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Plantar load characteristics among runners with different strike patterns during preferred speed

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Objectives: This study aimed to compare the plantar loads between habitual rearfoot strike (RFS) and non-RFS (NRFS) during running under the participant's preferred speed.
Methods: A total of 66 (36 RFS, 30 NRFS) healthy amateur male runners were included in our study. In-shoe pressure sensors were utilised to the test plantar loads when participants were running using their preferred foot strike pattern and running speed (RFS: 3.2 ± 0.3 m/s; NRFS: 3.4 ± 0.4 m/s).
Results: Results indicated that running speed has a significant effect on the total contact area [F (1, 64) = 7.061, P = 0.01, $\eta^2 = 0.101$], which also affects midfoot and forefoot regions. No significant difference was found on the total maximum force, force-time-integral, peak pressure (PP) and pressure-time-integral (PTI), but the total contact area of RFS was higher than that of NRFS runners [F (1, 64) = 77.406, P < 0.001, $\eta^2 = 0.551$]. Plantar loads were mainly focused on the heel and midfoot for RFS runners in all variables, and NRFS runners experienced increased PP and PTI in medial forefoot regions.
Conclusion: Habitual runners tend to adjust their contact area according to the running speed through midfoot and forefoot regions. RFS runners remain susceptible to high impact force on the heel and midfoot, and NRFS runners experience high impact force in the first metatarsal regions. Therefore, runners should note this situation to avoid running-related injuries.

Introduction

Running activity is one of the most popular physical activities with psychological and physical benefits.[1] Unfortunately, up to 79.3% of runners experience lower extremity musculoskeletal injuries.[2] A high rate of running injuries limits a runner's daily training and produces considerable pressure for medical care. Numerous studies have explored factors that contribute to running-related injuries (RRI),[3,4] Foot strike patterns (FSPs) are essential factors which have been studied in recent years.

Foot strike patterns, defined on the basis of the centre of pressure's (COP) initial contact with the ground during running, was also named as strike index and first described by Cavanagh and Lafortune (1980).[5] For long-distance runners, 75% are rearfoot strike (RFS) runners, 23% are midfoot strike runner and 2% are forefoot strike runners. Owing to the low occurrence of the latter foot strike patterns, many studies grouped them as non-RFS (NRFS).[6–9]

Although the proportion of NRFS runners is low, this landing pattern has many advantages. At the moment of landing on the ground, foot arch, plantar fascia and eccentric contraction of the triceps surae act as a natural mechanism to decrease the impact force and loading rate.[8,10] Prolonged and early activation of triceps surae increase the energy storage of the lower extremity.[10–12] NRFS is superior to RFS with a 22.8% injury rate of RRI compared with a 52.4% incidence in RFS runners.[13]

However, the majority of current literature explored the plantar loads of NRFS pattern by guiding runners who have habitual RFS pattern convert their foot strike pattern into an NRFS pattern temporarily.[8,14,15,16] In addition, most of the studies explored running kinetic, kinematic or plantar loads between RFS and NRFS under different limited speed.[9,16–20] The various limited speed may be acceptable to some researchers, but to increase the ecological validity of a study, the running speed should not be constrained.[21,23] The limited speed may also accompany varying degrees of kinetic and kinematic adaptation, which may not represent

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the actual running condition and increases the difficulty of explaining different results based on different speeds.[21] Furthermore, running in a limited speed may have a little maladjustment. Although studies allowed the participants some time to adapt to the new speed, but we suspected that which situation can not represent the actual running because of the learning effect.

Therefore, we mainly aimed to explore whether running speed, as a profound factor, affects plantar load. We likewise aimed to compare plantar loads between habitual RFS and NRFS runners under their preferred running speed. We hypothesis that plantar loads mainly focus on forefoot regions in the NRFS pattern, and the plantar loads of RFS runners are mainly focused on the heel. Additionally, running speed may be an essential factor in the distribution of plantar loadings.

Methods

Participants

Based on the sample size estimates provided by previous studies,[17,22] with an estimated power of 0.7 and a medium effect size. A total of 66 healthy distance male[4,20] runners with no diagnosed history of lower limb musculoskeletal injury or other medical problems in the previous six months volunteered to participate in the study. All runners were right leg dominant, which was determined by asking them to kick a football.[24] The participants run regularly for 10–15 km per week. Written informed consent was obtained from each participant, and this study was approved by the Human Ethics Committee of Shanghai University of Sport.

Data acquisition

Firstly, the participant's basic information was measured and then their self-reported weekly running mileage was recorded. The testing shoes were standard running shoes with a European size of 41–43.[20] (ASICS, SORTIEMAGIC RP 4 TMM467-0790, Japan) The Novel Pedar-X system (Novel, Munich, Germany) was used to test the plantar loads when the right foot touched the ground. Each insole included 99 force sensors and was linked to the Pedar-X box fixed to the waist of participants. Before the test, a standard calibration device was used to calibrate the censors.[25,26] The sampling frequency of the Pedar-X system was set at 100 Hz. Strike index[5] was used to verify the participant's foot strike pattern. If runners initial touched the ground on the posterior 1/3 of the foot length, they would be classified as rearfoot strike pattern, the anterior 1/3 of the foot length would be termed as forefoot pattern, the remaining 1/3 would be named as midfoot pattern. Given the low occurrence of midfoot strike and forefoot strike in long-distance runners, this study grouped the runners as NRFS,[7,20] indicating that the COP of NRFS runners will first touch the ground in the anterior two-thirds of the foot length.

Before the test, participants were allowed to warm up for 5 min with their preferred foot strike pattern on a treadmill. This test was performed on a standard synthetic rubber, with a 3 m measurement zone located at the middle of a 15 m indoor runway. Photoelectric timing system (Wittysem, Microgate, Italy) was used to calculate the speed in the testing region. A 100 Hz high-speed video camera (Motion Pro X-4, Integrated Design Tools Inc. USA) was used to record the right footsteps within the testing area. The data were collected when the camera captured a flash generated by the Pedar-X insole system. Subjects were allowed to familiarise themselves with the testing equipment and new shoes before testing in their preferred foot strike pattern and running speed. Three successful right foot stances within the testing area were recorded to calculate the mean for further statistical analysis. The participant's preferred running speed was also recorded.

Data reduction and statistical analysis

Novel Pedar-X system software was utilised to process plantar load variables. The right foot was divided into nine regions in accordance with previous studies.[20,27] (Fig. 1). The loading parameters of the total foot and the nine selected regions were calculated, including the maximum force (MF), force-time-integral (FTI), peak pressure (PP), pressure-time-integral (PTI) and contact area (CA). The loading parameters of FTI and MF were normalised to the participant's body weight.

All dependent variables were presented as mean and standard deviation (SD). Kolmogorov–Smirnov test was performed to confirm the normal distribution. To examine the difference of the total foot and nine selected regions between foot strike patterns, we applied analysis of covariance with running speed included as a covariate. Partial eta squared (η^2) effect sizes were calculated and interpreted as 0.14 = large, 0.06 = medium and 0.01 = small according to Cohen (Cohen J, 1988). Significance was set at alpha = 0.05. All statistics were performed using SPSS 22 software (IBM, Armonk, NY, USA).

Results

Of the participants included in our study, 36 (55%) participants were verified as habitual RFS (aged 24.0 ± 2.6 years; body height of 171.7 ± 5.7 cm; body mass of 67.8 ± 10.6 kg; running age 3.1 ± 1.9 years; preferred running speed 3.2 ± 0.3 m/s), while 30 (45%) participants were verified as habitual NRFS (aged 26.4 ± 4.4 years; body height of 173.1 ± 4.0 cm; body mass of 68.9 ± 9.6 kg; running age 4.3 ± 3.9 years; preferred running speed 3.4 ± 0.4 m/s). There was no significant difference of participant characteristics between RFS and NRFS. The specific values for total foot and the nine plantar regions are presented in Tables 1–3.

Running speed, which was applied as a covariate, had a confounding effect on total contact area [F (1, 64) = 7.061, P = 0.01, η^2 = 0.101]. No significant differences were found in the total MF, FTI, PP and PTI. Contact area was high in the midfoot and forefoot in RFS runners and was affected greatly by the running speed. Additionally, the FTI in the medial forefoot was high in NRFS runners and was also affected by the running speed [F (1, 64) = 4.071, P = 0.048, η^2 = 0.061].

For the total foot, no difference was found in the MF, FTI, PP and PTI between different foot strike patterns. However, the contact area was 25.93% greater [F (1, 64) = 77.406, P < 0.001, η^2 = 0.551] in RFS runners than in NRFS runners.

RFS runners experienced higher plantar loads at the midfoot and heel regions in all variables (CA, MF, FTI, PP and PTI) than did NRFS runners. For the forefoot regions, the PP of NRFS runners in the medial forefoot regions [F (1, 64) = 4.523, P = 0.037, η^2 = 0.067]

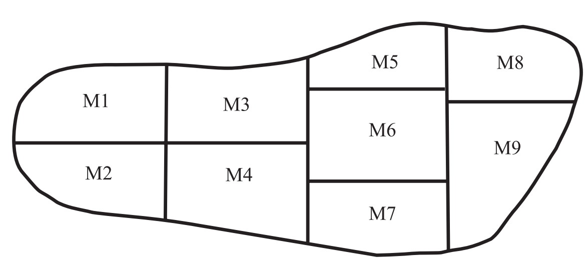

Fig. 1. Insole masks. M1 (medial heel), M2 (lateral heel), M3 (medial midfoot), M4 (lateral midfoot), M5 (medial forefoot), M6 (central forefoot), M7 (lateral forefoot), M8 (great toe), and M9 (lesser toes).

Table 1
Comparison of the CA values between rearfoot and non-rearfoot strikers.

		NRFS	RFS	Speed			FSP		
				F	P	η^2	F	P	η^2
CA (cm2)	Total foot	125.19 ± 19.25	157.65 ± 8.62	7.061	**0.010**	0.101	77.406	**0.000**	0.551
	M1	8.12 ± 6.37	18.79 ± 2.64	2.655	0.108	0.040	77.046	**0.000**	0.550
	M2	7.03 ± 5.85	16.12 ± 2.56	1.922	0.171	0.030	64.540	**0.000**	0.506
	M3	20.37 ± 6.87	25.12 ± 3.11	6.195	**0.015**	0.090	10.842	**0.002**	0.147
	M4	19.61 ± 3.44	22.13 ± 0.93	4.367	**0.041**	0.065	14.648	**0.000**	0.189
	M5	16.29 ± 0.47	16.97 ± 3.26	6.962	**0.010**	0.100	2.827	0.098	0.043
	M6	22.36 ± 0.60	22.79 ± 1.85	7.289	**0.009**	0.104	3.271	0.075	0.049
	M7	21.07 ± 0.48	21.17 ± 1.09	5.371	**0.024**	0.079	0.889	0.349	0.014
	M8	3.16 ± 1.57	4.77 ± 0.76	1.836	0.180	0.028	25.952	**0.000**	0.292
	M9	7.19 ± 3.75	11.19 ± 2.62	0.100	0.753	0.002	23.974	**0.000**	0.276

Note: Values are expressed as means ± standard deviation (SD); Significant differences (P < 0.05) are highlighted in bold.
RFS, rearfoot strike; NRFS, non-RFS; FSP, foot strike pattern; CA, contact area.
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.

Table 2
Comparison of the MF and FTI values between rearfoot and non-rearfoot strikers.

		NRFS	RFS	Speed			FSP		
				F	P	η^2	F	P	η^2
MF (%BW)	Total foot	166.77 ± 32.90	181.44 ± 40.05	0.091	0.764	0.001	2.255	0.138	0.0035
	M1	7.42 ± 11.00	35.24 ± 15.39	0.350	0.556	0.006	63.463	**0.000**	0.502
	M2	6.64 ± 10.29	33.20 ± 18.84	0.026	0.872	0.000	44.704	**0.000**	0.415
	M3	11.61 ± 6.97	21.62 ± 7.42	1.625	0.207	0.025	27.769	**0.000**	0.306
	M4	15.94 ± 6.81	27.11 ± 8.85	2.233	0.140	0.034	28.113	**0.000**	0.309
	M5	43.05 ± 15.34	36.19 ± 15.34	1.817	0.183	0.028	3.493	0.066	0.053
	M6	55.98 ± 12.08	51.73 ± 11.23	0.490	0.487	0.008	1.710	0.196	0.026
	M7	34.68 ± 8.03	33.51 ± 10.00	0.376	0.542	0.006	0.150	0.700	0.002
	M8	7.16 ± 6.12	9.83 ± 6.00	0.051	0.822	0.001	3.159	0.080	0.048
	M9	7.96 ± 6.50	11.44 ± 7.74	0.234	0.630	0.004	4.002	0.050	0.060
FTI (%BW* s)	Total foot	23.59 ± 4.84	26.86 ± 6.69	2.343	0.131	0.036	3.650	0.061	0.055
	M1	0.53 ± 0.92	2.68 ± 1.53	0.012	0.914	0.000	43.311	**0.000**	0.407
	M2	0.39 ± 0.71	2.24 ± 1.96	1.782	0.187	0.028	26.136	**0.000**	0.293
	M3	1.12 ± 0.79	2.13 ± 1.23	0.399	0.530	0.006	15.164	**0.000**	0.194
	M4	1.60 ± 0.90	3.21 ± 2.52	1.951	0.167	0.030	12.643	**0.001**	0.167
	M5	5.73 ± 2.04	4.96 ± 2.98	4.071	**0.048**	0.061	0.651	0.423	0.010
	M6	7.74 ± 4.62	7.16 ± 3.11	3.705	0.059	0.056	0.296	0.589	0.005
	M7	4.67 ± 1.14	4.26 ± 1.83	1.502	0.225	0.023	0.671	0.416	0.011
	M8	0.82 ± 0.90	1.09 ± 0.78	0.088	0.768	0.001	1.521	0.222	0.024
	M9	0.99 ± 1.01	1.27 ± 0.85	0.218	0.642	0.003	1.248	0.268	0.019

Note: Values are expressed as means ± standard deviation (SD); Significant differences (P < 0.05) are highlighted in bold.
RFS, rearfoot strike; NRFS, non-RFS; FSP, foot strike pattern; MF, maximum force; FTI, force-time-integral.
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.

was 20.99% greater than that in NRFS. Similarly, the PTI in NRFS runners in the medial forefoot region [F (1,64) = 5.340, P = 0.024, η^2 = 0.078] was 24.94% higher compared with that in RFS. On the other hand, the contact area in the great toe and lesser toes were 50.95% [F (1, 64) = 25.952, P < 0.001, η^2 = 0.292] and 55.63% [F (1, 64) = 23.974, P < 0.001, η^2 = 0.276] higher in RFS than in NRFS runners, respectively.

Discussion

Our study aimed to explore whether running speed affects plantar loads between foot strike patterns and compare the loading parameters under the runners' preferred speed. Running speed (RFS: 3.24 ± 0.26 m/s; NRFS: 3.36 ± 0.38 m/s) was included as a covariate in our study. The results demonstrated that running speed has no significant effect on the total MF, FTI, PP and PTI but have an apparent effect on the total contact area. Additionally, expected difference was found between foot strike patterns, with plantar loads mainly focused on the heel and midfoot for RFS runners in all variables. The NRFS runners also experienced high PP and PTI in the medial forefoot regions.

The contact area was related to sensor size and defined by researchers. Our results seem support recent analyses indicating that total contact area was higher in RFS runners,[17] but the speed in their study was limited. Kernozek et al. account for the results in their two studies[9,17] were the footwear (minimalist footwear standard vs. cushioned running shoes, respectively). We believe the testing speed might have also resulted in different results, because for the total foot, when runners were tested under high speed, the time spent in stance decreased because of the less frequency of contact with the ground. This condition resulted in a relatively smaller contact area compared with the show speed. This hypothesis is supported by a previous study indicating that when running speed increased from 2.24 m/s to 3.13 m/s, the time spent in stance decreased.[23] Similar results between limited testing speed may be related to the adaptation of participants.[20] In comparison with the preferred running conditions, different fixed testing speed values may be accompanied by various degrees of hip, knee and ankle kinematics and kinetic adaptation,[3,16,20] which may not represent the actual running biomechanical mechanism.

The current data revealed that the midfoot and forefoot characteristics would be adjusted according to the participant's

Table 3
Comparison of the PP and PTI values between rearfoot and non-rearfoot strikers.

		NRFS	RFS	Speed			FSP		
				F	P	η^2	F	P	η^2
PP (kPa)	Total foot	393.92 ± 116.62	361.12 ± 115.60	0.729	0.396	0.011	0.902	0.346	0.014
	M1	50.44 ± 66.20	202.11 ± 119.19	0.190	0.665	0.003	35.579	**0.000**	0.361
	M2	51.14 ± 75.35	213.36 ± 126.97	0.099	0.754	0.002	35.087	**0.000**	0.358
	M3	70.83 ± 31.72	109.68 ± 34.3	3.890	0.053	0.058	19.018	**0.000**	0.232
	M4	91.33 ± 35.47	130.71 ± 51.17	1.082	0.302	0.017	10.805	**0.002**	0.146
	M5	362.42 ± 133.96	299.55 ± 86.89	0.329	0.568	0.005	4.523	**0.037**	0.067
	M6	324.97 ± 76.41	302.82 ± 113.31	0.306	0.582	0.005	0.608	0.439	0.010
	M7	243.47 ± 63.19	226.85 ± 82.97	0.045	0.833	0.001	0.697	0.407	0.011
	M8	191.44 ± 145.58	235.00 ± 117.94	0.188	0.666	0.003	1.495	0.226	0.023
	M9	112.42 ± 72.33	134.39 ± 66.03	0.092	0.763	0.001	1.428	0.237	0.022
PTI (kPa*s)	Total foot	56.88 ± 17.63	52.63 ± 18.13	0.199	0.657	0.003	1.047	0.310	0.016
	M1	3.76 ± 5.15	14.80 ± 7.47	1.277	0.263	0.020	42.293	**0.000**	0.402
	M2	3.20 ± 4.87	14.26 ± 8.03	0.270	0.605	0.004	40.054	**0.000**	0.389
	M3	8.24 ± 4.34	12.94 ± 5.21	2.602	0.112	0.040	12.820	**0.001**	0.169
	M4	10.76 ± 5.00	16.50 ± 7.84	0.086	0.770	0.001	10.980	**0.002**	0.148
	M5	50.14 ± 19.23	40.13 ± 14.44	0.034	0.853	0.001	5.340	**0.024**	0.078
	M6	46.24 ± 11.08	40.30 ± 14.79	0.346	0.558	0.005	2.733	0.103	0.042
	M7	35.10 ± 9.21	30.73 ± 11.66	0.001	0.982	0.000	2.610	0.111	0.040
	M8	21.31 ± 20.58	26.69 ± 16.23	0.731	0.396	0.011	0.986	0.325	0.015
	M9	13.94 ± 11.45	15.88 ± 7.79	0.648	0.424	0.010	0.406	0.526	0.006

Note: Values are expressed as means ± standard deviation (SD); Significant differences ($P < 0.05$) are highlighted in bold.
RFS, rearfoot strike; NRFS, non-RFS; FSP, foot strike pattern; PP, peak pressure; PTI, pressure-time-integral.
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.

preferred speed. Habitual foot strike pattern runners have developed fixed running patterns in their lower extremities.[20] Hence, to minimise plantar loads and avoid some RRI, participants tend to adjust plantar loads automatically through these regions.[3,15,29] This hypothesis was further verified by Breine et al.[30] who stated that when running speed increases, runners transform foot strike pattern to anterior foot contact patterns to eliminate the speed-induced increase in vertical instantaneous loading rate. This finding indicates that the pressure in the midfoot and forefoot would be adjusted with increasing speed. This result also confirms previous findings related to the possible limitation of midfoot and forefoot areas because most of the studies in current literature did not employ the participant's preferred speed, which ranged from 2.90 m/s to 3.89 m/s.[9,17,18,20,31]

Running speed acts as a covariance, which has no effect on the MF of total foot and nine selected regions. This condition contradicts previous findings indicating that running speed significantly affects plantar loading variables.[23,32] In addition, Perraton et al.[21] established that peak vGRF act as an essential factor and has a linear relationship with running speed. The conflicting results may be associated with the testing method, because their study utilised limited speed on a treadmill, and the foot strike pattern of participants included in their study were not reported. Therefore, this situation may not represent the actual running condition. Our results indicate that although previous studies differ in the results of MF,[17,20] the conflicting results may not be related to the different testing speed.

Our data indicate that MF was higher in the heel and midfoot regions during RFS running. This study supported recent analyses showing that RFS runners experience high force on rearfoot and midfoot because of the high vertical ground reaction force (vGRF) and impact transient.[9,17,20] During the initial foot contact on the ground, vGRF produces a shockwave that is transmitted to the knee from the heel, which has a high possibility of resulting in anterior knee pain.[4,33,34] Impact transient is also characterised as a high-magnitude abrupt force, and different running speeds may produce various impacts on the calcaneal within a short time,[4] which may help explain the injuries in lower limb skeletal tissues, such as calcaneal stress fractures.[3,4,8]

For the total MF in our study, no difference was found between these foot strike patterns under the participant's preferred speed, which contradicts our previous results,[20] in which the plantar load difference between two different foot strike patterns under a fixed speed was within 5% of the 12.0 km/h. However, the results were identical with those of Kernozek et al.[9,17] under limited testing speed. They explained that runners could adapt through individual kinematic adaptations.[11] We propose that running speed should also be mentioned. Although the speeds may differ slightly, a mimic difference might be observed compared with the actual running situation. Numerous studies recommended NRFS running because they believe that total MF is relatively lower during NRFS running than during RFS running.[20] However, our results verified that during running under the preferred running speed, fixed running pattern may also account for the similar MF during running.

In the current study, no differences were observed between the running speed and plantar pressure. However, as expected, PP was significantly high in the rearfoot and midfoot regions during RFS running and in the first metatarsal region during NRFS running. For the RFS runners, the impact force can be moderated through contact area and running speed, which do not alleviate the plantar pressure in the heel and midfoot; this condition explains the high incidence of calcaneal[4,8] and tibial stress fractures.[35,36] For NRFS runners, the current data are supported by previous studies, which reported 29.7%[20] higher pressure for NRFS runners in the first metatarsal area compared with RFS runners. The high pressure in the first metatarsal may be related to metatarsal fractures, though runners have adapted to that running situation.[37,38] Kernozek et al.[39] demonstrated that when NRFS runners touch the ground initially, additional stress is applied to tendon degradation, making it more susceptible to Achilles tendinopathy.[40]

Our study supports recent analyses indicating that PP in the total foot is similar between foot strike patterns,[20] thus showing that runners would avoid RRI through the adaptation of contact area and running speed. Hence, although the participants ran under different preferred speeds, we supposed that running in the adapted running pattern would superior than utilizing limited speed, because their fixed impact force condition pattern of the lower extremities.

A limitation of this study is that the range of the runners' preferred speed is relatively large. Thus, further studies can explore plantar loads between different habitual foot strike patterns under the runners' preferred speed, which would provide them with a relatively safe running speed and avoid some RRI.

Conclusion

Habitual runners tend to adjust their contact area according to the running speed through the midfoot and forefoot regions. However, under the adaptation of contact area, habitual RFS runners remain susceptible to suffering from patellofemoral joint injuries because of the impact force on the heel and midfoot. For NRFS runners, loads in the medial forefoot regions may be related to metatarsal stress fractures and compensatory damage of the Achilles tendon. That is, even under runners preferred speed, different foot strike pattern may be accompanied by injuries in different parts of lower extremity, runners should take appropriate measures to prevent running injuries.

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Declaration of competing interest

No potential conflict of interest was reported by the authors.

Appendix A. Supplementary data

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