Hazzaa Walaa Eldin A[1,2], Mattes K[1]

The Effect of Local Muscle Fatigue and Foot Strike Pattern during Barefoot Running at Different Speeds

Die Wirkung der lokalen Muskelermüdung und Fußaufsatztechnik beim Barfußlaufen in verschiedenen Geschwindigkeiten

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1. UNIVERSITÄT HAMBURG, *Institut für Bewegungswissenschaft, Hamburg, Deutschland*

2. UNIVERSITÄT HELWAN, *Fakultät für Leibeserziehung, Training Sektion, AlHaram, Helwan, Ägypten*

Summary

- **Running** is a simple and inexpensive way to lose weight and improve cardiovascular fitness. It has been argued that barefoot running can be considered as a natural alternative to the traditional run with athletic shoes in recreational athletes.
- **The aim of the study** was to investigate the effect of foot strike patterns and local muscle fatigue of the plantar and dorsiflexors on plantar pressure distribution and the selected kinematic characteristics when running barefoot on the treadmill at three speeds. 26 voluntary forefoot and rearfoot runners of similar age and body mass participated in the study. Each group completed two tests, with a time interval of 3-7 days. The kinematic data were taken with the help of the three-dimensional measuring and analysis system while running on the treadmill. The fatigue protocol included the isometric maximal force test and an isokinetic endurance test. In order to check the differences, variance analysis with repeated measurements was used. The strength values of the two groups of runners showed significant differences in the plantar flexors in the endurance test and in the fatigue index on average, for both the left and the right legs.
- **The results** of the strength values are surprising, because the plantar flexors of this group of runners should be well-trained due to the forefoot preference during regular running. The pressure maxima reduced under the exposed foot regions after fatigue, which mean under the forefoot at forefoot strike and under the heel at rearfoot strike. The two groups of runners differed in foot angle at Foot on with higher values of the forefoot runners. The greater foot angle of the forefoot runner improved the shock absorption and thus can reduce the risk of injury.

KEY WORDS:
Fatigue, Foot Strike, Kinematic, Maximal Force Test, Endurance Test

Zusammenfassung

- **Laufen** ist eine einfache und kostengünstige Lösung, um Gewicht zu verlieren und die kardiovaskuläre Fitness zu verbessern. Es wird diskutiert, ob das Barfußlaufen als natürliche Alternative zum traditionellen Laufen mit Sportschuhen bei Freizeitsportlern in Betracht gezogen werden kann.
- **Ziel der Studie** war die Untersuchung der Wirkung der Fußaufsatztechnik und der lokalen Muskelermüdung der Plantar- und Dorsalflexoren auf die plantare Druckverteilung sowie ausgewählte kinematische Merkmale beim Barfußlaufen auf dem Laufband in drei Geschwindigkeiten. An der Studie nahmen 26 freiwillige Vor- und Rückfußläufer vergleichbaren Alters und Körpermasse teil. Jede Gruppe absolvierte zwei Testabläufe mit einem zeitlichen Abstand von drei bis sieben Tagen. Die kinematische Datenerfassung erfolgte mit Hilfe eines dreidimensionalen Mess- und Analysesystems während des Laufens auf dem Laufband. Das Ermüdungsprotokoll umfasste einen isometrischen Maximalkrafttest und einen isokinetischen Ausdauertest. Zur Überprüfung der Unterschiede wurde eine zweifaktorielle Varianzanalyse mit Messwiederholung berechnet. Die Kraftwerte der beiden Läufergruppen wiesen signifikante Unterschiede bei den Plantarflexoren im Kraftausdauertest und beim Ermüdungsindex mit im Durchschnitt höheren Werten der Rückfußläufer sowohl für das linke als auch das rechte Bein auf.
- **Die Ergebnisse** der Kraftwerte überraschten, denn aufgrund des Vorfußaufsatzes beim regelmäßigen Laufen sollten die Plantarflexoren dieser Läufergruppe gut trainiert sein. Nach Ermüdung reduzierten sich die Druckmaxima unter den exponiert belasteten Fußzonen, d. h. unter dem Vorderfuß beim Vorfußaufsatz und unter der Ferse beim Rückfußaufsatz. Die beiden Läufergruppen differierten im Fußwinkel bei Foot on mit höheren Werten der Vorfußläufer. Der größere Fußwinkel der Vorfußläufer verbesserte die Schockabsorption und kann so das Verletzungsrisiko verringern. In einer weiteren Studie sollten gewohnheitsmäßige Barfußläufer ausgewählt werden.

SCHLÜSSELWÖRTER:
Ermüdung, Fußaufsatz, Kinematik, Maximalkrafttest, Ausdauertest

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CORRESPONDING ADDRESS:
Prof. Dr. Klaus Mattes
Institut für Bewegungswissenschaft
Arbeitsbereich Bewegungs- und Trainingswissenschaft
Mollerstraße 2, 20148 Hamburg
: klaus.mattes@uni-hamburg.de

Introduction

Running is a simple and inexpensive way to lose weight, offset stress or improve cardiovascular fitness (29). The number of endurance runners has increased in recent years and so have running-associated complaints (10, 27). For this reason, many studies have addressed the different foot strike patterns in running and concentrated on forefoot and rearfoot runners (6, 19). Numerous studies found a greater number of rearfoot runners in running with shoes, while preference was given to forefoot strike in barefoot running (32, 34). However, forefoot strikes arise not only as a consequence of a lack of shoe shock absorption, but are also seen at greater running speeds and are independent of the running surface and the individual adaptation (32). A biomechanical comparison of the foot strike ›

Table 1

Results of the strength test, mean ± standard deviation, also data of variance analysis, maximal isometric force (Mx), mean of the maximal force in the strength endurance test (M60), fatigue index (M60/Mx), test values of inter-subject effect (ZE) foot strike, significance level (p), N=26.

LEG	MUSCLE	PARAMETER	FOOT ON TECHNIQUE		ZE
			FOREFOOT	BACKFOOT	P
Left	Plantar flexors	M_x [Nm]	162±48	186±36	.167
		M_{60} [Nm]	52±22	97±25	. 001
		M_{60}/M_x	0.33±0.15	0.52±0.08	.001
	Dorsal flexors	M_x [Nm]	33±14	40.7±5.9	.092
		M_{60} [Nm]	14.8±5.7	17.3±4.8	.238
		M_{60}/M_x	0.48±0.14	0.43±0.09	.259
Right	Plantar flexors	M_x [Nm]	148±27	144±32	.719
		M_{60} [Nm]	50±20	74±21	.007
		M_{60}/M_x	0.34±0.13	0.53±0.13	.001
	Dorsal flexors	M_x [Nm]	34.3±12.7	29.4±9.2	.281
		M_{60} [Nm]	18.1±13	12.7±3.7	.180
		M_{60}/M_x	0.54±0.29	0.45±0.12	.337

technique showed a greater initial passive peak of the ground reaction forces in rearfoot runners than in forefoot and midfoot runners (6). More recent studies found that striking with the forefoot results in a lower ground reaction force (3, 30, 32). Moreover, forefoot running leads to a reduced or lacking first passive force peak, but instead produces an elevated second active force peak (31, 32).

In another study, however, Laughton et al. (31) found no difference between forefoot and rearfoot runners in contact and ground reaction force. There are differences in the strike pattern especially in middle and long-distance runners. In this, rearfoot runners make initial ground contact with the heel and mid-foot runners with the heel and ball of the foot. Forefoot runners, on the other hand, make ground contact with the toes and ball of the foot (31). The first study by Hasegawa et al. (21), which reported on different foot strike techniques in long-distance runners, identified 75-99 % rearfoot runners, 0-24 % mid-foot runners and only 0-2 % forefoot runners (21). With respect to the plantar pressure distribution after fatiguing runs over various distances (10-km to marathon or 30-min-runs, respectively), various studies have chosen different foci and produced correspondingly various results.

Some studies address forefoot load and could demonstrate an increase after running (2, 45). Other examined the effect of fatigue due to running on the pressure distribution under the heel, the mid-foot and the toes. The results revealed both a significant increase under the heel (44, 45) and a decrease in peak pressure (2, 14). In addition, an increase could be observed under the metatarsis (2, 35, 44, 45) and under the medial mid-foot (44, 45). Another study, on the other hand, showed a decrease under the lateral, resp. medial mid-foot (2). With respect to the toes, a significant reduction was measured in pressure values (14, 35, 45). Two other studies, however, found no differences (2, 44). Studies of step frequency and stride length confirmed an influence of fatigue on both parameters. There are, however, slightly inconsistent findings concerning step frequency. On the one hand, results indicate a slight (23) or no change (1). On the other hand, a reduction in step frequency could be demonstrated. Moreover, this study found an increase in the stride length (14). In addition to fatigue, running on a treadmill presents another factor influencing the step frequency (14). Compared to running on natural ground, a shorter stride length and greater step frequency could be observed (31). Due to this influence, results obtained on a treadmill are subject to controversial discussion (14). Various authors still, however, consider this as representative for running tests (13, 37). With respect to kinematics, the ankle angle and knee angle of the runners were examined after fatigue.

Kellis and Liassou (26) determined that the angle of the knee and ankle at Foot on exert an influence on joint stability and play an important role at Foot off (26). Brüggemann et al. (4) observed an increase in the rearfoot angle at Foot on and a later reaching of its maximal value after fatigue. Christina et al. (7) found a decrease in the ankle angle after local muscle fatigue of the dorsal flexors, whereas fatigue of the plantar flexors may contribute to a marked increase in the angle of the ankle. The fatigue of ankle musculature due to movement results in a decrease in the dorsal flexor angle during the first landing phase (26). A reduced angle of the dorsal flexors means that a greater proportion of the heel touches the ground on landing, enabling greater absorption of the landing force (15). The kinematic adaptation of the joint includes an increased knee flexor angle (12) a reduced in the ankle on landing (7).

Despite numerous studies, there are no unequivocal findings which definitively state how the foot strike changes due to muscular fatigue. In studies with running fatigue, differentiation between which kinematic or kinetic changes are the direct result of local muscle fatigue and varied speeds cannot be made. One possibility for targeted analysis is the recording of standardized local fatigue protocols of the musculature of the knee and/or ankle prior to the run. Since the dorsal and plantar flexors in the foot are active in between 50-85 % of the running cycle (25), they may tire greatly. In addition to fatigue, the running speed also affects the foot strike technique. Among fast half-marathon runners, the number of rearfoot runners decreased and the number of midfoot runners increased (21). Keller et al. (24) and Nigg et al. (36) found that rearfoot running is selected at a running speed of 1-5 m/s (≙3.6-18 km/h). At a speed greater than 5-6 m/s (≙18-21.6 km/h), the midfoot or forefoot technique is preferred (24, 36).

Table 2

Results of the running test, mean ± standard deviation, also data of the variance analysis, stride frequency (f), stride length (SL), pressure maximum under the heel (pxh), the metatarsus (pxm) and the forefoot (pxf), Test values of the inter-subject effect (ZE) foot strike and the main effects (HE) running speed (Geschw.) and fatigue, significance level (p) and partial eta squared (ηp²). N=26. B=Baseline; F=Fatigue.

LEG	PARA-METER	TEST	FOOT ON TECHNIQUE						ZE		HE			
			FOREFOOT			REARFOOT			FOOT ON		SPEED		FATIGUE	
			V11 KM/H	V13 KM/H	V15 KM/H	V11 KM/H	V13 KM/H	V15 KM/H	P	ηP²	P	ηP²	P	ηP²
Left	f [Hz]	B	180±12.1	189±16.2	199±18	176±10.9	185±13.2	194±14.6	.414	.028	.001	.823	.053	.147
		F	182±17.4	192±19.7	202±23	178±10.9	185±11.4	196±16.2						
	s_L [cm]	B	102±7.1	115±9.7	126±10.6	104±6.6	117±8.5	129±9.8	.458	.023	.001	.950	.033	.176
		F	101±8.4	114±10.5	125±13	103±6.3	117±7	128±10.7						
	p_{xh} [N/cm²]	B	9.2±3	9.7±3.8	9±4.2	54.4±10.5	57.9±10.5	62.8±10.2	.001	.919	.001	.496	.300	.182
		F	8±4.2	8.6±4.7	8.7±2	51.8±11.5	56.4±10.5	60.3±12.7						
	p_{xm} [N/cm²]	B	36.3±14.8	36.9±15	36±16.7	22.3±6.1	21.9±5.3	22.4±5.5	.003	.313	0.84	.007	0.654	.009
		F	33.6±12	35.4±11.2	35±10.3	23.2±5.3	22±5.4	23.9±5.6						
	p_{xf} [N/cm²]	B	46.1±9.2	47.5±10.1	50.7±11.4	42.6±10.2	45.4±11.5	48.7±12	.472	.022	.001	.679	.004	.302
		F	44.9±9.2	46.2±10.1	48.3±10.8	39.4±9.4	43.1±9.7	47.1±10.9						
Right	f [Hz]	B	180±12.1	189±16.2	199±18	176±10.9	185±13.2	194±14.6	.410	.028	.001	.679	.174	.086
		F	181±16.1	193±22.6	202±24.7	177±11.8	185±13.8	196±15.5						
	s_L [cm]	B	102±6.4	115±9.3	125±11.4	104±7	117±8.7	129±10.3	.383	.032	.001	.936	.359	.035
		F	102±8.5	113±11.8	124±13.9	104±7.3	118±8.7	128±10.3						
	p_{xh} [N/cm²]	B	8.1±4.4	7.6±3.1	11.2±6.2	53.1±8.3	55.3±9.2	60.2±10.7	.001	.940	.001	.559	.796	.003
		F	8±5.4	7.7±4.6	7.6±2	50.4±10.2	55±10.1	58.8±11.2						
	p_{xm} [N/cm²]	B	34.4±12	34.5±12.6	36±14	22.3±5	21.8±4.6	23.1±6.2	.005	.283	.199	.065	.134	.091
		F	33.2±13.4	33.4±12.5	33±13.5	23±5.8	20.5±4.1	22.8±6.3						
	p_{xf} [N/cm²]	B	46.3±8	48.2±8	49.9±7.8	38.9±5.6	41±6.6	44.8±7.3	.021	0.203	.001	.613	.001	.416
		F	43±7.1	45.7±7	48.6±8	36.3±5.5	39.4±6.3	42.2±7.5						

Query and Objective

A preliminary literature search revealed that no study to date has examined the effects of local muscle fatigue of the plantar and dorsal flexors on the plantar pressure distribution in connection with the foot and knee angles during running on a treadmill at three speeds. The foot strike technique has also received little attention in studies to date. It is expected that the plantar pressure distribution under the foot and the kinematic characteristics differ in dependency on the foot strike technique and local muscle fatigue. Compared to rearfoot runners, forefoot runners will probably have lower plantar pressure maxima under the heel and higher pressure maxima under the forefoot.

Material and Methods

Study Design and Sample

The study was designed as a cross-sectional study of two voluntary groups of runners of comparable age and body mass but with different foot strike techniques (forefoot vs. rearfoot) (N=14; Age=27.8 (3.6) yrs; Body weight=81 (7.8) kg; Height=182.1 (5.1) cm and a rearfoot group (N=12; Age=27.7 (3.9) yrs; Body weight=80 (8.3) kg; Height=180.9 (5.1) cm). On average, the subjects performed two to three running sessions per week (ca. 21-25 km per week at a speed of 9 to 15 km/h). All subjects were healthy at the time of measurement and had no current orthopedic findings. Prior to starting the study, an Ethics Vote was obtained from the Medical Council Hamburg.

Study Procedure

The test procedure consisted of a total of three sessions. At the start, there was a special meeting to acquaint the study participants with the tests and the measuring equipment. Then, within three to seven days, the first test run was performed and a second test after an interval of another three to seven days. Only the results of Test 2 are presented, since there were no significant differences between the results of Tests 1 and 2. On the day of the test, the subjects performed a 10-minute run on the treadmill at a speed of 9 km/h as warm-up and to get used to the treadmill. The subjects then began with the first test procedure (Baseline), in which they ran at pre-determined speeds (11, 13, 15 km/h) on the treadmill without muscle fatigue. Then the participants performed the fatigue protocol, which consisted of an isometric maximum force test and an isokinetic endurance test. The tests were performed in randomized sequence for the left and right leg. The treadmill test followed the force test. This in turn was followed by the fatigue protocol of the second leg, followed by the treadmill test.

Test Description

Acclimatization included practice running on the treadmill for 15 minutes and a sample performance of the force tests. In this, the foot strike technique was noted, the positioning data for the force test registered and the settings for the force measuring equipment stored. As acclimatization and warm-up of the target musculature, a submaximal contraction prior to ›

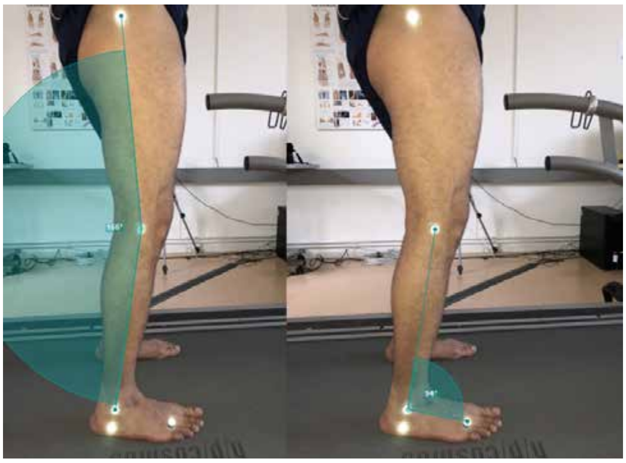

Figure 1
Joint angle determination. The calculation includes the joint movement of the entire tarsus, metatarsus and distal phalanx.

the maximal force test was set in the equipment. Information from the manufacturer was used for positioning. The subject was seated. The slope of the backrest was 70°. The upper thigh was fixed and the foot secured to the plate with a belt. The angle in the knee and ankle was 90° in both joints. The axis of rotation of the upper ankle joint (thickest point of the Malleolus lateralis to the medial Malleolus) and the dynamometer were adjusted using a laser. The isometric maximal force test consisted of two sets with maximal contraction. The force was to slope up to a maximum after 2-3 s. The set rest interval was 3 minutes. The isokinetic endurance test comprised 10 sets á 6 repeats of concentric contractions of the plantar and dorsal flexors at an angular velocity of 60°/s. The rest interval was 10 s. The extent of movement was set at maximal 55° for plantar flexion and 25° for dorsal flexion. The test started with the plantar flexion.

Measuring Equipment

The isometric maximal force test and the isokinetic endurance test of plantar and dorsal flexion in the ankle was made with the Isomed 2000 Dynamometer (D&R Ferst/GmbH, Hemau, Germany) using the adapter developed by the manufacturer. The precision of measurement at a measuring frequency of 200 Hz was 0.25 % at torque. The unit complied with medicine-technical safety standards. Recording the preparation of the test results was made using the manufacturer's computer software (IsoMed analyze 2008). Aus dem isometric maximal force test, the higher maximum torque (Mx) of a set was recorded as the test value. For the isokinetic endurance test, the mean of the torque maxima was determined from all 60 contractions (M60). In a test-retest comparison, a high relative reproducibility with ICC (3.1) values on average greater than 0.9 could be determined for the fatigue protocol of the plantar and dorsal flexors (M60). The calculated fatigue index (Mx/M60) for the plantar flexors had high (0.92) and for the dorsal flexors moderate relative reproducibility (0.88) (33).

The running analysis was made immediately after the fatigue protocol on the treadmill h/p/cosmos quasar (h/p/cosmos sports & zebris medical Gmbh, Germany), which was equipped with a pressure distribution measurement system (FDM-THQ-M from Firma zebris medical GmbH (Germany)). The treadmill had a damped and non-skid running area of 170 x 65 cm and was controlled by the software h/p/ cosmos para-control. The measuring system consisted of a force distribution measuring platform (Force Distribution Plattform – FDM-T) with capacitive pressure sensors (Range 1 to 120 N/cm2, Precision ± 5 %). The 10240 sensors integrated in the running surface were arranged in a matrix over an area of 135.5 x 54.1 cm (1.4 sensors/cm2) and had a measuring frequency of 200 Hz.

The kinematic data recording was made using the three-dimensional measuring and analysis system VICON (8 VICON MXT10 Camera System, from Oxford Metrics Ltd, Oxford, UK). This system consisted of eight infrared Type T10 cameras. The T10 camera has a resolution of 1 megapixel and records a 10-Bit grey-shade image with 1120 x 896 pixel. The cameras emitted infrared light, which reflected the markers attached to the body (Trochanter Major left and right, lateral condyle of the knee left and right, lateral side of the ankle joint left and right, heel posterior left and right, small toe left and right). The room was calibrated following instructions from the manufacturer. The recording frequency was 200 Hz with a measuring precision of ±2mm. For measurement, 12 retro-reflecting markers (14 mm in diameter) were placed in accordance with the Plug-in-Gait-Model (Vicon, Oxford Metrics, UK) on anatomical landmarks (pelvis and both lower extremities). The sagittal joint angles were calculated from the coordinates of the body points. The knee joint angle was determined by the coordinate points of the Trochanter Major lateral with condyle of the knee and condyle of the knee with the lateral side of the ankle (Fig.1). The ankle joint angle was determined from the coordinate points lateral condyle of the knee with the lateral side of the ankle and lateral side of the ankle with the small toe.

Data recording and processing was made with Vicon Nexus 1.7.1 (VICON, Oxford Metrics, UK). Ground contact (Foot landing) was defined by the changes in vertical velocity of the distal heel marker from negative to positive. At least 50 gait cycles were analyzed (25 per leg) and the tests were standardized to 100 % of the gait cycle. The Vicon Motion Capture System is a reliable method for analysis of the kinematics of a running process. The Zebris Software (Zebris Medical GmbH, Germany) was used to calculate the step frequency and stride length for each foot. The stride length was defined as the anterior-posterior distance between the first foot landing of two steps (left and right foot). The step frequency was measured as the number of steps during a 60-s interval.

Mathematical-Statistical Evaluation

The fatigue index was formed as the quotient of torques from the isometric maximal force test (Mx) divided by the mean of the torque maxima (M60) from the isokinetic endurance test, using the equation: Fatigue index= Mx/M60 for plantar and dorsal flexion. High local muscle fatigue is represented by a small coefficient. The statistical evaluation comprised description with arithmetic mean and standard deviation. Data were tested for normal distribution and variance homogeneity using the Kolmogorov-Smirnov and Levene tests. Differences were calculated using a multifactorial analysis of variance with repeated measures according to the general linear model and the intra-subject factors Leg (left and right), Test (Baseline, Fatigue left and fatigue right) and Speed (11, 13, 15 km/h) as well as the inter-subject factor Foot strike (forefoot versus rearfoot). The LSD (Least Significant Difference) was used to examine paired mean differences. The partial eta-squared (ηp^2) was taken as the parameter of effect strengths with the classification: small effect (ηp^2=0.08), moderate effect (ηp^2=0.20) and great effect (ηp^2=0.32) (9). The significance level was $p \leq 0.05$ and applying the Bonferoni correction, p-values were adjusted by multiplication with the number of tests (43). Statistical calculations were made using IBM SPSS 21.0 (Chicago, IL, USA).

Table 3

Results of the kinematic characteristics, mean ± standard deviation, also data of the variance analysis, knee angle Foot off (Kwof), knee angle Foot on (Kwon), foot angle Foot off (Fwof) and foot angle Foot on (Fwon), test values of inter-subject effect (ZE) foot strike and the main effects (HE) running speed (Geschw.) and fatigue, significance level (p) and partial eta squared (ηp^2). N=26. B=Baseline; F=Fatigue.

LEG	PARA-METER	TEST	FOOTSTRIKE						ZE		HE			
			FOREFOOT			REARFOOT			FOOT ON		SPEED		FATIGUE	
			V11 KM/H	V13 KM/H	V15 KM/H	V11 KM/H	V13 KM/H	V15 KM/H	P	ηP^2	P	ηP^2	P	ηP^2
Left	Kwof [°]	B	158.2±4.0	157.6±5.6	156.1±5.2	159.8±6	159.0±6.2	158.7±5.4	.349	.037	.001	.250	.213	.064
		F	157.6±5.2	156.5±6.2	154.7±6.0	159.3±5.9	158.3±6.8	156.7±5.7						
	Kwon [°]	B	163.0±5.7	163.8±6.0	162.2±6.6	164.8±6.1	164.9±5.3	163.3±4.9	.644	.009	.035	.131	.07	.268
		F	162.6±5.5	161.2±5.5	162.1±4.5	163.4±4.6	162.1±4.4	161.8±5.1						
	Fwof [°]	B	119.4±6.6	119.3±6.8	119.2±6.9	116.9±5.5	117.1±6.5	117.5±7.1	.611	.011	.604	.021	.096	.111
		F	117.6±5.8	118.1±6.7	116.2±8.8	117.5±6.4	117.3±8.0	115.7±10.9						
	Fwon [°]	B	125.2±5.9	125.5±6.4	123.1±6.4	97.6±5.0	97.8±4.1	98.6±4.5	.001	.858	.417	.036	.148	.085
		F	123.6±6.0	122.7±6.5	121.6±6.8	98.1±5.8	97.8±5.3	99.2±5.3						
Right	Kwof [°]	B	156.4±4.7	155.8±5.6	155.6±5.1	157.9±5.2	157.8±4.8	157.4±5.4	.411	.028	.005	.200	.104	.107
		F	156.4±5.9	155.1±6.2	153.9±6.4	157.5±5.2	157.2±5.5	155.2±5.0						
	Kwon [°]	B	161.2±5.6	161.6±5.8	160.9±6.2	160.5±3.7	160.1±4.7	159.2±4.8	.796	.003	.005	.196	.215	.063
		F	160.9±5.4	159.6±4.9	158.7±4.9	160.8±5.2	160.3±5.3	159.1±4.7						
	Fwof [°]	B	117.6±6.9	118.5±8.1	117.4±7.6	116.9±8.2	116.5±8.2	117.6±9.7	.950	.000	.573	.023	.001	.412
		F	114.7±8.4	114.2±9.3	112.2±10.1	114.4±8.0	114.1±10.1	113.8±8.0						
	Fwon [°]	B	124.6±3.0	124.4±3.4	123.4±5.3	98.2±3.4	97.8±3.6	98.5±4.8	.001	.890	.081	.099	.001	.395
		F	119.6±4.2	118.9±5.1	116.3±6.2	99.2±5.8	98.9±5.5	99.6±4.8						

Results

Force Test

The force values in both running groups differed significantly in the plantar flexors in the strength endurance test and in the fatigue index with higher values on average for the rearfoot runners in both the left and the right leg (Tab. 1). The isometric maximal force and isokinetic strength endurance of the plantar flexors presented higher values on the left than the right in both running groups, but the differences were not significant (Tab. 1). No significant differences were found for the dorsal flexors in the force tests.

Treadmill Test and Pressure Distribution

There were no significant differences between the groups in step frequency or stride length. By contrast, the plantar pressure distribution differed under the three foot zones. The rearfoot runners were found to have a greater pressure maximum under the heel and lower maxima under the midfoot or forefoot (Tab. 2). After the local fatigue protocol, the mean pressure maxima under the forefoot were reduced left and right in both groups. The step frequency and stride length increased in both groups with the running speed, as did the pressure maxima under the forefoot. The pressure maximum under the heel showed an interaction foot strike*running speed (left: $F\ (2.24) = 23.0; p=0.001; \eta p^2=0.47$; right: $F\ (2.24) = 11.9; p<0.001; \eta p^2=0.32$). The pressure maxima under the heel increased in rearfoot runners when running speed was increased. By contrast, the pressure maximum under the heel of forefoot runners remained unchanged (Tab. 2).

Treadmill Test and Kinematic Data

The two runner groups differed in the foot angle at Foot on with higher values in the forefoot runners. Moreover, at Foot on, there was interaction fatigue*foot strike technique (left: $F(2.24)=4.6; p=0.042; \eta p^2=0.17$; right: $F(2.24)=32.7; p<0.001; \eta p^2=0.58$). The forefoot runners decreased the foot angle under fatigue. By contrast, the foot angle among rearfoot runners remained unchanged. After the local fatigue protocol, the foot angle decreased at Foot off, whereby the values of the right leg exceeded the significance level. The knee angle at Foot on also showed lower values after the fatigue protocol, but only the data of the left leg differed significantly. The knee angle at Foot off and Foot on decreased at greater speed in both groups (Tab. 3).

Discussion

The objective of this study was to examine the effect of the foot strike technique and local muscle fatigue of the plantar and dorsal flexors on plantar pressure distribution and the kinematic characteristics in barefoot running on the treadmill at three speeds. It was assumed that the plantar pressure distribution under the foot and the kinematic characteristics differ in dependence on the foot strike technique and local muscle fatigue. The force values in the two runner groups showed significant differences in the plantar flexors in the strength endurance test and in the fatigue index, with higher values among rearfoot runners. This result is surprising, since the plantar flexors in this group should be well-trained due to the forefoot strike in regular running. However, possibly not all of the subjects were habitually forefoot runners. The short running time in the test of 1 minute each and running on the treadmill may have provoked a forefoot strike in these subjects. The unaccustomed foot strike then already resulted in fatigue of the plantar flexors during the 10-minute warm-up, so that lower values were determined in the force test for the forefoot runners.

The isometric maximal force and isokinetic strength endurance of the plantar flexors in both groups showed higher values left than right, but there were no significant differences. ›

This finding emphasizes the performance dominance of the left ankle bone or support leg (42). The different function as support and active leg was not reflected in the dorsal flexors in differences in performance, since no significant differences were observed in the force test for this muscle group.

Neither runner group showed significant differences in the step frequency and stride length. Contrary to the step frequency and stride length, the plantar pressure distribution under the three foot zones differed. Comparing the two groups, a lower pressure maximum under the heel and a greater angle of the foot on landing could be observed in the forefoot runners. The rearfoot runners showed a higher pressure maximum under the heel and a smaller foot angle on landing. These results agree with those of other studies (17, 20, 32, 41). Various authors assume that forefoot runners have a lower risk of injury thanks to the reduced load under the heel (10, 17, 32). Other authors, however, assume that the connection between foot strike technique and the risk of injury has not been proven (28, 38).

Based on the foot strike technique and the fatigue protocol, the mean plantar pressure values under the heel, midfoot and forefoot differed between the two groups of runners. In studies which include a running fatigue protocol, however, this connection has not yet been definitively proven, since there are contradictory findings on the effect of fatigue on plantar pressure distribution. Some studies determined a decrease of the pressure value under the heel (2, 14), while another study reported on a significant increase (44). For the pressure values under the toes, both a significant reduction (14) and no differences have been reported (2, 44). The study by Nagel et al. (35) also permits the conclusion that there is only a reduction of pressure under the toes after a marathon race (35). It is thus not surprising that significant changes in plantar pressure distribution are apparent in local muscle fatigue, but not in fatigue caused by running. The question therefore arises of why the pressure distribution increases or decreases. One explanation could be that tired leg muscles cause the joint to become stiff, increasing the pressure distribution. Pre-activation of the stabilizing musculature can also lead to an increase in pressure distribution. This connection between the pre-activation of the M. gastrocnemius and the pressure distribution in runners has been demonstrated in various studies (19, 39, 40).

With respect to the knee angle at Foot on, lower values were measured after the fatigue protocol, but only the data of the left leg differed significantly, since in this study, only the ankle musculature was fatigued. Kellis and Liassou (26) found increased knee bending both at Foot on and at Foot off. This increase knee bending indicates that the runners prefer knee bending to absorb the pressure on landing (26). This adaptation can reduce the potential risk of injury. Several studies have shown that forefoot runners activate the M. gastrocnemius earlier than rearfoot runners to stiffen the ankle joint (19). The foot arch plays an important role in shock absorption. Not only tensing of the foot, but also bending the knee may contribute to shock absorption (18).

In the foot angle, there was interaction fatigue*foot strike technique at Foot on, whereby forefoot runners reduced the foot angle and thus under fatigue, made more contact with the middle foot. The forefoot strike technique was found to be less stable than the rearfoot strike technique. This finding must, however, be viewed in relationship with the more greatly fatigued plantar flexors in the forefoot runners.

Finally, the influence of speed on the kinematics and pressure distribution was examined in the runners. Several studies show that rearfoot running is suitable for long-distance running at moderate speed, while forefoot running is preferred for short distance runs or sprints at greater speed (24, 36). The running speed influences the foot strike technique (16) and the peak plantar pressure values. The findings confirm that a high running speed leads to elevated peak pressure values (5, 8). These results agree with those reported by Chuckpaiwong et al. (8) and Ho et al. (22). Ho et al. (22) found that a greater pressure distribution can be measured both under the forefoot and under the rearfoot if the speed is increased from 1.5 m/s to 2.5 m/s (≙ from 5.4 to 9 km/h).

The pressure maximum under the heel shows interaction foot strike technique*running speed with greater peak pressure values in the rearfoot runners. This enables a conclusion for the rearfoot runners that increased running speed increases the landing pressure under the heel and thus increases the demands for amortization of the vertical ground reaction force.

Different running speeds also changed the angle of the knee. In both subject groups, the knee angle of the left and right leg at Foot off and Foot on became smaller with increasing running speed. A greater knee bending and shortened stride length on increasing the speed has already been proven in forefoot runners (32, 40). In another study, a shorter stride length and additionally an increase step frequency was found in forefoot runners (11). A greater step frequency shortens the ground contact time and influences the plantar pressure distribution (41).

In interpreting the findings, there are some limitations to be noted. Running without shoes is a limitation, since this influences the foot strike technique and tends to provoke a forefoot strike. Moreover, some of the subjects classified during the barefoot run might usually prefer the rearfoot strike in running with shoes. The participants in the study were mostly leisure runners, who usually run in shoes. Another point is that no differentiation in pressure distribution was made between the medial and lateral part of the foot, so no conclusion can be drawn about possible changes in pronation and supination of the foot in running barefoot. The 2D kinematic analysis from the sagittal perspective was made with a reduced marker model that focused on the lower extremities. The movement of the upper body and the upper extremities was not explicitly taken into account .

Conclusion

In this study, the kinematics of the lower extremities of healthy runners were examined before and after local muscle fatigue at three running speeds. The rearfoot runners showed higher pressure maxima under the heel, which increased further with increasing running speed. By contrast, the forefoot runners showed a greater foot angle than the rearfoot runners, which improved shock absorption and, at the same time, may reduce the risk of injury. The forefoot strike technique of the participants was, however, less stable, the foot angle decreased under fatigue and the foot strike was made more with the middle foot. With increased speed, the knee angle decreased in both runner groups and thus enabled less impact on landing. Further studies are needed to examine the comparison between barefoot runners and shod runners. In these, fatigue protocols should be performed for the flexors and extensors in the knee joint, since the knee angles at Foot on and Foot off were identical in the two groups. For better study results, runners accustomed to barefoot running should be selected. Special strength training programs are needed to strengthen the ankle joint musculature of the runners and thus prevent injuries.

Conflict of Interest
The authors have no conflict of interest.

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