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Influence of heel design on lower extremity biomechanics and comfort perception in overground running

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ABSTRACT

The study investigated whether an alteration of the shoe heel curvature would influence lower extremity biomechanics and comfort perception in running. Twenty recreational habitual rearfoot strikers performed five running trials in running shoes with three different heel curvature designs (short-parallel, long-parallel and oblique curvatures). Synchronised force plate and motion capturing systems were used to collect three-dimensional lower extremity joint kinetics and kinematics, followed by subjective comfort perception on the 15 cm Visual Analogue Scale. The results showed that participants wearing oblique and long-parallel curvature shoes exhibited larger initial frontal shoe-ground angle (p= 0.003, p= 0.016) and ankle inversion angle (p= 0.008, p= 0.032) as well as higher maximum sagittal foot slap velocity (p= 0.041, p = 0.011) compared with a short-parallel curvature shoe. When wearing the short-parallel curvature shoe, participants had better rearfoot stability perception than the oblique curvature shoes (p = 0.028). These results suggest that the short parallel curvature shoes had better motion control and stability perception than the other two curvature conditions. However, the design of heel curvature seems to have minimal influence on the cushioning related variables in running.

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KEYWORDS
Footwear; heel curvature; stability; cushioning; subjective comfort

Introduction

Running is one of the most popular sports worldwide as it can promote cardiovascular fitness, muscular strength, and mental health (Jiang, 2009; Lee et al., 2014; Xu et al., 2006). However, previous studies have shown that 66% of runners suffer from running-related injuries each year and about 56% of the injured runners sustain the reoccurrence injury at least once time (Messier et al., 2018). As the key equipment for running activity, well-designed running shoes have been hypothesized to play an important role in optimize impact loading and foot motion that is related to running injury risks and performances. One mainstream of shoe technology (cushioning) is developed to reduce impact loading (Divert et al., 2005), as high impact loading is considered as one key risk factor of overuse injuries such as patellofemoral pain, tibial stress fracture, and plantar fasciitis (Pohl et al., 2009; Van der Worp et al., 2016).

Another shoe technology (motion control) is designed to reduce excessive rearfoot motion that may also relate to the injury risk factor during running (Cheung et al., 2011). Most runners strike landing on the lateral region of the shoe heel (Hasegawa et al., 2007), in which the foot is an inverted position and followed by gradual eversion during the foot loading phase. Rearfoot eversion (as a component of foot pronation) is a natural movement during the stance phase of running (normal range: between 8° and 15°). However, excessive rearfoot eversion (i.e., >18°) has been identified as the contributing factor of overuse running injuries (Clarke et al., 1984) and altered the movement pattern of the proximal joints (Cheung & Ng, 2007a). As such, it might potentially increase the risks of knee injury (Willems et al., 2006). In general, reduction of foot pronation is a common clinical approach to manage running injuries (Cheung et al., 2011; Willems et al., 2006), even though the relationship between excessive foot pronation and potential risk is still under debate (Hintermann & Nigg, 1998; Nielsen et al., 2014; B.M. Nigg, 2001). Since the type of running shoes is considered to be the major extrinsic factor relating to rearfoot eversion (B.M. Nigg, 1988; Stacoff et al., 1991), considerable efforts have been made to develop shoes for controlling excessive pronation.

In principle, shoe cushioning and motion control display the opposite tendencies (B.M. Nigg, 1995). For example, footwear with a thicker midsole is expected to provide better impact attenuation during rearfoot strike landing (Law et al., 2018b; B. M. Nigg, 1988; Sun et al., 2020), but it might reduce the mechanical stability of a shoe as for larger the rearfoot eversion angle (TenBroek et al., 2013). A good running shoe should be able to attain good cushioning and motion control concurrently (Sterzing et al., 2015). Previous footwear studies have mainly focused on midsole thickness (Law et al., 2018b; B.M.

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Nigg, 1988), crash-pad structures (Sterzing et al., 2015) as well as shoe upper designs (TenBroek et al., 2013), but little attention was given to heel curvature design (Sun et al., 2020). Biomechanically, heel curvatures could alter the touchdown angle and thus influence joint positioning and leg stiffness as well as impact loading and joint moments in running (B.M. Nigg & Morlock, 1987; Hintermann & Nigg, 1998). One badminton study found that rounded heel curvature shoes reduce the maximum vertical loading rate of a badminton lunge (Lam et al., 2017). Furthermore, previous research (B.M. Nigg & Morlock, 1987) modified shoe lateral heel geometry and showed that a rounded lateral flare has a positive influence on reducing running injuries, however, the medial flare effect was not considered in their studies. To date, it is questionable if a lateral and medial curvature modification of shoe heel would affect running biomechanics. The investigation of the heel design (e.g. curvature and orientation) in running footwear seems warranted.

Apart from objective biomechanical factors, subjective comfort perception also plays an important role in running performance and injury prevention. Increased comfort can result in lower incidence of injuries (Hennig et al., 1996) and minimized energy expenditure during running (Luo et al., 2009). As a consequence, footwear comfort has received considerable interest by coaches and sports scientists, as it is prerequisite to minimize adverse effect on human musculoskeletal system and enhance performances (Hennig et al., 1996; Luo et al., 2009). Changes in comfort perception have also been associated with biomechanical alterations. Hennig and his colleagues reported a strong relationship between shoe comfort perception and impact-related variables. Consequently, as runners perceived differences using diverse midsole materials, it would be interesting to investigate if runners are capable of perceiving differences using different heel curvature designs.

The purpose of this study was to examine the effect of heel curvature on lower limb mechanics and comfort perception during overground running. Three pairs of shoes with heel curvature design shoes were built (i.e. long-parallel, short-parallel and oblique) in this study. It is hypothesized that oblique curvature shoes would reduce the GRF, alter the ankle and knee biomechanics, and improve comfort perception compared to the parallel heel curvature shoes.

Methods

Participants

Twenty recreational male habitual rearfoot strike runners (mean age = 25.8 ± 5.2 years, 176.3 ± 4.9 cm, 72.1 ± 5.9 kg), who ran at least 30 km per week and completed a 10-km race below 50-min, participated in the biomechanical and comfort perception sessions of this study. Their foot size (US 9.0 ± 0.5) was confirmed with a Brannock foot device (The Brannock Device Co, Liverpool, NY, USA). All participants were free from lower extremity neuromuscular or musculoskeletal injuries or pain in the past six months. Ethics approval was granted from institutional ethics committee. All participants provided their written consent prior to the data acquisition.

Shoe conditions

Three identical shoes in US size 9.0 with only different heel curvatures were built from the existing shoe model (LN AGCN175, Li Ning company, Beijing, China). The heel curvature characteristics were based upon the dimension analysis of heel curvatures from 37 pairs of commercially available professional running shoes. All of the shoes were US size 9.0 and covered the brands including Asics, Nike, Adidas, New Balance, Reebok, Brooks, and Mizuno. These shoes were designed to maximize cushioning and stability for rearfoot runners. We extracted and identified three key dimensions of shoe heel (i.e., posterior height, lateral-end point, and medial-end point of the curvature) from all competitor shoes to determine the heel curvature designs of our tested shoes (short-parallel, long-parallel, and oblique, Figure 1(a)). The mean (and range) of lateral-end point, medial-end point, and posterior height of the heel from the competitor shoes were 4.0 (1.5 to 7.0 cm), 2.5 (1.0 to 5.5 cm), and 1.0 (0.8 to 1.2 cm), respectively. The three tested shoes had the same posterior-proximal height of heel curvatures which was defined at the end of the curvature from the tip of the posterior heel. The test shoes differed in the distal points of the lateral (i.e., lateral-end point) and the medial (i.e., medial-end point) curves (Figure 1(b)). To check for midsole consistency (Sterzing et al., 2013), the midsole hardness and mechanical shoe cushioning were quantified with a durometer (1600 Asker SP-698 Rex Durometers, Rex Gauge Co., Buffalo Grove, IL, USA) and an impact tester (Exeter Research V2.6, Brentwood, NH, USA), respectively, for each tested shoe. The midsole hardness and the mechanical shoe cushioning (peak acceleration, g) were similar across short-parallel (54 C, 11.8 g), long parallel (55 C, 11.8 g) and oblique heel curvature shoes (55 C, 11.6 g).

Biomechanics session

The participants performed five running trials over a 13 m runway at 3.0 ± 0.1 m/s, which was controlled by timing gates (Brower Timing Systems, Salt Lake City, UT, USA). An eight-camera infrared motion analysis system (Oxford Metrics Ltd, Oxford, UK, sampling 200 Hz) was synchronized with a 0.9 m x 0.6 m force plate (AMTI, Watertown, MA, USA, sampling at 1000 Hz) to collect the GRF, lower limb kinetics and kinematic information during running (Figure 2(a)). Twenty-one reflective markers were attached over the pelvis and the right lower limb of the participants (Figure 2(b)): the right and left anterior and posterior superior iliac spines, the lateral and medial knee epicondyles, the lateral and medial malleoli, the first and fifth metatarsal heads medial (shoe markers), two rigid clusters of four markers on the thigh and leg segment, and the additional tracking markers (shoe markers) were attached at the medial, lateral and posterior calcaneus. The markers on the medial and lateral malleolus and femoral epicondyles were used for the static trial and removed during the dynamic trials. Before the data acquisition, participants were provided a 5-min warm-up and familiarization period for each of the test shoe conditions. A successful trial was defined if the participant landed the force plate with their right foot at the target speed. Five successful trials were obtained for each shoe condition. All shoe conditions were randomized across participants.

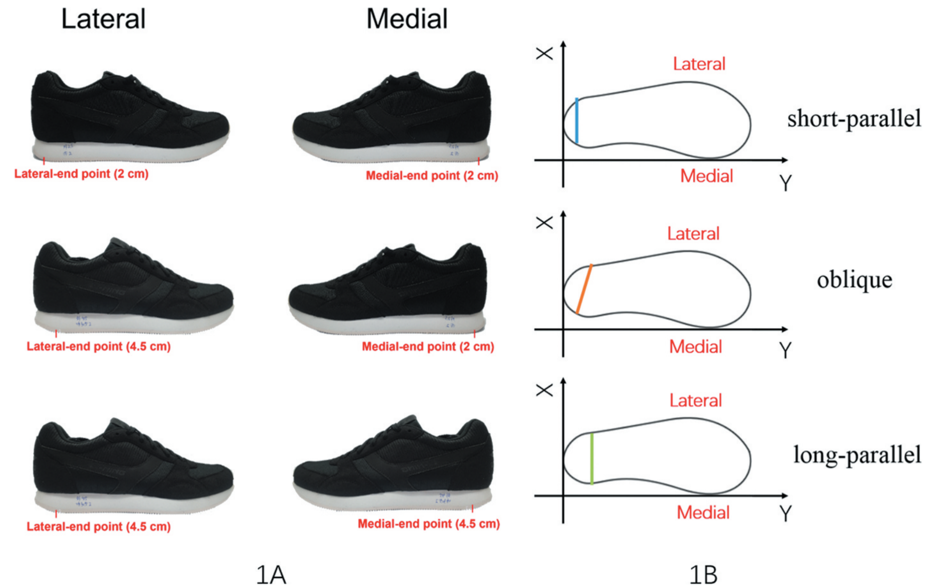

Figure 1. (a) Definition of shoe heel design dimensions. Lateral-end (Medial-end) point refers to the starting point of the curvature at the lateral (medial) heel and (b) Lateral and posterior views of the tested shoes.

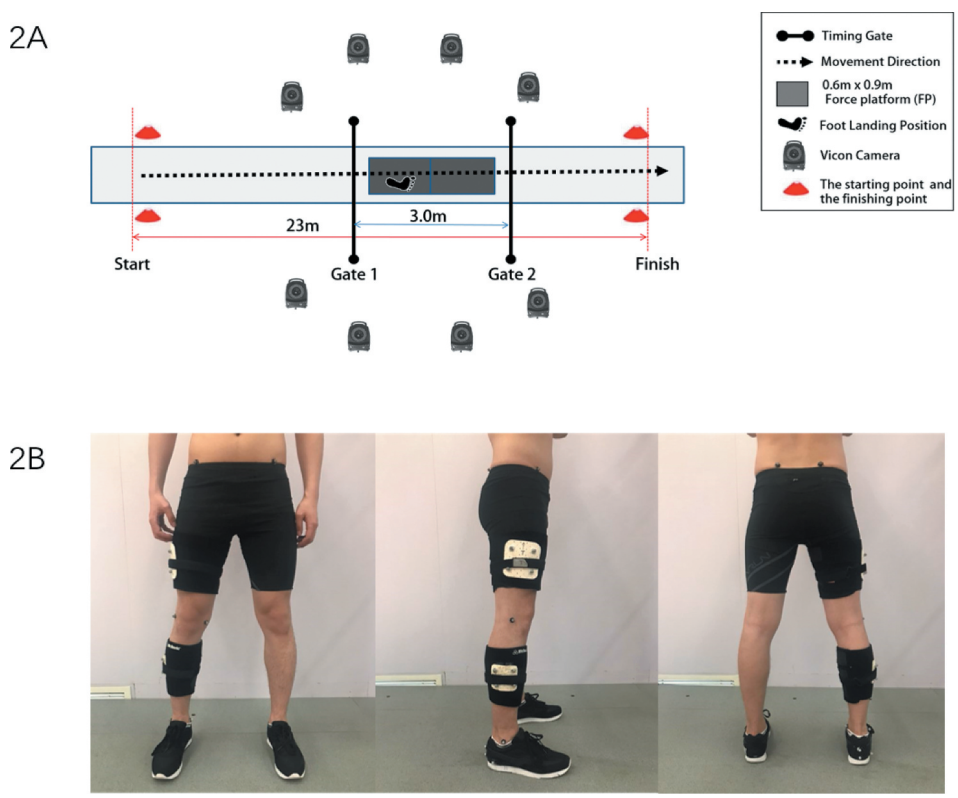

Figure 2. (a) Experiment setup for biomechanical test and (b) Marker placement.

Comfort perception session

Comfort perception testing took place on a 200 m indoor running loop on court surface (Sterzing et al., 2013; 2015). For each shoe condition, the participants were asked to give their rating on five perception variables (forefoot cushioning, rearfoot cushioning, rearfoot stability, heel-to-forefoot transition, and overall comfort) onto a 15-cm visual analogue scale (VAS) immediately after each 200 m run (Heidenfelder et al., 2010; Sterzing et al., 2013; 2015). After warm-up, the participants ran three laps at their preferred speed. The forefoot and rearfoot cushioning were evaluated immediately after the first lap; the rearfoot stability and heel-to-forefoot transition after the second lap; and the overall comfort was measured after the final lap. Two perception variables measured in each lap would allow for reliable perception rating scores as indicated by higher inter-day reliability and better shoe differentiation for smaller amount of perception content (Lam et al., 2015). All shoe conditions were randomized across participants.

Data processing

All biomechanical data were processed with Visual 3D (C-Motion Inc., Rockville, MD, USA) for definition of body segments and calculation of joint kinetic variables. A spline interpolation was performed to rectify minor missing trajectory data using three frames of data before and after the missing data. A fourth-order Butterworth filter with cut-off frequency of 150 Hz and 30 Hz were applied to determine the impact loading and joint ankle variables, respectively (Sterzing et al., 2013; 2015). To calculate joint moment, the same cut-off frequency of 30 Hz was applied to the raw kinetics and kinematic data, according to the previous studies (Kristianslund et al., 2012). Ankle (knee) angle was defined as the orientation of foot (lower leg) segment relative to the lower leg (thigh) segment. Shoe-ground angle was defined as the orientation of shoe relative to the ground. The braking and propulsion periods were based on zero-crossing point of anterior-posterior GRF. The maximum sagittal foot slap velocity was defined as the maximum plantarflexion velocity from initial foot contact to foot flat (Sterzing et al., 2013; 2015). The instantaneous loading rate (VILR) was calculated to take the derivative of the force per frame (B.M. Nigg & Bahlsen, 1988). Ankle and knee joint moments were determined by inverse dynamics. The GRF was normalized by body weight while joint moment was normalised by body height and leg length.

Statistical analysis

Initial Shapiro–Wilk tests were used to validate that the data were normally distributed. One-way repeated measures ANOVAs were performed on each of the GRF, lower limb kinetics and kinematics, and comfort perception variables. When any significant effect was determined, Bonferroni corrected post hoc tests were performed accordingly. Greenhouse–Geisser's epsilon adjustment was used in all cases when Mauchley's test indicated that the sphericity assumption had been violated. Alpha level was set at 0.05. Effect size was calculated using partial eta-squared (η_p^2) for ANOVA and interpreted as small ($0.01 \le \eta_p^2 < 0.06$), medium ($0.06 \le \eta_p^2 < 0.14$) and large ($\eta_p^2 \ge 0.14$) (Cohen, 1998). All statistical analyses were conducted using SPSS 20.0 (SPSS Inc., Chicago, IL, USA).

Results

GRF and joint loading variables

For GRF variables (Table 1), the short-parallel curvature shoes significantly increased time to peak impact force compared to oblique ($p = 0.002$) and long-parallel curvature shoes ($p = 0.031$), while long-parallel curvature shoes had longer time to peak impact force than oblique curvature shoes ($p = 0.004$). For joint loading variables, participants wearing the short-parallel curvature shoes demonstrated smaller maximum knee abduction moment than the oblique ($p = 0.0047$) and long-parallel curvature shoes ($p = 0.009$). There were no significant differences in the ankle joint moments between shoe conditions ($p > 0.05$).

Joint kinematics variables

Participants wearing short-parallel curvature shoes exhibited small initial frontal shoe-ground angle ($p = 0.003$, $p = 0.016$) and maximum sagittal foot slap velocity ($p = 0.041$, $p = 0.011$) compared to the oblique and long-parallel curvature conditions (Table 2). Additionally, the oblique curvature shoes significantly increased the initial ankle inversion angle compared to the short-parallel curvature shoes ($p = 0.008$). Smaller maximum ankle eversion was found in the long-parallel curvature shoe than the oblique ($p = 0.032$) and short-parallel curvature conditions ($p = 0.046$). Larger maximum eversion velocity and ankle frontal range of motion were determined for oblique curvature shoes than short-parallel and long-parallel curvature shoes ($p = 0.013$, $p = 0.004$). However, there were no significant differences in any knee kinematics variables among shoe conditions ($p > 0.05$).

Table 1. Ground reaction force and joint moment variables by three tested shoes. A significant *p*-value is bolded.

				ANOVA		
Variable	Short-parallel	Oblique	Long-parallel	p	η^2	β
GRF						
Peak impact force (BW)	1.61 ± 0.22	1.71 ± 0.32	1.69 ± 0.26	0.181	0.109	0.652
VILR (BW/s)	103.39 ± 23.62	107.47 ± 33.08	111.86 ± 27.72	0.059	0.315	0.555
Time to peak impact force (ms)	34.0 ± 3.4	32.0 ± 2.7	32.9 ± 3.2	0.002	0.271	0.873
Ankle moment (BW.H)						
Peak dorsiflexion	0.122 ± 0.019	0.127 ± 0.011	0.123 ± 0.019	0.186	0.182	0.523
Peak eversion	0.013 ± 0.002	0.014 ± 0.005	0.013 ± 0.003	0.321	0.146	0.239
Peak external rotation	0.002 ± 0.006	0.002 ± 0.003	0.002 ± 0.003	0.237	0.215	0.556
GRF moment arm (mm)	19.3 ± 8.0	17.8 ± 6.1	20.4 ± 6.3	0.870	0.207	0.423
Knee moment (BW.H)						
Peak extension	0.212 ± 0.004	0.213 ± 0.003	0.210 ± 0.002	0.052	0.319	0.524
Peak abduction	0.030 ± 0.004	0.037 ± 0.003	0.037 ± 0.003	0.048	0.192	0.543
Peak internal rotation	0.035 ± 0.002	0.036 ± 0.002	0.035 ± 0.002	0.832	0.004	0.03

Table 2. Lower extremity kinematic variables by three tested shoes. A significant *p*-value is bolded.

Variable	Short-parallel	Oblique	Long-parallel	ANOVA		
				p	η^2	β
Contact time (ms)	247.5 ± 19.1	246.3 ± 17.8	246.8 ± 19.9	0.070	0.190	0.825
Braking time (ms)	93.1 ± 16.1	91.4 ± 12.9	90.3 ± 13.2	0.074	0.396	0.531
Shoe angle						
Initial shoe ground angle – sagittal (°)	26.1 ± 5.1	26.2 ± 5.2	26.8 ± 5.2	0.118	0.130	0.403
Initial shoe ground angle - frontal (°)	8.7 ± 2.6	10.3 ± 2.8	9.6 ± 2.9	0.003	0.312	0.891
Max foot slap velocity-sagittal (°/s)	801.5 ± 97.1	857.5 ± 70.7	864.3 ± 88.4	0.001	0.495	0.998
Ankle joint angle						
Initial inversion angle (°)	6.7 ± 2.3	8.3 ± 2.6	8.1 ± 3.1	0.002	0.309	0.973
Max eversion angle (°)	9.2 ± 2.3	8.9 ± 2.4	8.1 ± 2.5	0.006	0.247	0.875
Max eversion velocity (°/s)	354.1 ± 76.9	395.2 ± 98.3	360.1 ± 93.1	0.002	0.297	0.965
Rearfoot RoM (°) – frontal	10.5 ± 2.7	11.5 ± 3.0	10.6 ± 3.0	0.027	0.180	0.773
Knee joint angle						
Initial flexion angle (°)	8.7 ± 5.0	8.7 ± 6.1	9.8 ± 4.6	0.284	0.088	0.280
Max flexion angle (°)	39.7 ± 5.9	39.6 ± 6.5	41.5 ± 5.6	0.052	0.184	0.548

Table 3. Comfort perception scores by three tested shoes. A significant *p*-value is bolded.

Variable	Short-parallel	Oblique	Long-parallel	ANOVA		
				p	η^2	β
Rearfoot cushioning	9.74 ± 2.88	8.87 ± 3.24	9.77 ± 2.63	0.552	0.040	0.468
Forefoot cushioning	9.09 ± 3.05	8.60 ± 2.52	9.58 ± 2.89	0.580	0.033	0.471
Rearfoot stability	10.24 ± 1.78	9.36 ± 2.9	9.32 ± 2.46	0.041	0.236	0.592
Heel-to-forefoot transition	10.11 ± 2.56	9.35 ± 2.69	10.35 ± 2.62	0.306	0.065	0.329
Overall comfort	9.89 ± 2.57	9.74 ± 2.25	9.94 ± 2.55	0.742	0.007	0.131

Comfort perception variables

Only rearfoot stability revealed significant differences between shoe conditions ($p = 0.041$, Table 3). Increased rearfoot stability perception was found for short-parallel curvature shoes than the oblique curvature shoes ($p = 0.028$).

Discussion

This study examined the effect of heel curvature on the GRF, ankle and knee mechanics and comfort perception during running. The current results showed that the heel curvatures had an influence on running biomechanics and comfort perception. The change in heel curvature was associated with rearfoot stability-related variables but not with the cushioning related variables (i.e., perceptual and biomechanical), which is in contrast to our hypothesis. Oblique curvature shoes had a shorter time to peak impact force compared to the parallel curvature conditions (i.e., short-parallel and long parallel curvature), but no significant differences were found in the peak impact force and instantaneous loading rate (VILR). It suggests that the small alteration of the heel curvature in our tested shoes were insufficient to cause significant changes in impact loading related variables. As for the perception, our perception findings revealed no significant shoe differences in forefoot and rearfoot cushioning perceptions, implying that shoe curvature design did not affect cushioning perception performance in rearfoot strike running. The lack of effect on impact loading related variables could also be explained by the lack of differences in the mechanical properties between tested shoes, as indicated by the impact test measurements.

The movement of foot/ankle in frontal plane motion is an indicator of the motion control characteristics of a shoe (Cheung & Ng, 2007a). Participants wearing shoes with longer lateral-end point (4.5 cm, oblique and long-parallel curvatures) exhibited larger initial inversion and frontal shoe-ground angles than the shoes with shorter lateral-end point (2.0 cm, short-parallel curvature). Participants wearing oblique curvature shoes demonstrated larger rearfoot range of motion, higher maximum eversion and foot slap velocity than the short-parallel curvature shoes. Additionally, our findings revealed that heel curvature design influenced the shoe ground angle and ankle kinematics, but did not change the GRF during running. These findings are similar to the previous study (Perry & Lafortune, 1995), which suggested that there was no reduction in impact loading during normal pronation.

Interestingly, the heel curvature design has considerable effect on the maximum knee abduction moment but not for ankle joint moment during running (Table 1). It could be explained by the relationship between GRF vector and joint position/moment arm (Perkins et al., 2014). The anterior-posterior alteration in the GRF direction may only cause minimal changes in the moment arm around the ankle joint but may have a larger influence on the moment arm around the knee joint due to the larger distance from the ground.

The rearfoot stability perception refers to the subjective feelings of rearfoot position control by the shoe during running (Law et al., 2018a; Leong et al., 2018; Mundermann et al., 2002; Sterzing et al., 2015). Participants wearing oblique curvature shoes showed poorer rearfoot stability perception than the short-parallel curvature shoes, but no significant difference were found in other comfort perceptual variables. The perceptual findings are in line with the biomechanical results (e.g., maximum eversion angle, maximum eversion velocity, and total eversion RoM). Together with the biomechanical and perceptual findings, it concludes that short-parallel shoes can improve the rearfoot stability performance during running.

When interpreting our results, few limitations should be considered. First, only male rearfoot strike runners were recruited and hence our findings may not be generalized to female runners and non-rearfoot strike runners. Second, the foot kinematic model relied on shoe markers and did not represent the actual rearfoot movement during running (Nester et al., 2007), although shoe and foot movements (i.e., bone measurements) were reported to be highly correlated between total shoe and bone eversion (r= 0.88) and between maximum shoe and bone eversion velocity (r = 0.79) (Stacoff et al., 2000). Third, although the tested shoes were built with the identical sole thickness, the shoes with various curvature designs at the posterior aspect of the heel region (Figure 1). It might still have a slight influence on the material thickness at the instant of initial contact. Computational studies may help to simulate and examine the impact characteristics for different combinations of material thickness, hardness and heel curvatures. Forth, we focused on the immediate effect of the heel curvature design, and thus its long-term effect remains inconclusive. Studying different running speeds (preferred or non-preferred) and running mileage, interplay with gender and foot-arch types would allow comprehensive analyses for heel shoe design in runners.

Conclusion

Different heel curvature designs can influence the ankle joint positioning, knee joint moment and rearfoot stability perception during heel-toe running. Shoes with short-parallel curvature design accounts for smaller knee abduction moment and smaller frontal plane movement of ankle joint and better shoe stability than the oblique curvature design. However, the alteration of heel curvature seems to have minimal effect on the impact loading related variables. Such information would aid coaches, physicians and players in understanding the potential mechanism of running mechanics that are related to injuries and performance. The findings from this study would also contribute to running shoe development.

Disclosure statement

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