How foot morphology changes influence shoe comfort and plantar pressure before and after long distance running?

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Purpose: Prolonged running has been popularized globally in recent decades. This study was aimed to reveal information about foot morphology, shoe comfort and plantar loading among recreational heel-strike runners. *Methods:* Twenty-six runners participated in foot morphology, perceived scores and peak pressure tests after 10- and 20-km track running. The foot morphology was measured using a 3D foot scanner, perceived scores were recorded using a visual analogue scale and plantar pressure was measured via insole plantar pressure measurement system. The statistical significance level was set at 0.05. *Results:* The heel midsole materials properties were measured before and after 20 km. Significant changes were observed in ball width and girth, arch height and foot volume. The perceived scores showed significance in overall, forefoot and heel comfort, arch support and forefoot width. Peak pressure to the heel, medial mid-foot and metatarsal greatly increased. The first metatarsal showed consecutive increase from static to 10 km, and 20 km, while big-toe showed a decrease. *Conclusions:* The morphology variations and forefoot loading concentration may lead to discomfort and possibly imply dermatological problems and metatarsal bone stress, particularly on the first metatarsal. Combining changes of heel midsole property, knowledge of foot shape, shoe perception and plantar pressure is of great value for recreational long-distance running shoes design and materials selection.

Key words: *foot shape, plantar pressure, footwear, comfort, long distance running*

1. Introduction

Running has attracted extensive participation globally. As one of the most accessible physical activities to improve fitness and prevent obesity, cardiovascular diseases and other chronic health issues, participants tend to run long distances in order to further benefit from aerobic and endurance exercise [6], [14], [20], [27]. As reported, the number of finishers of full marathons increased by about 30% and number of participants of half marathons increased about by 300% over the past decade in the U.S. alone [23]. In China, participation reached the highest record of 2.8 million in long distance running events around the country throughout 2016 [3]. However, wide participation of repetitive prolonged running may lead to increased injury rates [14], particularly to the lower limb, such as knee, lower leg, foot and upper leg [27], [29].

Since the 1980s, an increase in number of research and publications was observed in the field of footwear technology aimed to develop novel products that will help reduce potential injuries [6] and increase performance in running [13], [24]. Athletic footwear usage provides advantages to foot plantar surface protection, traction, dynamic motion control (stability), impact force attenuation [13] and comfort [28]. Particularly, shock-attenuating sport shoe properties (cushioning) are a key [4], as repetitive impact during running may lead to overuse injuries [14], [24], [26], [27].

The foot is the primary interface of the human motor system with its external environment [15]. In

addition to aforementioned properties including cushioning, stability or motion control, participants tend to select footwear with comfort from somatosensory perception [25] as the main deciding factor. Hence, comfort is becoming another primary objective for shoe manufacturers. While comfort is a subjective metric, some studies have attempted to relate objective measurements, such as foot-shoe interface characteristics, to perceived comfort [2], [6], [17], [18], [28]. Comfort was shown to be related to plantar and upper pressure distribution, impact, stability, and foot shape [17], [18], [28].

Foot shape is not static and depending on a person and their characteristics features, such as obesity and long-time physical activities leading to deformities and shape variations in the foot [5]. The fit of the shoes is often defined under static standing conditions, however, foot shape morphs during dynamic running or walking situations [5], [9]. Foot morphology variations may lead to shoes being ill-fitted, and ill-fitted footwear has been shown to be related with dermatologic problems (like blisters and corns) [11], which leads to abnormal compensatory movements, and potentially increases risks of musculoskeletal injuries [12], [27].

Altered plantar pressure distribution characteristics have been reported with increased medial forefoot and mid-foot loading during long distance running, compared to static condition, and increased loading concentration would lead to pain on foot [22], which may explain increased running injuries [20], [27], [29]. Nevertheless, little information has been reported concerning how foot morphology varies, when discomfort occurs and whether shoes materials will be deformed during prolonged running activities. Therefore, the purpose of this study was to investigate foot morphology changes, plantar pressure distribution and subjective perception during a 20 km run, including an interval test after 10 km, comparing with the pre-running static condition. It was hypothesized that a) foot shape would be different after running 10 and 20 km, b) the plantar pressure would distribute medially as running distance increased, and c) the perceived comfort would reduce significantly after running 10 and 20 km.

2. Materials and methods

Twenty-six male recreational shod (rearfoot strike) runners participated in this study (age of 28.6 ± 3.4 years, height of 173.6 ± 5.4 cm, weight of 72.7 ± 4.8 kg, foot length of 252 ± 5 mm, and average weekly running distance of 30 km). They all had experience of half or full marathon running, and preferred the same shoe size of 8 (US) or 41 (Europe). Ethics approval was obtained from the Human Ethics Committee in the University of Ningbo (ARGH20160518). All participants knew the requirements and procedures of this test and provided written consent.

The same running shoes (Fig. 1a) with EVA midsole were distributed to participants. The EVA midsole of heel region has a thickness of 25 mm, density of 0.2 g/cm^3 and Young's Modulus of 0.52 MPa. Participants were required to wear the shoes performing
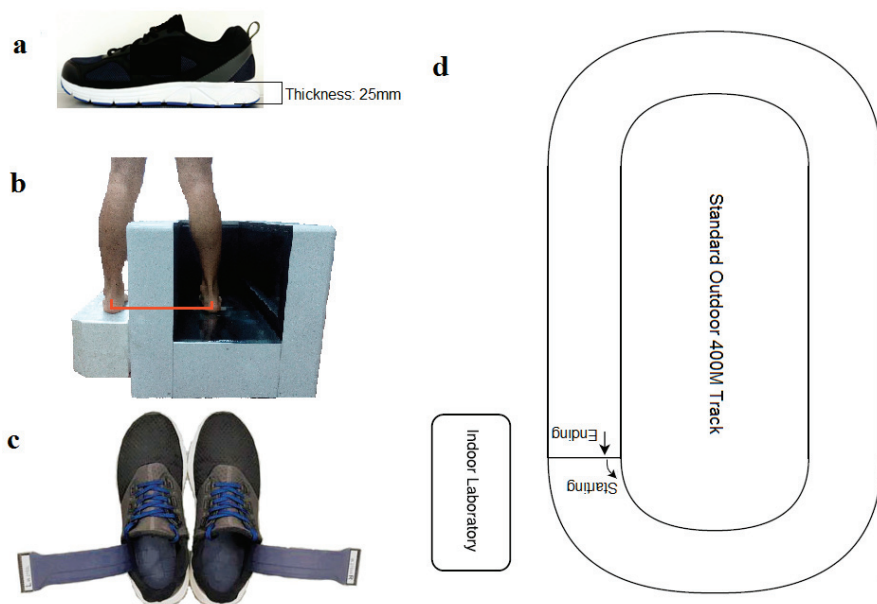

Fig. 1. Illustration of running shoes (a), foot morphology (b) and plantar pressure (c) collection and running test setup (d)

daily activities (including physical exercise and basic working) for one week before the running test, to stretch and adapt to the new shoes to increase the flexibility of shoe upper and sole [21].

Prior to the test, the foot shape data under static standing conditions were collected with a 3D foot scanner (Easy-Foot-Scan, EFS, OrthoBaltic, Kaunas, Lithuania) (Fig. 1b), with accuracy of 0.3 mm and scanning volume of 400(L)*200(W)*200(H) mm³. Participants had both feet surface scanned while standing and legs separated at a shoulder's width (43.2 ± 4.6 cm). The plantar pressure distribution was recorded with a Novel Pedar insole measurement system (Novel, Munich, Germany) (Fig. 1c) with a frequency of 100 Hz while participants ran with a velocity at 12 km·h⁻¹. The subjective perceived shoe comfort was measured with a 150 mm visual analogue scale (VAS) previously established by Mündermann et al [18], and has been proven as a reliable measurement of footwear comfort [17]. The scale used 150 mm length with the left end as "not comfortable at all" and the right end as "the most comfortable" for the variables of overall comfort, upper comfort, forefoot comfort, and heel comfort. The scale for shoes arch support was as the lowest and highest, with the forefoot width as the tightest and loosest, the heel cushioning as the softest and

stiffest, the medio-lateral control as most and least stable, and the weight was the lightest and weightiest.

During the running test, participants ran on an outdoor standard 400-m track (Fig. 1d) with the same velocity range at 12 km h⁻¹. Stopwatch was used by participants to control time per km. The averaged running velocity recorded among participants was 12 ± 1.3 km h⁻¹. The indoor foot morphology measurement lab was located 30 meters beside the starting and ending point of the track. The foot morphology data, subjective-perceived scores and plantar pressure data were separately collected immediately after finishing 10 km with the 3D foot scanner, VAS and Novel Pedar insole plantar pressure measurement system. After completion the 10 km tests, participant kept running another 10 km and did the 20 km tests following the above protocol. During each test session, the insoles were placed into the running shoes for the running plantar pressure collection while scanning participants' foot shape. Three trials with ten-step running on a 20-meter track were conducted to record the plantar pressure distribution. Recorded peak pressures in ten steps of all three trials were averaged as mean peak pressure values to reduce inter trial errors.

The shock-attenuating properties of the heel midsole were tested using a mechanical impact tester
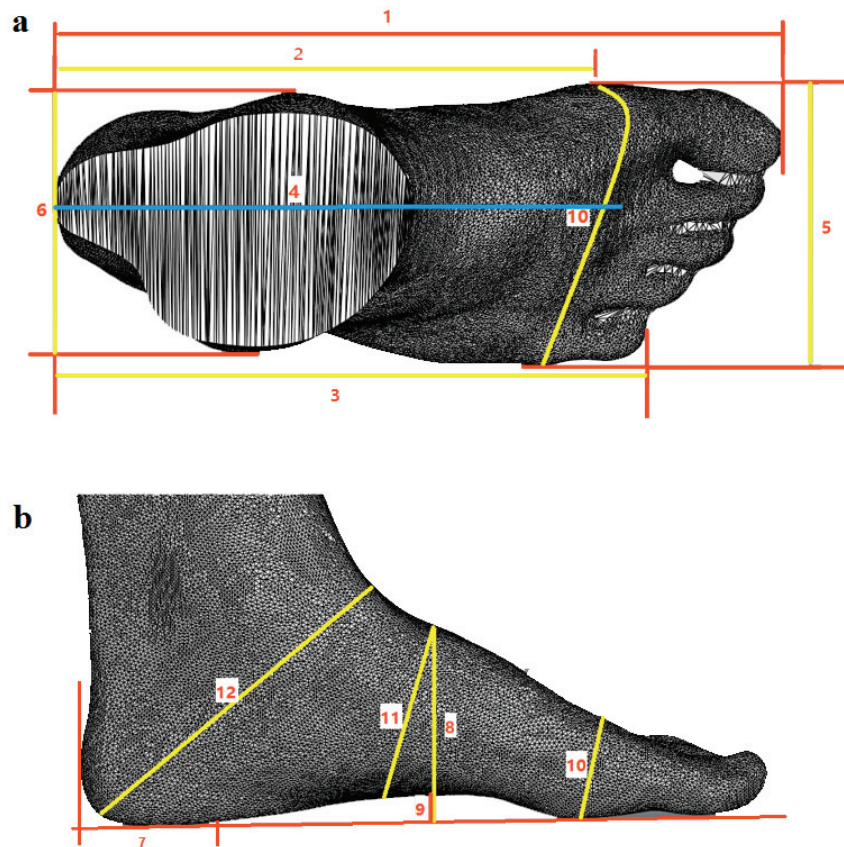

Fig. 2. Illustration of foot morphology variables from top (a) and medial (b) view

(HY-835XZ, HengYu Instrument Limited, China) following the ASTM (American Standard for Testing and Materials) F1614-99 (2006), with the drop mass and height of 8.5 kg and 50 mm, respectively. The energy return (in percentage) and peak G-score were measured and calculated before and after the 20 km running.

The foot morphology data (Fig. 2a and b) included foot length (1), arch length (2), heel-to-fifth toe length (3), mid-ball-to heel length (4), ball width (5), maximal heel width (6), maximal heel location (7), dorsal height (8), arch height (9), ball girth (10), instep girth (11), short heel girth (12), and foot volume was based on a previously established protocol [30]. The subjective perception VAS [18] scores for the shoes included overall comfort, upper comfort, forefoot comfort, heel comfort, arch support (high/low support), forefoot width (tight/loose), heel cushioning (stiffness), medio-lateral control (stability), and weight (light/ weight). The peak pressure was selected among the plantar pressure indices (maximal force, force time integral, pressure time integral, contact area etc.) as an objective index to illustrate comfort [2]. The insole was divided into eight anatomical regions, including Big Toe (BT), Other Toes (OT), First Metatarsal (M1), Second and Third Metatarsals (M2&M3), Fourth and Fifth Metatarsals (M4&M5), Medial Mid-foot (MM), Lateral Mid-foot (LM), and Heel (H).

The Shapiro–Wilk test was conducted to check data normality. The repeated measures ANOVA with a Bonferroni adjustment from SPSS 19.0 (IBM, Armonk, NY, USA) were taken to analyse the significance of foot shape data, perceived comfort scores

and peak pressure among the baseline static condition (ST), 10 km and 20 km. The significance level was set at 0.05.

3. Results

Compared with baseline static (ST) condition, foot morphology data, perceived comfort scores and peak pressure altered after 10 km and 20 km running. In terms of foot shape, heel to fifth toe length increased significantly from 160.6 ± 3.5 mm (static conditions) to 161.9 ± 3.5 mm after 20 km running. The ball width reduced significantly to 99.7 ± 1.6 mm after 10 km running, compared to the normal static conditions of 100.5 ± 1.6 mm, with $p = 0.008$. Ball girth significantly ($p = 0.029$) reduced to 242.6 ± 2.1 mm after 20 km running, compared to 244.7 ± 2.5 mm in normal conditions. Arch height reduced significantly ($p = 0.039$) to 11.7 ± 3.3 mm versus normal conditions (13.1 ± 3.2 mm). Foot volume reduced with significance from $0.91e^{-3} \pm 2.9e^{-2}$ m^3 in ST condition to $0.89e^{-3} \pm 2.3e^{-2}$ m^3 (after 10 km, $p = 0.033$), and $0.88e^{-3} \pm 3.2e^{-2}$ m^3 (after 20 km, $p = 0.008$) (Table 1).

The perceived shoe comfort measured using the VAS scores showed significant differences among ST condition, 10 and 20 km of running, particularly in heel comfort, forefoot comfort, arch height, forefoot width, and overall comfort. The overall comfort was reduced as running distance increased, from 105 ± 16.5 at ST, to 94.9 ± 18.15 at 10 km and 79.9 ± 29.6 at 20 km, though only statistically significant ($p = 0.006$)

Table 1. Foot morphology variables under static condition and immediate after 10 km and 20 km running

Foot shape data	Static		10 km		20 km		P value		
	Mean	SD	Mean	SD	Mean	SD			
Foot Length	252.4	5.0	252.9	4.9	252.8	5.1	0.1	0.1	0.8
Arch Length	186.6	3.3	186.8	3.3	186.8	3.5	0.240	0.418	0.747
Heel to Fifth Toe Length	160.6	3.5	161.1	2.5	161.9	3.5	0.073	**0.049$^{\&}$**	0.760
Mid-Ball to Heel Length	173.7	3.4	175.0	4.9	174.0	3.5	0.249	0.124	0.362
Ball Width	100.5	1.5	99.7	1.6	99.6	1.6	**0.008****	0.057	0.691
Maximal Heel Width	67.4	2.1	67.0	2.1	66.8	2.1	0.148	0.116	0.096
Maximal Heel Location	46.1	0.6	46.2	0.5	46.1	0.8	0.272	0.244	0.862
Dorsal Height	67.0	4.5	66.6	4.8	66.6	4.7	0.224	0.479	0.908
Arch Height	13.1	3.2	12.1	3.6	11.7	3.3	0.167	**0.039$^{\&}$**	0.234
Ball Girth	244.7	2.5	243.4	3.4	242.6	2.1	0.076	**0.029$^{\&}$**	0.384
Instep Girth	248.1	5.4	247.2	4.8	247.0	4.5	0.226	0.214	0.604
Short Heel Girth	322.1	8.2	320.7	8.9	320.6	8.4	0.280	0.449	0.956
Foot Volume	$0.91e^{-3}$	$2.9e^{-2}$	$0.89e^{-3}$	$2.3e^{-2}$	$0.88e^{-3}$	$3.2e^{-2}$	**0.033***	**0.008$^{\&\&}$**	0.311

Notes: * indicates significance between Static and 10 km, $^{\&}$ means significance between Static and 20 km, $^{\#}$ represents significance between 10 km and 20 km (Unit: mm for length, width and girth, and m^3 for foot volume).

Table 2. Perceived VAS scores under static condition and immediate after 10 and 20 km of running

VAS scores (mm)	Static		10 km		20 km		P value		
	Mean	SD	Mean	SD	Mean	SD			
Overall comfort	105	16.5	94.9	18.15	79.9	29.6	0.076	**0.006**[&]	0.052
Upper comfort	109.6	18.6	105	13.4	109.9	18.2	0.064	0.18	0.47
Forefoot comfort	107.6	14.7	94.9	27.9	77.6	32.1	**0.034**[*]	**0.009**[&]	0.06
Heel comfort	113.9	18.8	107.8	21.3	102.5	18.1	0.49	**0.018**[&]	**0.021**[#]
Arch support	109.9	18.2	110.8	20.6	107.6	32.1	0.8	**0.012**[&]	0.91
Forefoot width	96	5.8	97.5	8.3	94.9	24.5	0.88	**0.021**[&]	**0.031**[#]
Heel cushioning	112.9	20.6	109.9	20.6	105	25.1	0.72	0.64	0.62
Medio-lateral control	109.9	15.5	115.5	15.8	112.8	20.7	0.24	0.79	0.98
Weight	110.9	12.5	106.6	16.9	103.6	19.9	0.67	0.39	0.13

Notes: [*] indicates significance between Static and 10 km, [&] means significance between Static and 20 km, [#] represents significance between 10 and 20 km.

Table 3. Peak pressure under static condition and immediate after 10 and 20 km running

Peak Pressure [kPa]	Static		10 km		20 km		P value		
	Mean	SD	Mean	SD	Mean	SD			
BT	214.38	54.16	211.25	50.58	205	41.97	0.23	**0.025**[&]	0.09
OT	155.63	44.09	155.21	37.71	153.33	45.89	0.9	0.51	0.32
M1	277.29	83.03	299.58	84.65	317.29	81.29	**0.036**[*]	**0.008**[&]	**0.038**[#]
M2&M3	243.96	86.92	250.83	104.72	256.25	102.29	0.08	**0.027**[&]	0.062
M4&M5	197.08	76.23	193.13	58.55	197.29	59.73	0.18	0.57	0.069
MM	96.25	11.51	110	14.25	121.46	21.83	0.48	**0.013**[&]	0.06
LM	124.17	25.64	125.21	21.86	132.71	18.14	0.72	0.44	0.62
H	209.79	37.45	208.96	37.78	226.67	37.93	0.31	**0.024**[&]	**0.029**[#]

Notes: [*] indicates significance between Static and 10 km, [&] means significance between Static and 20 km, [#] represents significance between 10 and 20 km.

difference was observed between static conditions and 20 km. The forefoot comfort reduced to 94.9 ± 27.9 at 10 km ($p = 0.034$) and 77.6 ± 32.1 at 20 km ($p = 0.009$) compared to 107.6 ± 14.7 at ST. The heel comfort was reduced significantly from 113.9 ± 18.8 ($p = 0.018$) at ST, and 107.8 ± 21.3 ($p = 0.021$) at 10 km to 102.5 ± 18.1 at 20 km of running. Arch support perception presented significant variation after 20 km of running (107.6 ± 32.1) from ST (109.9 ± 18.2), with $p = 0.012$. The forefoot width also varied greatly after 20 km (94.9 ± 24.5), compared to 10 km (97.5 ± 8.3, $p = 0.031$) and ST (96 ± 5.8, $p = 0.021$).

The peak pressure in BT, M1, M2&M3, MM, and H regions altered significantly throughout the running test (Fig. 2B). BT region presented significantly reduced peak pressure from 214.38 ± 54.16 kPa at ST to 205 ± 41.97 kPa after 20 km running, with $p = 0.025$. Peak pressure in M1 showed a significant increase from 277.29 ± 83.03 kPa at ST, to 299.58 ± 84.65 kPa at 10 km, and 317.29 ± 81.99 kPa at 20 km. There was a statistical difference between ST and 10 km ($p = 0.036$), ST and 20 km ($p = 0.008$), and 10 and 20 km ($p = 0.038$). After 20 km of running, peak pressure in M2&M3 reached 256.25 ± 102.29 kPa, which is sig-

nificantly ($p = 0.027$) larger than 243.96 ± 86.92 kPa (ST). The peak pressure of MM increased significantly to 121.46 ± 21.83 kPa after 20 km ($p = 0.013$) with 96.25 ± 11.51 kPa at ST. In H region, the peak pressure significantly increased to 226.67 ± 37.93 kPa after 20 km, compared to 10 km (208.96 ± 37.78 kPa, $p = 0.029$) and ST (209.79 ± 37.45 kPa, $p = 0.024$).

As all participants ran with rearfoot strike, the shock attenuating properties of EVA midsole were measured before and after 20 km of running. The energy return significantly reduced to $44.73 \pm 2.63\%$ after 20 km of running, compared to $48.45 \pm 1.41\%$ (ST), with $p = 0.024$. The peak G score was 12 ± 0.33 after 20 km of running, while the static value was 11.47 ± 0.42, without significance ($p > 0.05$).

4. Discussion

This study aimed to measure the foot morphological changes, plantar pressure distribution and perceived shoe comfort difference after a continuous 10 and 20 km run, compared to ST conditions. Consistent

with the first hypothesis, ball width narrowed significantly after 10 km of running, ball girth and arch height were reduced greatly after 20 km of running, and foot volume was reduced from 10 to 20 km of running. The perceived overall comfort in this study reduced significantly after 20 km of running, and forefoot and heel comfort also greatly decreased, and foot alignment variations have been reported to affect subjective comfort [16]. Previous studies of plantar pressure and subject comfort reported that peak pressure was closely related with perceived comfort [2], [6], [8], [9]. The second hypothesis was confirmed in the observation that peak pressure increased significantly in the H, MM and M2&M3, decreased significantly in the BT after 20 km of running, and increased in the M1 from 10 to 20 km of running.

The popularity of long distance running has been accompanied by high injury risks [26], [27]. Van Gent et al. [27] divided contributing factors into systemic factors (age, gender, weight, height and other anthropometric factors), health factors (medical history), lifestyle factors (smoking or drinking alcohol), and running-related factors (training distance, running surface and shoes usage). Furthermore, most shoe fit and comfort metrics were measured under either static or short-term dynamic conditions [6], and limited research has focused on foot shape variation during prolonged running. In this study, the observed reduced ball width and girth may be explained by the loss of sweat in the foot after 10 and 20 km of running (Table 1). The foot volume reduction could lead to support instability through the foot being less conforming to the shoe shape, consistent with previous studies [16]. This was most prevalent in the forefoot with increased shoe forefoot width scores, where the forefoot width decreased and the participant perceived the shoe width to increase due to more space. This is an environment that encourages potential friction between foot and shoe interface leading to blisters and callouses [11], and possible modification in ambulation to reduce discomfort, which potentially increases the risk of musculoskeletal injuries [16], [27].

Both intrinsic and extrinsic foot muscles have been shown to contribute to foot posture and shape [7], [19]. In our study we observed a decreased arch height after 20 km, consistent with half marathon running reported by Cowley et al [5]. Studies evaluating muscle function have suggested that intrinsic foot muscles fatigue may lead to the destabilized medial longitudinal arch and navicular drop [7]. Another possible explanation is foot pronation in repetitive rearfoot strike during long distance running [24], which contributes to the drop in medial longitudinal arch [5], [10], [19]. Consequently, after 20 km of running, an increase of medial foot loading was observed [20], [29], which may explain the significant difference of peak pressure in MM, M2&M3 and M1 in this study. With shoe fit and comfort closely linked with peak pressure [2], [6], [9], these results suggest the reduced comfort scores in the forefoot region are due to increased pressures in this study. Furthermore, the foot arch drop exhibited in this study is compensated by the shoe arch support. Interestingly, Alfuth and Rosenbaum [1] found no immediate effects of long distance running on plantar sensitivity, which could eliminate the influence of fatigue on sensory feedback, thus confirming the validity of the VAS perceived comfort metric in this study.

Previous research concerning foot strike patterns during marathon running revealed that rearfoot strikers represented 88.9% of all recreational and sub-elite runners [10]. Hence, perceived comfort and measured plantar pressure could be modified through the rear sole material properties of running shoes [4], [9]. The characteristics of the EVA heel region midsole were measured before and after 20 km of running, showing significant reduction of energy return but no significance in peak G score. This may explain the why the perceived heel cushioning scores in this study showed no significance, as peak G score was an indicator of impact attenuating properties [4], possibly due to the fat cushioning in the heel and prior adaptation [21]. However, the decreased energy return of rearfoot striking participants in the heel midsole in this study may possibly contribute to the significantly increased peak pressure to the H region.

A key finding of this study was the significant increasing peak pressures to the M1 and greatly reduced peak pressure to the BT, which was in agreement with previous studies [8], [20], [24], [29]. This was attributed to the loss of toes' active control mechanism in the push-off phase, thus, transferring loading to the metatarsal (particularly medial metatarsal regions) after long distance running [20]. The dynamic function of toes and foot would not only affect the perceived comfort of sports shoes [16], but also influence the lower limb kinematics and kinetics performance [14]. As reported with externally manipulated toes, functions, such as like gripping and ambulatory actions, were reversible and could share forefoot loading [14], [15]. Hence, toe-function during the push-off phase has important implications to injury risk management [12], [20], [27], [29].

One limitation that should be considered in this study is that all participants were running on the standard 400 m track to complete the 20 km of running test not on the trail or asphalt road. The benefit was that the distance covered was accurately recorded

throughout the test, which guaranteed that the tests were conducted immediately after 10 and 20 km of running. Although the running surface, such as treadmill, natural grass, or asphalt road, has been shown to influence plantar pressure characteristics [26], this was not considered in this study.

5. Conclusion

The foot morphology variations and forefoot loading concentration may lead to discomfort and have possible implications in foot dermatological problems and potential metatarsal bone stress. This was consistent with the reduced shoe comfort metric in this study. The observed increasing peak pressure on the first metatarsal suggests that this is a region susceptible to accumulative bone stress, whereas the big-toe, which showed decreased loading, suggests a modification in the running style to offload this region. It was observed that the midsole of the shoe was less worn after a single long distance run among recreational runners, which may suggest a lower running shoes replacement among recreational runners during a single long-distance running event. Combining with heel midsole property changes, knowledge of foot shape, shoe perception and plantar pressure are of great value for recreational long-distance running shoes design and materials selection.

Acknowledgements

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