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Original Research

Plantar loads characteristics of male non-rearfoot strikers running on different overground surfaces at preferred speed

Zhangqi Lai[1,†], Min Liu[2,†], Lin Wang[1,*], Zhiwang Zhang[1,*]

[1]Shanghai Frontiers Science Research Base of Exercise and Metabolic Health, Shanghai University of Sport, 200438 Shanghai, China
[2]Department of Rehabilitation Science, School of Health, Shanghai Normal University Tianhua College, 201815 Shanghai, China
*Correspondence: wanglin@sus.edu.cn (Lin Wang); zhangzhiwang@sus.edu.cn (Zhiwang Zhang)
[†]These authors contributed equally.

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Abstract

Background: This study aimed to investigate the plantar loads of male non-rearfoot strike runners running on different overground surfaces at their preferred speeds. **Methods**: A total of 32 male runners with non-rearfoot strike were required to run for 15 m on concrete, synthetic rubber and grass surfaces at their preferred speeds. An insole sensor system was used to determine the runners' foot strike pattern and measure peak pressure, pressure-time integral, maximum force, force-time integral and contact area of the total foot and nine selected foot regions. **Results**: No significant differences on their preferred speeds were observed running on concrete, synthetic rubber and grass surfaces. No significant differences on plantar loads parameters of the total foot were found when running on the three overground surfaces. Running on concrete showed higher peak pressure in the lateral forefoot compared with grass and synthetic rubber (283.49 kPa vs. 264.31 kPa, $P < 0.023$; 283.49 kPa vs. 263.18 kPa, $P < 0.019$, respectively). Maximum force in the medial forefoot was lower when running on concrete compared with grass and synthetic rubber (40.16 %BW vs. 42.52 %BW, $P < 0.042$; 40.16 %BW vs. 43.21 %BW, $P < 0.022$, respectively). **Conclusions**: Repetitive and excessive plantar loads during long-distance running may result in loads-related injury in lower extremity skeletal tissues for non-rearfoot runners at preferred speeds. Therefore, male non-rearfoot strikers should choose the appropriate overground surface to reduce the risk of lower extremity musculoskeletal injuries.

Keywords: Male non-rearfoot striker; Running; Plantar loads

1. Introduction

Running is one of the most popular sports activities and an effective way to improve health [1]. However, it is also associated with a high risk of lower extremity loads-related injuries, the rate of incidence range of which is between 18.2% and 92.4% [2,3]. Sports injuries during running have several potential risk factors, including abnormalities in running kinematics [4] and shod conditions [5]. Overground surface has been proven to be a risk factor in developing overuse sports injuries whilst running [6–10].

Common overground surfaces include asphalt, concrete, rubber, and natural grass. Running is also performed on artificial grass and woodchip trail surfaces. Running on different overground surfaces could perform different load absorption mechanisms of the lower extremity [7,11–13]. The loading rate of impact force during running increases when running on harder surfaces compared with softer surface [14]. Running on less compliant surfaces will lead to increased loads of the lower extremity musculoskeletal structures [15]. Furthermore, excessive and repetitive plantar loads during running may result in a high incidence of plantar stress-related foot injuries [16,17].

Plantar loads, which represents the impact relationship between the foot and support surface during everyday activities, are calculated for the analysis of foot and lower limb biomechanics [18]. Moreover, plantar loads are widely used in the diagnosis and prevention of sports injuries [19,20]. Numerous studies have investigated plantar loads amongest different overground surfaces. Higher peak pressures were observed on asphalt surface at the central and lateral rearfoot, and lateral forefoot compared with running on natural grass surface [11]. Running on natural grass showed lower peak pressure at the total foot, lateral midfoot, central forefoot and lateral forefoot when compared with running on concrete surface [8]. Therefore, soft surfaces can increase the cushioning properties and reduce plantar loads from overground surfaces. However, inconsistent findings have typically been found when running on different surfaces with diverse cushioning properties [21]. A previous study has determined that no significant differences were shown in terms of the time of occurrence of peak plantar pressures, peak pressure distribution and pressure, time integral when running on different surfaces [22].

Furthermore, foot strike pattern (FSP) [23], running speed [12] may act as potentially confounding factors in limiting the understanding of the surface effect. Participants in the majority of previous studies that have explored plantar loads during running on different surfaces are rearfoot strike pattern [8,24] or recreational runners regardless of their foot strike patterns [7]. In recent years, numerous investigations have evaluated plantar loads on different running surfaces using fixed speeds [8,11], thereby possibly changing the biomechanics of the lower limbs [25] and cannot precisely represent plantar loads. Therefore, the effect of plantar loads when running on different surfaces remain unknown amongst non-rearfoot strikers at preferred speeds.

This study aimed to investigate the plantar loads characteristics of habitual non-rearfoot strikers whilst running on three commonly different surfaces, namely, concrete, synthetic rubber and grass at their preferred speeds. It was hypothesized that running on grass and synthetic rubber surface would result in lower plantar loads than running on concrete surface, particularly in the forefoot regions.

2. Materials and methods

2.1 Participants

This was a cross-sectional study to investigate the plantar loads characteristics when running on different surfaces. A total of 32 with non-rearfoot loading pattern male runners were recruited through posters from local universities. The participants reported that they run at least 20 km per week. Only male participants were recruited to eliminate gender differences in lower extremity biomechanics during running [26]. Exclusion criteria consisted of musculoskeletal disorders, cardiovascular diseases, surgery on the lower extremities in the past six months and other conditions (e.g., vestibular, visual and mental diseases) that preventing runners from participating in this study. Informed consent was obtained from each runner before they participated in the research. This study was approved by the local ethical committee of Shanghai University of Sport (2018076) and conducted in accordance with the Declaration of Helsinki.

2.2 Equipment and procedure

Concrete (C), grass (G) and synthetic rubber (R) are common overground surfaces used by recreational and marathon runners [8,24,27]. In our study, the thickness of the synthetic rubber and grass surfaces was 2-cm and the concrete surface was made of concrete tiles with a thickness of 1-cm. Moreover, a 15-m long, 1-m wide runway with polyvinyl chloride mattress (1.6-mm) was also used in the laboratory to reduce friction between the running surfaces and floor. The construction of the runway was used in our previous studies [28,29].

Body mass, height and age were measured and recorded. The dominant limb, which is identified as the preferred leg for runner, was determined by kicking a ball [30]. Uniform pairs of shoes (Sortiemagic Rp 4 Tmm467-0790, European size 41 to 43, ASICS, Japan) were distributed to the participants to reduce the influence of various running shoes on the impact from the running surface [31].

Each runner performed a 5-min warm-up on a treadmill under their preferred running speed. Strike pattern was determined using Pedar-X system (Novel, Munich, Germany) [32]. Only runners whose centre of pressure (COP) location was at the anterior 66% of the foot length at the initial loading contact were studied and classified as non-rearfoot striker [33,34]. Thereafter, they adapted to the different surfaces and new running shoes before the actual trial began. According to the procedure in previous studies on plantar loads [8,24,29], all runners completed all the tests at a single visit.

The Pedar-X system, which was calibrated using a standard calibration device (Trublu Calibration, Novel, Munich, Germany) before the trial [8,32], was also used to obtain running plantar loads data with a sampling frequency of 100 Hz. This measurement system demonstrated great reliability and validity [35] and allows the researcher and clinician to examine the plantar loading parameters [8,29]. The insoles of this system, which included 99 pressure sensors, were placed between the foot and running shoes and telemetrically transmitted data to a computer via a control unit worn at the waist. The runners were instructed to run at their preferred speeds on the runway. Running speed was recorded using a 3-m photoelectric timing system (Witty-SEM, Microgate, Italy) located in the middle of the runway. The runners were specifically instructed not to alter their speed during the entire experiment. A high-speed camera (MotionPro X-4, Integrated Design Tools Inc., Pasadena, CA, US) at a sampling rate of 100 Hz, was synchronised with a turning-on flash of Pedar-X system, and recorded the feet steps to confirm that the dominant leg fell within the 3-m measurement zone of the photoelectric timing system. The order of the three overground surfaces was randomly assigned to runners. For each overground surface, runners completed three successful trials. In order to eliminate the impacts of different surfaces, runners were given 15-min to get accustomed to each surface. Plantar loads data and the participants' preferred running speeds on each surface were collected for further statistical analysis.

2.3 Data reduction

Regional plantar data under the determined foot were processed using the multimask evaluation (Novel Multimask, Germany) [8,32]. The foot was divided into nine regions similar to previous studies (Fig. 1) [8,27]. The loading parameters of the total foot and nine selected regions were calculated during the stance phase, including the maximum force (MF), peak pressure (PP), pressure-time integral (PTI), force-time integral (FTI) and contact area (CA). FTI and MF were normalised on the basis of the runners' respective body weights.

2.4 Statistical analysis

The Shapiro-Wilk test was used to test the normal distribution, and homogeneity was confirmed thereafter using Levene's test. Repeated measure analysis of variance was used to determine the effect of surfaces on plantar loads and to affirm the differences amongs running speeds on the three surfaces. A total of 95% confidence interval (CI) and partial η^2 were calculated for the difference amongst the

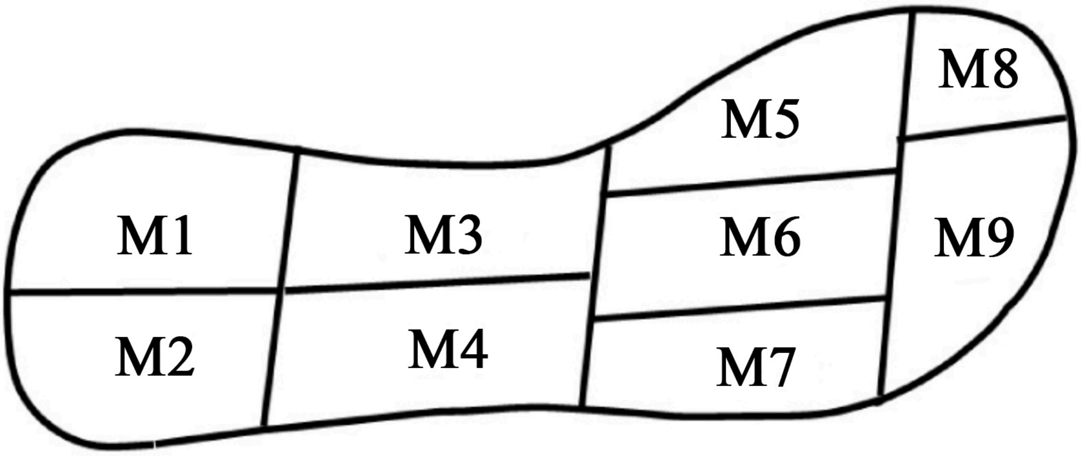

Fig. 1. Insole masks. M1 (medial heel), M2 (lateral heel), M3 (medial midfoot), M4 (lateral midfoot), M5 (medial forefoot), M6 (central forefoot), M7 (lateral forefoot), M8 (great toe), and M9 (lesser toes).

running surfaces (standardised mean differences were calculated as partial η^2 and the thresholds for small, moderate and large were 0.10, 0.25 and 0.40). When significant effect was found, least significant difference (LSD) post-hoc test was conducted to compare the specific difference. The Cohen's D was used to observe effect size and the thresholds for small, moderate and large were 0.20, 0.50 and 0.80. All data were presented as mean and standard deviation (SD). Significance level was set at alpha <0.05. Statistical analyses were preformed using SPSS, version 20 (IBM Corp, Chicago, IL, USA).

3. Results

A total of 32 healthy runners (age: 28.3 ± 6.4 years; height: 173.1 ± 4.2 cm; weight: 69.0 ± 9.8 kg; BMI: 23.0 ± 2.7 kg/m^2) were included in this study. Average running speed was 3.41 ± 0.36 m/s and no significant difference were observed for the running speeds on grass, concrete and synthetic rubber (3.41 ± 0.37 m/s, 3.40 ± 0.38 m/s and 3.43 ± 0.35 m/s, respectively; F (2, 62) = 0.390, P = 0.679).

3.1 PP and PTI

There was a significant difference of the PP in the lateral forefoot (F (2, 62) = 3.363, P = 0.041) as illustrated by Table 1. Further LSD test showed PP in the lateral forefoot was significantly higher when running on concrete compared with that on synthetic rubber (95% CI = 3.512 to 37.113 kPa, P = 0.019, Cohen's D = 0.306) and grass (95% CI = 2.799 to 35.360 kPa, P = 0.023, Cohen's D = 0.303). Overground surfaces had no significant effect on PTI.

3.2 MF and MTI

Table 2 shows that the MF in the medial forefoot (F (2, 62) = 3.613, P = 0.033) demonstrated significant difference amongst the three surfaces. MF in medial forefoot on concrete was significantly lower than that on synthetic rubber (95% CI = –4.643 to –0.088 %BW, P = 0.042, Cohen's D = 0.178) or grass (95% CI = –5.620 to –0.473 %BW, P = 0.022, Cohen's D = 0.221). MTI data of were not significantly different amongst three surfaces.

3.3 CA

Table 3 shows the comparison of CA amongst the three overground surfaces. No significant differences (P > 0.05) were observed in this parameter.

4. Discussion

The current study determined the plantar loads characteristics when non-rearfoot landing male runners ran on three different surfaces under preferred speeds. This study is the first to describe the plantar loads characteristics of non-rearfoot strikers running on different overground surfaces. We found that overground surfaces did not influence running speeds. Furthermore, we observed that peak pressure in the lateral forefoot was higher when comparing concrete with grass or synthetic rubber surface, thereby partially supporting our hypothesis that grass and synthetic rubber surfaces could reduce plantar loads in the forefoot regions. Maximum force in medial forefoot was lower when running on concrete surface than on grass or synthetic rubber surface, thereby rejecting our hypothesis that the maximum force would be greater when running on concrete surface.

In the current study, plantar loads parameters in the total foot were not significantly different amongst the three surfaces. These results were consistent with a previous study that found similar data in contact time, PP and PTI amongst four surfaces (i.e., synthetic track , natural grass, concrete and a normal treadmill) under a fixed speed (3.33 m/s) [22]. These unified results may be related to the ability to alter the stiffness of the leg to different surfaces for runners [36]. Human runners could change leg stiffness

Table 1. Comparison of PP and PTI for running on different surfaces.

Variable	Area	C	G	R	P values
PP (kPa)	Total foot	418.09 ± 116.98	412.69 ± 118.91	402.91 ± 117.54	0.438
	M1	23.33 ± 25.83	25.91 ± 30.11	32.14 ± 38.95	0.416
	M2	22.47 ± 22.91	24.58 ± 28.41	33.46 ± 48.25	0.304
	M3	57.73 ± 27.07	56.34 ± 23.25	65.66 ± 31.49	0.155
	M4	84.77 ± 41.31	80.03 ± 33.71	93.48 ± 42.59	0.073
	M5	372.92 ± 124.71	372.34 ± 128.29	369.89 ± 132.19	0.955
	M6	367.14 ± 90.18	342.69 ± 88.48	342.14 ± 83.26	0.069
	M7	283.49 ± 67.50	264.31 ± 57.54	263.18 ± 66.73	**0.041**
	M8	184.56 ± 142.38	166.79 ± 161.32	176.82 ± 147.94	0.571
	M9	108.04 ± 70.96	93.31 ± 69.82	106.49 ± 79.47	0.199
PTI (kPa·s)	Total foot	61.65 ± 17.07	60.17 ± 20.67	57.91 ± 18.74	1.157
	M1	1.69 ± 2.26	2.07 ± 2.89	2.09 ± 2.65	0.639
	M2	1.43 ± 2.03	1.83 ± 2.56	1.84 ± 2.51	0.489
	M3	6.64 ± 3.83	7.03 ± 4.38	7.92 ± 4.65	0.172
	M4	10.02 ± 5.36	9.45 ± 5.16	11.02 ± 5.82	0.108
	M5	53.26 ± 17.98	52.44 ± 20.51	51.61 ± 19.71	0.739
	M6	53.73 ± 14.37	49.42 ± 15.44	48.88 ± 12.73	0.086
	M7	41.19 ± 9.31	37.83 ± 7.69	37.99 ± 9.82	0.066
	M8	19.62 ± 19.45	19.87 ± 21.89	18.92 ± 20.17	0.890
	M9	13.45 ± 11.35	12.33 ± 10.25	12.89 ± 11.62	0.653

All data were means ± standard deviation (SD). PP, peak pressure; PTI, pressure–time integral; C, concrete; G, grass; R, synthetic rubber; M1, medial heel; M2, lateral heel; M3, medial midfoot; M4, lateral midfoot; M5, medial forefoot; M6, central forefoot; M7, lateral forefoot; M8, great toe; M9, lesser toes. Significant differences ($P < 0.05$) are highlighted in bold.

Table 2. Comparison of MF and FTI for running on different surfaces.

Variable	Area	C	G	R	P values
MF (% BW)	Total foot	160.07 ± 25.18	162.87 ± 25.02	167.41 ± 29.25	0.091
	M1	2.86 ± 3.84	3.51 ± 5.28	4.16 ± 6.36	0.539
	M2	2.21 ± 2.93	2.79 ± 4.26	3.89 ± 6.71	0.301
	M3	8.61 ± 5.87	9.11 ± 5.85	10.87 ± 6.82	0.142
	M4	13.41 ± 7.84	13.37 ± 6.87	15.36 ± 6.99	0.167
	M5	40.16 ± 12.98	42.52 ± 13.56	43.21 ± 14.59	**0.033**
	M6	58.14 ± 9.21	57.46 ± 11.41	57.91 ± 11.06	0.877
	M7	37.17 ± 9.02	36.22 ± 8.47	37.62 ± 9.09	0.383
	M8	7.08 ± 6.10	6.26 ± 6.73	6.52 ± 6.12	0.433
	M9	7.51 ± 6.77	6.79 ± 6.46	7.47 ± 6.75	0.409
FTI (% BW·s)	Total foot	23.43 ± 4.13	23.05 ± 4.34	23.61 ± 4.63	0.602
	M1	0.16 ± 0.25	0.24 ± 0.38	0.22 ± 0.37	0.473
	M2	0.12 ± 0.21	0.17 ± 0.29	0.17 ± 0.29	0.536
	M3	0.84 ± 0.68	0.91 ± 0.74	1.11 ± 0.83	0.146
	M4	1.36 ± 0.94	1.33 ± 0.83	1.53 ± 0.88	0.225
	M5	5.64 ± 1.86	5.82 ± 2.01	5.79 ± 1.98	0.649
	M6	8.42 ± 1.44	8.07 ± 1.74	8.08 ± 1.53	0.334
	M7	5.21 ± 1.28	4.89 ± 1.06	5.08 ± 1.22	0.160
	M8	0.75 ± 0.85	0.74 ± 0.88	0.72 ± 0.86	0.900
	M9	0.94 ± 1.04	0.88 ± 0.92	0.91 ± 1.00	0.831

All data were means ± standard deviation (SD). MF, maximum force; FTI, force-time integral; C, concrete; G, grass; R, synthetic rubber; M1, medial heel; M2, lateral heel; M3, medial midfoot; M4, lateral midfoot; M5, medial forefoot; M6, central forefoot; M7, lateral forefoot; M8, great toe; M9, lesser toes. Significant differences ($P < 0.05$) are highlighted in bold.

to accommodate different surfaces, thereby leading to similar peak vertical ground reaction force when running on all overground surfaces [36]. Additionally, runners can actively adapt the increased surface stiffness with decreased

Table 3. Comparison of CA for running on different surfaces.

Variable	Area	C	G	R	P values
CA (cm^2)	Total foot	118.15 ± 21.59	119.08 ± 20.93	124.49 ± 23.83	0.232
	M1	6.01 ± 6.39	6.25 ± 7.14	6.93 ± 6.17	0.709
	M2	5.27 ± 5.12	5.37 ± 5.99	6.28 ± 5.59	0.465
	M3	18.91 ± 6.99	19.62 ± 5.99	20.81 ± 7.63	0.250
	M4	18.48 ± 4.73	18.99 ± 4.01	19.82 ± 4.03	0.310
	M5	15.87 ± 1.13	16.04 ± 1.21	16.54 ± 1.54	0.070
	M6	22.24 ± 1.29	22.14 ± 1.36	22.72 ± 2.09	0.186
	M7	20.88 ± 0.97	20.94 ± 1.12	21.40 ± 1.97	0.197
	M8	3.21 ± 1.74	2.94 ± 1.91	3.04 ± 1.75	0.434
	M9	7.29 ± 4.11	6.78 ± 4.38	6.94 ± 4.15	0.495

All data were means ± standard deviation (SD). CA, contact area; C, concrete; G, grass; R, synthetic rubber; M1, medial heel; M2, lateral heel; M3, medial midfoot; M4, lateral midfoot; M5, medial forefoot; M6, central forefoot; M7, lateral forefoot; M8, great toe; M9, lesser toes. Significant differences ($P < 0.05$) are highlighted in bold.

hip and knee flexion at contact, reduced maximal hip flexion; and increased peak angular velocities of the hip, knee, and ankle [37]. Thompson *et al.* [38] found that non-rearfoot strike runners showed a significant decrease in stride length rather than peak vertical ground reaction force when changing from shod to barefoot running. Meanwhile, running on different surfaces (asphalt, gravel and grass surfaces) was associated with different activation patterns of the peroneus longus and brevis and gastrocnemius [39]. Therefore, non-rearfoot strike runners may use a compensatory mechanism, which changes leg stiffness, kinematics and muscle activation to adapt to different surfaces during their real activities [37] and maintain similar plantar loads. However, previous studies have determined that PP in the entire foot showed significant differences when running on concrete and grass surfaces [8,24]. The differences may account for the foot strike pattern (rearfoot strike vs. non-rearfoot strike) and running speed (3.8 m/s vs. 3.41 m/s).

However, the surface type influenced plantar loads at specific foot regions. In this study, lower peak pressure was found in the lateral forefoot when running on grass or synthetic rubber than running on concrete and the effect sizes were moderate. It is consistent with our previous study [28], which found a lower plantar pressure in the lateral forefoot when running on the synthetic rubber surface than running on concrete. Likewise, Wang *et al.* [8] found that peak pressure in the lateral forefoot was lower on grass than on concrete. The possible reason for the different plantar impact is that synthetic rubber and grass, which are similar to a markedly compliant surface described in the literature [14], decrease loads with increased cushioning properties [7,11,15]. The higher peak pressure on the lateral forefoot in the present study may also be related to increased ankle stiffness. Zhou *et al.* [21] detected that ankle stiffness when running on concrete was greater compared with synthetic rubber for non-rearfoot strikers. Higher lateral pressure suggests that the centre of pressure is located more laterally during running [40]. The lateral centre of pressure trajectory of the foot during running can reduce peak pronation and peak medial longitudinal arch angle [40] , thereby making the ankle considerably stiff.

In our study, grass and synthetic rubber, which were recommended for recreational runners to reduce the risk of sports injury [8], demonstrated higher maximum force in medial forefoot than that on concrete and the effect size between grass and concrete was moderate. This finding may be the result of the adaptability of the foot and ankle for different overground surfaces. When the supination of the foot creates propulsion at toe-off during running, the ankle is plantar flexed, the foot is inverted, and the forefoot is adducted [41]. Meanwhile, the foot was considerably plantar flexed on hard surfaces during running [42]. All participants in the present study were non-rearfoot strikers and they contacted with the ground in midfoot or forefoot. Therefore, the feet of our participants may be significantly plantar flexed, inverted and adducted at toe-off during running on concrete, thereby possibly decreasing the impact force on the medial forefoot. Further investigation should be conducted on multi-segment foot kinematics for non-rearfoot strikers running on different overground surfaces. However, no differences were reported in maximum force and peak pressure on the medial forefoot amongst surfaces for forefoot strikers in our previous study [28]. This discrepancy can likely be explained by different running speed conditions (fixed speed, preferred speed).

Repeated loads during distance running may result in excessive microdamage accumulation in lower extremity skeletal tissues, particularly causing stress fractures in the forefoot [43]. Football players with fifth metatarsal stress fracture displayed higher maximum force at the lateral forefoot compared with healthy players during kicking and curved running [44]. Therefore, higher plantar loads in the forefoot may increase the probability of sports injuries when running with non-rearfoot strike. However, demonstrating the threshold value of force or pressure that resulted in sports injury is difficult [45]. Hence, future studies should include follow-up work that is designed to evaluate the relationship between plantar loads and sports injuries under various running surfaces for non-rearfoot strikers.

Our results indicated that these running speeds (3.41 m/s, 3.40 m/s and 3.43 m/s) in this study had no significant differences, thereby implying that surfaces have no effect on running speeds. This condition corresponds with a previous finding indicating no significant differences were found in running speed and stride frequency for treadmill and overground running [46]. Wei *et al*. [32] found that running speed, which was shown as a covariate, had an effect on the total CA, midfoot area and forefoot area, and FTI in the medial forefoot. However, all participants in their study included habitual rearfoot strike and non-rearfoot strike patterns. Although a markedly fast running speed could change runners' FSP [33,47], all participants in this study were non-rearfoot strike runners and they did not alter their FSP when running on different surfaces. Therefore, our results provided evidence that runners have the ability to not change their preferred speeds to adapt to different running surfaces.

There are several limitations in the current study. A limitation of this study is that three-dimensional plantar loads was not discussed because the Pedar-X system can only obtain plantar loads data in the vertical direction. Therefore, further research is needed on three-dimensional loading characteristics during non-rearfoot strike running. We did not consider the test-retest reliability for each condition and lacked the intra-subject reliability and instrument stability in our study. Another limitation of the study is that the runners recruited were all males and our findings can only be extrapolated to males only.

5. Conclusions

This is the first study to our knowledge to investigate the plantar loads characteristics in non-rearfoot strikers amongst concrete, grass and synthetic rubber surfaces at their preferred running speeds. The findings of this study indicated plantar loads were higher in the lateral forefoot region on the concrete surface and in medial forefoot region on grass and synthetic rubber surfaces, respectively. Non-rearfoot runners should choose the appropriate overground surface to reduce the influence of excessive plantar loads in distance running and reduce the risk of lower extremity musculoskeletal injuries.

Abbreviations

FSP, foot strike pattern; MF, maximum force; PP, peak pressure; PTI, pressure-time integral; FTI, force-time integral; CA, contact area; C, Concrete; G, grass; R, synthetic rubber.

Author contributions

LW conceived and designed the experiments. ZL, ZZ and ML performed the experiments and wrote the paper. ZL and ML analyzed the data. All authors read and approved the final manuscript.

Ethics approval and consent to participate

This study was conducted after review and approval by the Ethics Committee of Shanghai University of Sport (2018076). The participants were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study.

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Conflict of interest

The authors declare no conflict of interest.

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