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Investigation into the kinetics and kinematics during running in the heelless shoe

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Background: Recent evidence suggests that runners who habitually rearfoot strike suffer higher rates of chronic injuries compared to those who adopt a mid/forefoot strike pattern. Based on this information new experimental heelless footwear was developed with the aim of mediating a mid/forefoot strike pattern.
Objectives: The aim of the current investigation was to examine the three-dimensional (3D) kinematics and ground reaction forces (GRFs) of running in conventional footwear in comparison to the heelless shoes.
Methods: Twelve male participants ran at $4.0\ m.s^{-1} \pm 5\%$ in each footwear condition. Angular joint kinematics from the hip, knee and ankle in the sagittal, coronal and transverse planes were measured using an eight-camera optoelectric motion capture system. Synchronous ground reaction forces were also obtained allowing impact load parameters and estimates of Achilles tendon force to be quantified. Differences in GRFs and 3D kinematics between footwear were assessed using paired t-tests.
Results: The kinematic analysis indicated that, in comparison to the conventional running footwear, the heelless shoes were associated with significantly greater plantarflexion at foot strike and peak ankle eversion angle. Furthermore, the GRF analysis revealed that, compared to the conventional footwear, impact parameters were significantly lower in the heelless footwear.
Conclusions: Given the reduction in impact loading rates and increases in ankle eversion that were observed in heelless footwear, running in this type of footwear may reduce the incidence of chronic injuries linked to excessive impact forces. However, it may increase the injury potential that is associated with excessive ankle eversion.

Keywords: biomechanics; footwear; strike pattern; ground reaction force; Achilles tendon load

Introduction

Epidemiological studies analysing the prevalence of running injuries suggest that overuse injuries are a prominent complaint for both recreational and competitive runners (Hreljac 2004). Each year approximately 19.4-79.3% of runners will experience a pathology related to running (van Gent et al. 2007).

Recent evidence provided by Daoud et al. (2012) suggests that runners who habitually adopt a rearfoot strike pattern have significantly higher rates of repetitive stress injuries when compared to those who typically utilise a mid/forefoot strike. Daoud and colleagues (2012) hypothesised that the absence of a distinct impact peak in the vertical ground reaction force during a mid/forefoot strike compared with a rearfoot strike may contribute to lower rates of injuries in runners who utilise a non-heel/toe running pattern.

Consequently a non-rearfoot strike pattern does reduce the likelihood of an impact peak in the vertical ground reaction force (GRF)-time curve compared to a rearfoot strike pattern that is characterised by a greater vertical loading rate of the GRF (Warburton 2001, Lieberman et al. 2010). Higher levels of impact loading have been shown by previous analyses to correlate significantly with the aetiology of chronic injuries such as stress fractures (Folman et al. 1986, Milner et al. 2006), osteoarthritis (Collins and Whittle 1989) plantar fasciitis (Hamill et al. 2008), medial tibial stress syndrome, and patellofemoral pain syndrome (Pohl et al. 2008).

Heelless running shoes with adapted soles that do not feature a heel section have been developed to encourage runners to utilise a mid/forefoot strike pattern (Hartveld 2007). It has been hypothesised that in non-rearfoot strike a reduced posterior impulse at foot to ground contact is prevalent leading to a reduction in angular momentum exchange of the lower extremities about the hip as well as a reduction in linear momentum of the overall mass of the body (Lieberman et al. 2010). Recent evidence has shown that shod rearfoot strikers who switch to a mid/forefoot running pattern are able to reduce the magnitude of the loading rate of the vertical GRF (Delgado et al. 2013, Shih et al. 2013). The evidence above can potentially

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indicate that the heelless footwear may be effective in reducing the GRF parameters linked to the development of chronic injuries.

Despite the possible effectiveness in reducing the vertical impact forces, mid/forefoot strike patterns are typically associated with higher plantarflexion moments at the ankle (Williams et al. 2000). This may indicate that non-rearfoot strike running may be associated with increased internal loading, specifically to the Achilles tendon which itself may account for !10% of chronic running injuries (Taunton et al. 2003). Therefore whilst running without a rearfoot strike may reduce the external load applied to the musculoskeletal system (Lieberman et al. 2010), the inter- nal load experienced by specific musculoskeletal struc- tures may be increased.

Furthermore, there has yet to be any published information regarding the efficacy of footwear without a heel profile such as the heelless in comparison to a conven- tional running shoe. Thus, claims regarding the injury pre- vention characteristics of this type of footwear remain unsubstantiated. The aim of the current investigation is to examine the three-dimensional (3D) kinematics and GRFs of running in conventional footwear in comparison to the heelless prototype running shoes. This study evaluates the hypothesis that the heelless footwear will reduce the load- ing rate of the ground reaction force through an increased plantarflexion angle at footstrike compared to conven- tional footwear.

Methods

Participants

Twelve male participants (age 27.22 Æ 4.76 years, height 1.79 Æ 0.09 m and body mass 78.65 Æ 8.26 kg) volunteered to take part in the current investigation. Participants were recreational runners who trained at least three times per week who ran a minimum of 35 km per week. All were free from musculoskeletal pathologies at the time of data collection and provided informed consent. All run- ners were considered to be rearfoot strikers as they exhib- ited a clear first peak in their vertical ground reaction force time-curve when running in the conventional foot- wear (Cavanagh and Lafortune 1980). This was further verified through individual examination of participant's sagittal plane ankle positions at foot strike. Ethical approval was obtained from the University Ethics Com- mittee and the procedures outlined in the declaration of Helsinki were followed.

Procedure

The participants completed 10 running trials over a 22 m walkway at 4.0 m.sÀ1 Æ5% in the laboratory. The participants struck an embedded piezoelectric force platform (Kistler Instruments, Model 9281CA; Dimensions ¼ 0.6 Â 0.4 m) sampling at 1000 Hz with their right foot (Sinclair et al. 2013b). Running velocity was monitored using infra-red timing gates (SmartSpeed Ltd, UK). The stance phase of the running cycle was delineated as the time over which a minimum of 20 N vertical force was applied to the force platform (Sinclair et al. 2011). 3D kinematics were collected using an eight-camera optoelectric motion capture system. The synchronised kinematic and ground reaction force data were obtained using Qualisys track manager software (Qualisys Medical AB, Goteburg, Swe- den) with a capture frequency of 250 Hz.

The calibrated anatomical systems technique (CAST) was utilised to quantify joint kinematics (Cappozzo et al. 1995). To define the anatomical frames of the right foot, shank and thigh, retroreflective markers were positioned onto the calcaneus, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral epicondyle of the femur and greater trochanter. To define the pelvic seg- ment, additional markers were placed on the anterior (ASIS) and posterior (PSIS) superior iliac spines. The hip joint centre was determined using regression equations based on the separation between ASIS markers (Bell et al. 1989). Rigid carbon-fibre tracking clusters comprising four retroreflective markers were positioned onto the pel- vis, thigh and shank segments and secured using tape. The foot was tracked using the calcaneus, 1st and 5th metatar- sal markers. Static calibration trials (not normalised to standing posture) were obtained with the participant in the anatomical position in order for the positions of the ana- tomical markers to be referenced in relation to the track- ing clusters/markers. Separate static trials were obtained for each footwear condition.

Data processing

GRF and 3D kinematic data were analysed using Visual 3-D (C-Motion, Germantown, MD, USA) after being fil- tered at 50 Hz and 12 Hz respectively using a low pass Butterworth 4th order zero-lag filter. 3D kinematics of the lower extremities were calculated using an XYZ Cardan sequence of rotations (where X ¼ sagittal plane; Y ¼ coronal plane and Z ¼ transverse plane). Kinematic curves were normalised to 100% of the stance phase then processed trials were averaged. Discrete kinematic parameters in all planes of rotation, of the hip, knee and ankle included in statistical analyses were 1) angle at foot strike, 2) angle at toe-off, 3) range of motion during stance, 4) peak angle during stance and 5) relative range of motion from foot strike to peak angle. These variables were extracted from each of the 10 trials for each joint in all the three planes of rotation, and the data were then averaged within subjects for statistical analysis.

Ankle joint kinetics were computed using Newton-Euler inverse-dynamics. Net external ankle joint moments

Table 1. Ground reaction force variables (mean þ/- SD) for both footwear types (Ã ¼ Significant main effect p 0.05).

	Saucony	Healus	p-value
Vertical Impact Peak (BW)	2.17 Æ 0.22	1.77 Æ 0.45	0.018Ã
Peak Loading Rate (BW.sÀ1)	354.41 Æ 66.98	286.41 Æ 73.61	0.026Ã
Average Loading Rate (BW.sÀ1)	100.34 Æ 35.97	91.0 Æ 39.41	0.423
Time to Peak Impact (ms)	25.54 Æ 9.23	24.65Æ 21.61	0.852
Peak Braking Force (BW)	0.47 Æ 0.09	0.54 Æ 0.18	0.654
Peak Propulsive Force (BW)	0.41 Æ 0.25	0.49 Æ 0.43	0.215
Peak Medial Force (BW)	0.12 Æ 0.19	0.19 Æ 0.10	0.189
Peak Lateral Force (BW)	0.14 Æ 0.10	0.09 Æ 0.04	0.236
Stance Time (ms)	185.34 Æ 65.43	181.68 Æ 66.98	0.369

were then calculated. To estimate Achilles tendon kinetics the plantarflexion moment calculated was divided by an estimated Achilles tendon moment arm of 0.05 m (Komi et al. 1990, Scott and Winter 1990). From the Achilles tendon force measures of peak force, time to peak force, average loading rate and instantaneous loading rate were obtained in accordance with Almonroeder et al. (2013). From the GRF data, four parameters including average vertical loading rate, instantaneous vertical loading rate, peak vertical impact force and time to peak impact were calculated and subsequently included in statistical analy- sis (Sinclair et al. 2013a). Achilles tendon and ground reaction force parameters were all normalised to the par- ticipant's bodyweight (BW).

Footwear

The shoes used during this study consisted of conven- tional footwear (Saucony pro grid guide II) and heelless (Healus™) footwear, (shoe size 7-10 in UK men's).

Statistical analyses

Means and standard deviations of 3D kinematic and kinetic parameters were calculated for each footwear con- dition. Footwear induced differences these parameters were examined using paired samples t-tests with signifi- cance accepted at the p 0.05 level (Rothman 1990). Effect sizes for all significant observations were calcu- lated using Cohen's D. The data were screened for nor- mality using a Shapiro-Wilk test which confirmed that the normality assumption was met. All statistical actions were conducted using SPSS 21.0 (SPSS Inc, Chicago, USA).

Results

Ground reaction forces

Table 1 presents the vertical ground reaction force varia- bles obtained for both footwear types.

A significantly ($t_{(11)}$ ¼ 2.84, p ¼ 0.018, Cohen's D ¼ 1.20) lower vertical impact peak was associated with run- ning in heelless footwear as compared to the conventional running shoe. In addition the heelless footwear showed significantly ($t_{(11)}$ ¼ 2.56, p ¼ 0.026, Cohen's D ¼ 1.15) lower instantaneous loading rate.

Achilles tendon load

Table 2 presents the Achilles tendon load parameters obtained for both footwear types.

No significant differences were observed between footwear for Achilles tendon load parameters.

Three-dimensional joint kinematics

Figure 1 presents the stance phase 3D kinematic curves from the hip, knee and ankle. Tables 3-5 present the dis- crete 3D kinematic parameters from the hip, knee and ankle for both footwear types.

No significant differences were observed at the hip and knee joints between footwear conditions.

In the sagittal plane, when running in the heelless foot- wear a significantly greater ($t_{(11)}$ ¼ 2.99, p ¼ 0.015, Cohen's D ¼ 1.36) plantarflexion angle at footstrike was observed. In addition, the heelless footwear was shown to significantly ($t_{(11)}$ ¼ 5.93, p ¼ 0.000009, Cohen's D ¼ 2.26) increase the plantarflexion angle at toe-off when compared to the conventional running shoe. Finally the

Table 2. Achilles tendon force variables (mean þ/- SD) for both footwear types (Ã ¼ Significant main effect p 0.05).

	Healus	Conventional	p-value
Peak force (BW)	6.25 Æ 0.93	5.88 Æ 0.68	0.169
Time to peak force (ms)	127.72 Æ 19.96	134.50 Æ 27.10	0.225
Average tendon loading rate (BW.sÀ1)	49.89 Æ 18.89	43.83 Æ 15.54	0.153
Instantaneous tendon loading rate (BW.sÀ1)	160.96 Æ 62.16	147.60 Æ 46.77	0.104

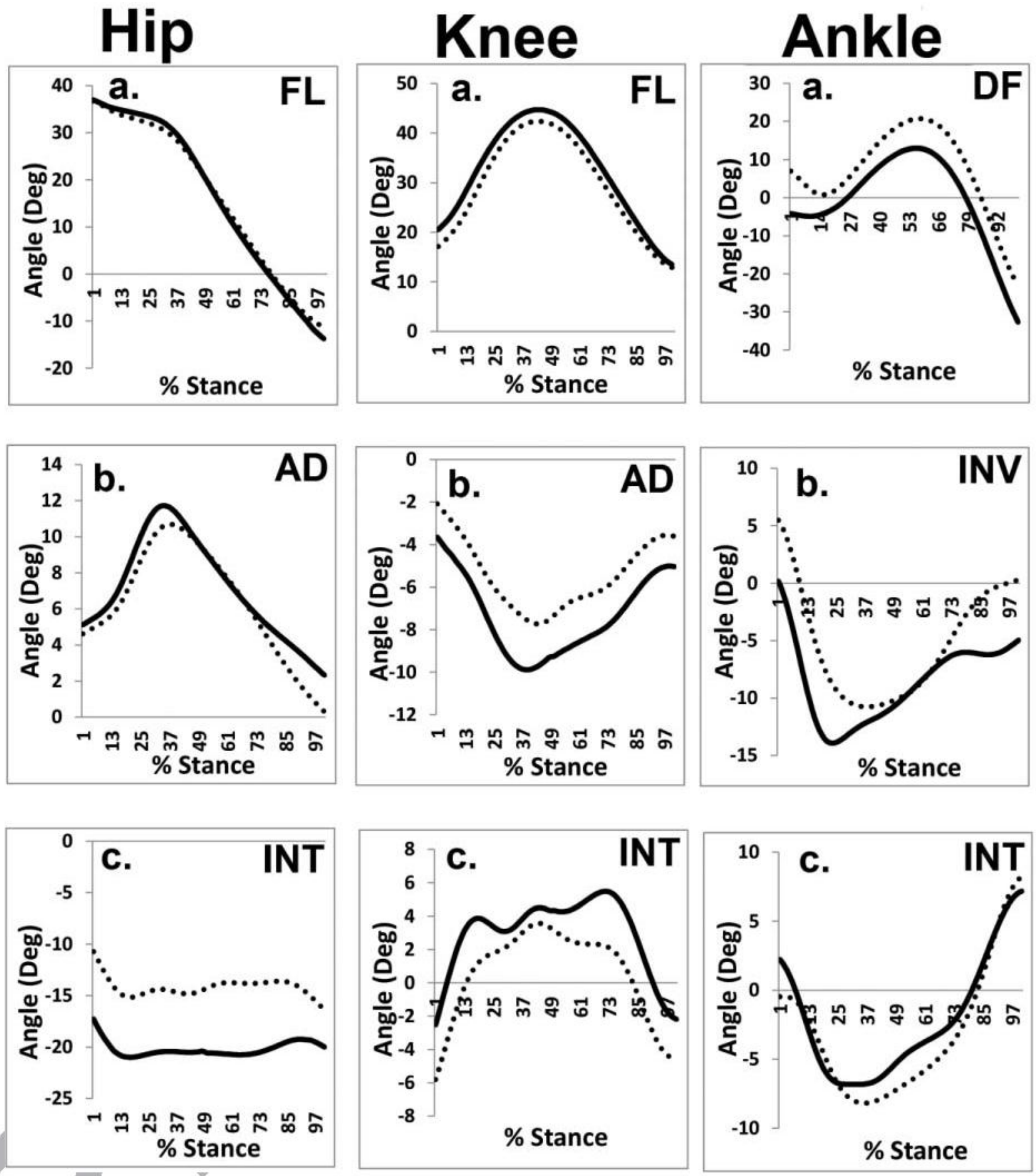

Figure 1. Mean hip, knee and ankle joint kinematics in the (a) sagittal, (b) coronal and (c) transverse planes for heelless (solid line) and conventional shoe conditions (dotted line). FL ¼ flexion, AD ¼ Adduction, EV ¼ Eversion and INT ¼ Internal.

conventional footwear showed significantly greater ($t_{(11)}$ ¼ 7.74, p ¼ 0.0000004, Cohen's D ¼ 3.20) peak dorsiflexion.

In the coronal plane the heelless footwear showed significantly greater ($t_{(11)}$ ¼ 3.23, p ¼ 0.008, Cohen's D ¼ 3.23) eversion at foot strike. In addition the heelless footwear was shown to significantly increase ($t_{(11)}$ ¼ 2.90, p ¼ 0.014, Cohen's D ¼ 2.90) eversion at toe-off when compared to the eversion angles that were achieved running in the conventional footwear. Finally the heelless footwear was shown to be associated with significantly greater ($t_{(11)}$ ¼ 2.95, p ¼ 0.011, Cohen's D ¼ 1.30) peak eversion.

Discussion

The aim of the current investigation was to examine the 3D kinematics and kinetics of running in conventional footwear in comparison to the new heelless running shoes.

Table 3. Hip kinematics (mean þ/- SD) for both footwear types (Ã ¼ Significant main effect p 0.05).

	Healus	Conventional	p-value
Hip			
X (þ ¼ flexion/- ¼ extension)			
Angle at Footstrike (^{1})	37.90 Æ 12.42	37.55 Æ 13.74	0.756
Angle at Toe-off (^{1})	À13.15 Æ 15.99	À10.72 Æ 16.63	0.122
Range of Motion (^{1})	51.05 Æ 11.88	48.27 Æ 12.33	0.134
Peak Range of Motion (^{1})	0.49 Æ 0.70	0.20 Æ 0.39	0.225
Peak Flexion (^{1})	38.38 Æ 12.53	37.74 Æ 13.88	0.533
Y (þ ¼ adduction - ¼ abduction)			
Angle at Footstrike (^{1})	5.56 Æ 5.92	4.29 Æ 4.50	0.493
Angle at Toe-off (^{1})	1.56 Æ 5.09	À0.42 Æ 6.60	0.237
Range of Motion (^{1})	5.49 Æ 3.89	6.11 Æ 3.39	0.638
Peak Range of Motion (^{1})	6.28 Æ 3.58	6.66 Æ 3.12	0.608
Peak Adduction (^{1})	11.84 Æ 5.38	10.96 Æ 5.96	0.558
Z (þ ¼ internal/- ¼ external)			
Angle at Footstrike (^{1})	À13.07 Æ 12.65	À8.53 Æ 9.18	0.234
Angle at Toe-off (^{1})	À16.22 Æ 13.04	À14.87 Æ 9.93	0.378
Range of Motion (^{1})	7.41 Æ 4.88	7.69 Æ 5.64	0.816
Peak Range of Motion (^{1})	8.27 Æ 5.17	9.44 Æ 5.33	0.166
Peak External Rotation (^{1})	À21.34 Æ 12.43	À17.98 Æ 11.00	0.104

The GRF analysis supports the hypothesis that the heelless footwear was associated with significantly lower impact peaks and instantaneous vertical rates of loading when compared to the conventional footwear. This obser- vation may have potential clinical significance given the proposed relationship between impact loading magnitude and the aetiology of chronic running injuries. It appears, based on these observations, that running in heelless shoes has the potential to reduce the impact force parameters linked to the development of chronic injuries (Whittle 1999).

One of the key observations from the kinematic analy- sis was a significant increase in plantarflexion angle at

Table 4. Knee kinematics (mean þ/- SD) for both footwear types (Ã ¼ Significant main effect p 0.05).

	Healus	Conventional	p-value
Knee			
X (þ ¼ flexion/- ¼ extension)			
Angle at Footstrike (^{1})	20.21 Æ 4.83	17.53 Æ 3.91	0.081
Angle at Toe-off (^{1})	13.75 Æ 3.63	12.66 Æ 5.58	0.351
Range of Motion (^{1})	6.80 Æ 4.71	6.54 Æ 6.44	0.989
Peak Range of Motion (^{1})	24.76 Æ 4.65	25.14 Æ 5.60	0.805
Peak Flexion (^{1})	44.97 Æ 4.91	42.67 Æ 6.39	0.077
Y (þ ¼ adduction - ¼ abduction)			
Angle at Footstrike (^{1})	À3.39 Æ 4.91	À1.51 Æ 8.66	0.310
Angle at Toe-off (^{1})	À4.87 Æ 3.95	À3.29 Æ 6.60	0.192
Range of Motion (^{1})	2.76 Æ 1.39	3.03 Æ 1.89	0.692
Peak Range of Motion (^{1})	7.55 Æ 4.56	7.61 Æ 4.68	0.834
Peak Angle (^{1})	À10.94 Æ 8.88	À9.12 Æ 10.45	0.288
Z (þ ¼ internal/- ¼ external)			
Angle at Footstrike (^{1})	À4.04 Æ 7.80	À6.88 Æ 10.82	0.289
Angle at Toe-off (^{1})	À3.64 Æ 6.73	À3.29 Æ 6.60	0.540
Range of Motion (^{1})	4.05 Æ 1.75	5.17 Æ 3.47	0.348
Peak Range of Motion (^{1})	10.39 Æ 3.04	12.48 Æ 4.06	0.091
Peak Internal Rotation (^{1})	6.36 Æ 6.66	5.59 Æ 9.24	0.758

foot strike in the heelless footwear. This moderation in kinematics is produced by the design characteristics of the shoe sole and suggests that the heelless shoes are indeed effective in mediating a flatter foot position in comparison to conventional footwear. As noted previously a non-rear- foot strike pattern serves to attenuate the exchange of momentum between foot and ground (Lieberman et al. 2010), thus the observed reduction in impact loading mediated by the heelless footwear was to be expected.

In the coronal plane, running in heelless footwear was shown to significantly increase ankle eversion in relation to the conventional footwear. This finding does have potential clinical significance as excessive rearfoot ever- sion parameters are implicated in the aetiology of a num- ber of overuse injuries such as tibial stress syndrome, plantar fasciitis, patellofemoral syndrome and illiotibial band syndrome (Taunton et al. 1982, Whittle 1999, Duffey et al. 2000, Willems et al. 2006, Lee et al. 2010).

The increase in Achilles tendon load experienced in the heelless footwear concurs with Almonroeder et al. (2013) who found that non-rearfoot strike runners exhib- ited sizeable yet non-significant increases in Achilles ten- don force compared to rearfoot strike runners. The results of the current study may have relevance to the aetiology of chronic Achilles tendon pathology which has been linked to repeated mechanical loading of the tendon (Magnusson et al. 2010). The findings from the current investigation suggest that habitual rearfoot strike runners will experience an additional but not statistically significant 10% increase in Achilles tendon load when wearing the heelless footwear. However additional work using a longitudinal design is required before conclu- sions with regards to Achilles tendon pathology can be drawn.

Table 5. Ankle kinematics (mean þ/- SD) for both footwear types (Ã ¼ Significant main effect p 0.05).

	Healus	Conventional	p-value
Ankle			
X (þ ¼ dorsi /- ¼ plantar)			
Angle at Footstrike (1)	À4.42 Æ 9.60	7.66 Æ 8.15	0.015ÃÃ
Angle at Toe-off (1)	À33.06 Æ 3.13	À23.04 Æ 5.43	0.000009
Range of Motion (1)	28.79 Æ 9.46	30.70 Æ 10.16	0.565
Peak Range of Motion (1)	17.60 Æ 8.17	13.41 Æ 5.24	0.085
Peak Dorsiflexion (1)	13.18 Æ 2.32	21.07 Æ 3.60	0.0000004Ã
Y (þ ¼ inversion/ - ¼ eversion)			
Angle at Footstrike (1)	0.16 Æ 4.34	5.29 Æ 3.94	0.008Ã
Angle at Toe-off (1)	À4.74 Æ 4.77	À0.21 Æ 5.83	0.014Ã
Range of Motion (1)	5.19 Æ 3.67	6.56 Æ 3.78	0.206
Peak Range of Motion (1)	14.49 Æ 2.60	16.62 Æ 4.61	0.051Ã
Peak Eversion (1)	À15.34 Æ 3.52	-10.33 Æ 3.50	0.011
Z (þ ¼ external/ - ¼ internal)			
Angle at Footstrike (1)	2.47 Æ 4.52	0.10 Æ 6.66	0.136
Angle at Toe-off (1)	7.36 Æ 2.73	8.39 Æ 3.75	0.119
Range of Motion (1)	5.57 Æ 3.78	8.43 Æ 4.18	0.101
Peak Range of Motion (1)	5.29 Æ 2.54	8.43 Æ 4.25	0.124
Peak External Rotation (1)	7.76 Æ 2.98	8.39 Æ 3.75	0.208

A limitation of the current study is the utilisation of a generic moment arm for the calculation of Achilles tendon force parameters. Tendon moment arms are important in musculoskeletal modelling for the determination of tendon loading and are highly dependent on individual unique anatomical characteristics (Fath et al. 2010). Fur- thermore utilising direct measurement techniques it has been shown that the Achilles tendon moment arm changes throughout the stance phase as a result of the changes in the ankle angle in the sagittal plane (Fath et al. 2010). In future studies employment of a subject-specific moment arm may provide more insight on the effect of heelless footwear to each individual.

In conclusion, this study adds to the current knowl- edge by providing a comprehensive evaluation of the GRFs and 3D kinematics of running in footwear designed to promote a mid/forefoot strike pattern in relation to con- ventional shoes during the stance phase. The significant reduction in impact loading in the heelless footwear sug- gests it may have the potential to reduce the impact parameters linked to the development of chronic injuries. However, that the heelless shoes were associated with sig- nificant increases in ankle eversion may suggest that they accentuate the injury risk associated with skeletal mal- alignment. Designers and manufacturers of such novel footwear should take this into consideration whilst con- ceptualising future footwear designs. Future research should investigate further the long term effects of foot- wear designed to promote a non-rearfoot running pattern. Prospective epidemiological analyses using randomised controlled trails should also be a focus for future investi- gations in the effect of mid/forefoot strike patterns on injury and performance.

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