received significant research attention. The popularity of barefoot and in minimally shod running is due to the suggestion that these footwear modalities may be able to reduce the incidence of chronic running injuries (Lieberman, et al., 2010; Warburton, 2000). However, the findings in relation to changes in transient loading when running in these footwear conditions in relation to traditional running shoes are somewhat conflicting.

The impact phase of stance is initiated when the foot strikes the ground and loses the momentum associated with its motion, in a manner proportional to the integral of the GRF (Whittle, 1999). Effective mass is representative of the portion of total bodyweight that is decelerated to zero during the impact phase; and predominantly encompasses mass from the foot, shank and thigh segments (Addison & Liebermann, 2015). Both effective mass and the integral of the GRF have received some attention in biomechanical literature, with specific focus on un-shod running, footwear stiffness and gait velocity (Addison & Liebermann, 2015; Chi & Schmidt, 2005; Liebermann, et al., 2010). However, currently no published scientific investigations exist which have quantitatively examined the effects of barefoot and minimally shod running on these parameters using a repeated measures approach. Indicating that further investigation into the effects of different footwear on effective mass and integral of the GRF is warranted.

Therefore, the purpose of this investigation was to explore the effects of barefoot and minimally shod footwear on effective mass and determine the implications for transient loading of the lower extremities during running. A study of this nature may provide further information regarding the mechanical effects that occur when running in different footwear.

Methods

Participants

Fifteen male runners volunteered to take part in this study. Participants self-identified themselves as recreational runners, who trained a minimum of 3 times/week completing a minimum of 35 km/week. All were habitual rearfoot strikers as they exhibited an impact peak in their vertical GRF curve when running in traditional running trainers. All runners were free from musculoskeletal pathology at the time of data collection and provided written informed consent. The mean characteristics of the participants were: age 25.33±4.39 years, body height 1.79±0.11 cm and body mass 78.54±7.15 kg. The procedure utilized for this investigation was approved by the University of Central Lancashire.

Experiential footwear

Footwear examined in this study consisted of a running trainer (New Balance 1260 v2), Vibram five-fingers (M108 Classic), Inov-8 (Evoskin) and Nike-Free (5.0) in sizes 8-10 men's UK (Figure 1). The running trainer had a mean mass of 0.285 kg, heel thickness of 25 mm and heel drop of 14 mm; the Vibram five-fingers had an average mass of 0.167 kg, heel thickness of 7 mm and a heel drop of 0 mm; Inov-8 had an average mass of 0.100 kg, heel thickness of 4 mm and a heel drop of 0 mm, and Nike-Free had an average mass of 0.240 kg, heel thickness of 23 mm and a heel drop of 13 mm. The New Balance 1260 were selected to provided a good representation of commercially available traditional running footwear as they provide both midsole cushioning and medial support. The Nike Free 3.0, Vibram Five Fingers and Inov-8 Evoskin were chosen for similar reasons to represent the continuum of commercially available minimalist footwear.

Procedure

Participants ran at 4.0m/s±5 %, striking an embedded piezoelectric force platform (Kistler, Kistler Instruments Ltd.), which sampled at 1000 Hz, with their right (dominant) foot. Foot dominance was determined by simply asking partici-

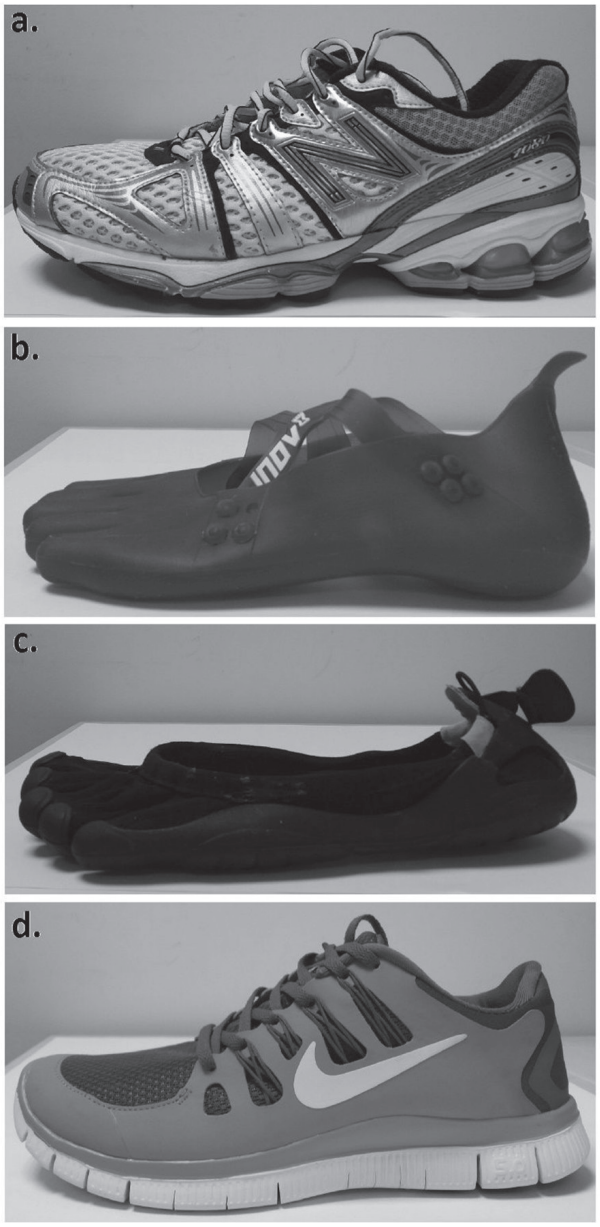

Figure 1. Experimental footwear (a. = running trainer, b. = Inov-8, c. Vibram five-fingers, d. = Nike-free).

pants to state which foot they would kick a ball with. Running velocity was monitored using infrared timing gates (Newtest, Oy Finland). The stance phase was delineated as the duration over which >20N vertical force was applied to the force platform (Sinclair, Greenhalgh, Brooks, Edmundson, & Hobbs, 2013a). Runners completed five successful trials in each footwear condition in a counterbalanced manner. A trial was considered successful when the right foot cleanly contacted the force platform without alteration of running pattern, within ±5 % of the prescribed velocity. Kinematic data was captured at 250Hz via an eight camera motion capture system (Qualisys Medical AB, Goteburg, Sweden). GRF and kinematic data were collected synchronously using an analogue to digital interface board. Participants were non-habitual barefoot/minimalist footwear users, and were thus given time to accommodate to each footwear prior to the commencement of data collection in that footwear. This involved five minutes of running through the testing area without concern for striking the force platform (Sinclair, et al., 2013).

To define the segment co-ordinate axes of the right foot, retroreflective markers were placed unilaterally onto the 1st metatarsal, 5th metatarsal, calcaneus, medial and lateral malleoli. The foot was tracked using the 1st metatarsal, 5th metatarsal and calcaneus markers. The centre of the ankle joint was delineated as the mid-point between the malleoli markers (Graydon, Fewtrell, Atkins, & Sinclair, 2015). Static calibration trials (not normalized to static trial posture) were obtained for the anatomical markers to be referenced in relation to the tracking markers/clusters. The Z (transverse) axis was oriented vertically from the distal segment end to the proximal segment end. The Y (coronal) axis was oriented in the segment from posterior to anterior. Finally, the X (sagittal) axis orientation was determined using the right hand rule and was oriented from medial to lateral.

Processing

Trials were processed in Qualisys Track Manager and then exported as C3D files. Kinematic parameters were quantified using Visual 3-D (C-Motion Inc, Gaithersburg, USA). Marker and kinetic data were smoothed at cut-off frequencies of 12 and 100 Hz, respectively, using a low-pass Butterworth 4th order zero-lag filter (Addison & Liebermann, 2015; Sinclair, Taylor, & Hobbs, 2013).

We specifically quantified GRF and lower limb kinematics during the impact peak of the vertical GRF. GRF parameters were normalized to the participants' bodyweight (BW). In accordance with the protocol of Addison and Liebermann (2015), we examined only the vertical element of the experimental parameters as >90 % of the total GRF during the impact phase of running is caused by the vertical GRF. An impulse-momentum modelling approach was utilized to calculate effective mass (% BW), which was quantified in accordance with the below equation [1]:

Effective mass = vertical GRF integral / (*Δ foot velocity + g * Δ time)* [1]

The impact peak was defined in the running trainer as the first peak in vertical GRF. In footwear conditions where no impact peak was present, according to the protocols of Liebermann et al. (2010) and Sinclair (2016), we defined the position of the impact peak at the same relative position as in the running trainer which was shown to be 10.35 % of the stance phase. The time (ms) to impact peak (Δ time) was quantified as the duration from footstrike to impact peak. The vertical GRF integral (BW·ms) during the period of the impact peak was calculated using a trapezoidal function. The change in foot velocity (Δ foot velocity) was determined as the instantaneous vertical foot velocity averaged across the 10 frames prior to the impact peak (Liebermann, et al., 2010). The velocity of the foot was quantified using the centre of mass of the foot segment in the vertical direction, within Visual 3D (Sinclair, 2016).

Instantaneous loading rate (BW/s) was quantified as the maximum increase in vertical force between frequency intervals. Finally, the strike index was calculated as the proportion of the centre of pressure location at foot strike, relative to the total length of the foot (Squadrone, Rodano, Hamill, & Preatoni, 2015). A strike index of 0-33 % denotes a rearfoot, 34-67 % a midfoot and 68-100 % a forefoot strike pattern.

Statistical analyses

Means, standard deviations (SD) and 95 % confidence intervals (95 % CI) were calculated for each outcome measure for all footwear conditions. The data was screened for normality using Shapiro-Wilk, which confirmed that the normality assumption was met. Differences between footwear conditions were examined using one-way repeated measures ANOVA. Effect sizes were calculated using partial eta^2 (pη^2), and contextualized using the following guidelines: very small = 0-0.1, small = 0.1-0.3, moderate = 0.3-0.5, large = 0.5-0.7, very large = 0.7-0.9 and distinct = 0.9-1.0 (Hopkins, 1997). *Post-hoc* pairwise comparisons were conducted on all significant main effects. In the event of a *post-hoc* comparison indicating statistical significance, the number of participants (N) who followed the direction of the statistical difference was reported. Finally, linear regression analyses were utilized to explore the association between effective mass and instantaneous loading rate and also to determine which of the components

of equation [1] are most strongly associated with effective mass. Statistical analyses were conducted using SPSS v23.0 (SPSS, USA).

Results

Table 1 presents footwear differences in effective mass and transient loading. Figures 2 and 3 present linear associations between effective mass and instantaneous loading rate and between effective mass and the vertical GRF integral. The results indicate that the experimental footwear significantly affected both effective mass and transient loading parameters.

A significant effect ($F_{(4, 56)}$=11.35, p<.001, $p\eta^2$=.45) was evident for the integral of the vertical GRF (Table 1; Figure 2). *Post-hoc* pairwise comparisons showed that the integral of the vertical GRF was significantly larger in the barefoot (p=.002, N=13), Inov-8 (p=.002, N=14), Nike-free (p=.001, N=13) and Vibram five fingers (p=0.04, N=10) in relation to the running trainer. In addition, it was also revealed that the vertical GRF integral was significantly greater in the barefoot (p=.002, N=12) and Inov-8 (p=.002, N=11) footwear in relation to the Vibram five fingers.

In addition, a significant effect ($F_{(4, 56)}$=2.99, p=.026, $p\eta^2$=0.18) was also observed for Δ *time*. *Post-hoc* pairwise comparisons showed that this duration was significantly shorter in the barefoot (p=.01, N=10), Inov-8 (p=.01, N=8) and Vibram five fingers (p=.01, N=8) conditions in relation to the running trainer.

A significant effect ($F_{(4, 56)}$=15.13, p<.001, $p\eta^2$=0.52) was evident for Δ *foot velocity*. *Post-hoc* pairwise comparisons showed that Δ foot velocity was significantly reduced in the barefoot (p<.001, N=14), Inov-8 (p<.001, N=14) and Vibram five fingers (p=.002, N=13) conditions in relation to the running trainer. It was also revealed that Δ foot velocity was significantly lower in the barefoot (p<.001, N=14) and Inov-8 (p<.001, N=12) in relation to the Nike-free footwear.

A significant effect ($F_{(4, 56)}$=13.33, p<.001, $p\eta^2$=0.49) was also shown for effective mass. *Post-hoc* pairwise comparisons showed that effective mass was significantly greater in the barefoot (p<.001, N=14), Inov-8 (p<.001, N=14), Nike-free (p<.001, N=14) and Vibram five fingers (p=.02, N=10) conditions in relation to the running trainer. In addition, it was also revealed that effective mass was significantly larger in the barefoot (p<.001, N=10) and Inov-8 (p<.001, N=11) footwear in relation to the Vibram five fingers.

A significant effect ($F_{(4, 56)}$=20.79, p<.001, $p\eta^2$=0.60) was noted for instantaneous load rate. *Post-hoc* pairwise comparisons showed that instantaneous load rate was significantly greater in the barefoot (p<.001, N=14), Inov-8 (p<.001, N=15), Nike-free (p<.001, N=14) and Vibram five fingers

Table 1: Effective mass and transient loading parameters (mean, SD and 95 % CI) as a function of footwear

	Barefoot			Running trainer			Vibram five-fingers			Inov-8			Nike-free		
	Mean	*SD*	*95 % CI*	**Mean**	*SD*	*95 % CI*	**Mean**	*SD*	*95 % CI*	**Mean**	*SD*	*95 % CI*	**Mean**	*SD*	*95 % CI*
Δ *time* (ms)	21.78 ***A***	1.99	20.67-22.88	23.02	1.90	21.97-24.07	22.31 ***A***	2.33	21.02-23.60	22.40 ***A***	1.76	21.34-23.29	22.12	1.97	21.22-23.40
Vertical GRF integral (BW·ms)	24.42 ***AC***	6.68	20.72-28.12	15.55	3.00	13.88-17.21	19.41 ***A***	6.64	15.73-23.08	26.36 ***AC***	9.14	21.30-31.42	21.60 ***A***	4.51	19.10-24.10
Δ *foot velocity* (m/s)	1.17 ***AB***	0.23	1.04-1.29	1.40	0.31	1.22-1.57	1.23 ***A***	0.31	1.06-1.40	1.20 ***AB***	0.27	1.05-1.35	1.33	0.25	1.19-1.47
Effective mass (% BW)	11.47 ***AC***	3.36	9.61-13.33	6.86	1.56	6.00-7.73	8.84 ***A***	2.79	7.30-10.38	12.10 ***AC***	4.46	9.63-14.58	9.81 ***A***	1.92	8.75-10.87
Instantaneous load rate (BW/s)	347.55 ***AB***	177.72	249.13-445.97	133.18	44.43	108.57-157.79	339.37 ***AB***	171.73	244.27-434.47	369.93 ***AB***	196.64	261.03-478.38	178.76 ***A***	52.85	149.49-208.03
Strike index (%)	39.93	22.02	27.73-52.12	26.42	15.48	17.85-34.99	36.57	15.64	27.91-45.23	39.25	16.66	30.03-48.48	35.33	14.38	27.36-43.29

Note. ***A*** = significantly different from running trainer,
B = significantly different from Nike-free,
C = significantly different from Vibram five-fingers.

(p<.001, N=15) conditions in relation to the running trainer. In addition, instantaneous load rate was significantly greater in the barefoot (p=.001, N=13), Inov-8 (p<.001, N=14), and Vibram five fingers (p=.001, N=14) compared to the Nike-free.

There was no significant effect ($F_{(4, 56)}$=1.90, p=.124, $p\eta^2$=0.12) for strike index.

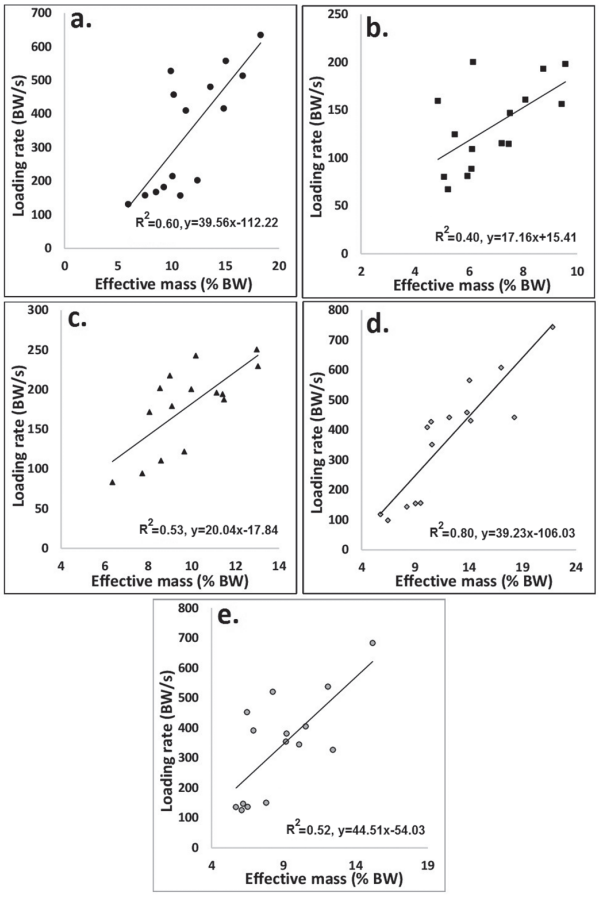

Figure 2. Linear associations between effective mass and instantaneous loading rate (a. = barefoot, b. = running trainer, c. = Nike-free, d. Inov-8, e. = Vibram five-fingers).

Regression analyses

The results revealed significant positive relationships between effective mass and instantaneous loading rate for each footwear condition (Figure 2). The findings also showed significant positive relationships between the vertical GRF integral and effective mass for each footwear condition (Figure 3).

Discussion and conclusion

The current investigation aimed to examine the influence of barefoot and minimally shod footwear on effective mass and determine the implications that this has for transient loading of the lower extremities during running. An impulse-momentum modelling approach was utilized to examine the

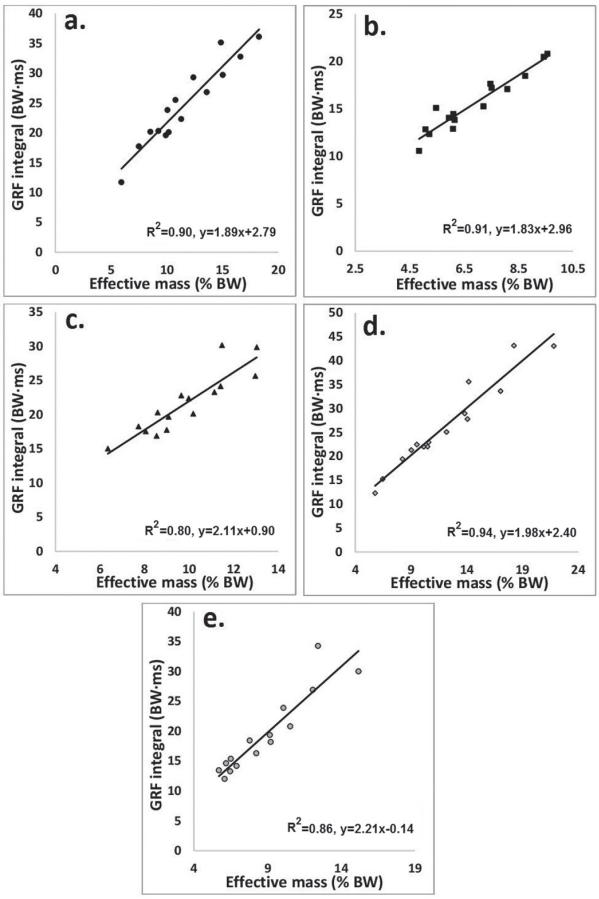

Figure 3. Linear associations between GRF integral and effective mass (a. = barefoot, b. = running trainer, c. = Nike-free, d. Inov-8, e. = Vibram five-fingers).

impact phase of stance during running, which may help us to better understand the mechanical effects that occur when running in different footwear.

Importantly, the current investigation showed that effective mass was significantly influenced by the experimental footwear. Specifically, the barefoot, Inov-8, Nike-free and Vibram five fingers footwear were found to be associated with the largest effective mass magnitudes in relation to the running trainer. Importantly, effective mass was shown to be most strongly predicted by the integral of the vertical GRF; this is to be expected taking into account the impulse-momentum model whereby the GRF integral is proportional to the change in momentum of the foot during the impact phase (Whittle, 1999).

The findings from this study provide a partial support to those of Addison and Liebermann (2015), in that alterations in effective mass were altered as a function of different experimental footwear. However, unlike Addison and Liebermann (2015), the current investigation revealed significant reductions in Δ foot velocity in the barefoot and least cushioned minimal footwear conditions, compared to the running trainer and Nike free. This indicates that there was some attempt at compensation

by the runners in response to the lack of midsole cushioning in these footwear conditions. However, contrary to Squadrone et al. (2015), the specific results of this current study showed that although the initial contact position was further from the heel in the minimalist footwear, there were no statistical alterations in strike index. Running barefoot and in minimalist footwear can cause runners who habitually land with their rearfoot to adopt a mid/forefoot strike pattern (Sinclair, Greenhalgh, Brooks, Edmundson, & Hobbs 2013b; Sinclair, Fau-Goodwin, Richards, & Shore, 2016). Implementing a mid/forefoot strike pattern has been shown to reduce effective mass in relation to landing with the rearfoot (Liebermann, et al., 2010). Though it has been shown that adaptation to barefoot/minimalist footwear can take several weeks (Moore, Pitt, Nunns, & Dixon., 2015; Sinclair, 2016), which may explain the lack of any change in strike index, as the current study used non-habitual barefoot/minimalist footwear users. The observations from the current analysis therefore show that the proportion of total body mass decelerated during the impact phase of running is larger when barefoot and minimally shod footwear are adopted by runners who habitually wear traditional running footwear.

A further key observation from the current investigation is that the instantaneous rate of loading was significantly larger in the barefoot and minimally shod footwear in comparison to the running trainer. Transient loading is governed by the rate at which the momentum of the foot changes, so further consideration of the impulse-momentum model indicates that midsole material at the foot-ground interface strongly influences the magnitude of transient forces generated as a function of footstrike (Whittle, 1999). As the current investigation showed that the experimental footwear conditions did not alter the strike index, it is proposed therefore that this result relates to the absence of midsole interface in the barefoot and minimal footwear conditions. Causing the rate at which the change in momentum of the foot to increase and thus increasing the magnitude of the transient forces experienced in these footwear conditions (Sinclair, et al., 2016). Given the proposed association between the instantaneous rate of loading and the aetiology of chronic injuries, this finding may have clinical significance, (Milner, Ferber, Pollard, Hamill, & Davis, 2006; Whittle, 1999). Therefore, the current study shows that running barefoot and in minimally shod footwear may place runners at increased risk from impact-related injuries compared to the traditional running shoes.

It is also an important observation that effective mass and instantaneous rate of loading were found to be significantly and positively associated for each footwear condition. This finding makes intuitive sense in that the rate of loading is positively associated with the extent of total body mass that is decelerated to zero during the impact phase of stance. This indicates that effective mass and impulse-momentum modelling has key implications for the generation of transient forces and is important as we seek to further understand the mechanical effects that occur when running in different footwear.

In conclusion, the biomechanical effects of barefoot and minimally shod footwear have received considerable research attention. However, current knowledge of differences in effective mass and the implications for transient loading have not been explored previously when barefoot and wearing minimally shod footwear in relation to traditional running trainers. The present investigation therefore adds to the current knowledge by providing a comprehensive effective mass and transient loading parameters when running barefoot, or in minimally shod, or in traditional running footwear. Importantly, the current study showed that effective mass and the instantaneous rate of loading were significantly larger in barefoot and minimally shod footwear compared to the running trainer. Furthermore, it was also revealed that there were significant positive associations between effective mass and the instantaneous rate of loading. Importantly, the findings from the current investigation indicate, firstly, that effective mass has key implications for the generation of transient forces and, secondly, that running barefoot and in minimally shod footwear may place runners at increased risk from impact-related injuries compared to the traditional running shoes.

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