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# INFLUENCE OF LOCAL FATIGUE OF THE PLANTAR FLEXORS AND DORSIFLEXORS ON PLANTAR PRESSURE DURING RUNNING AT THREE RUNNING SPEEDS

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## ABSTRACT

Muscle fatigue can affect the absorption of impact forces during running which can increase the risk for running injuries. Conflicting results exist about the change of plantar pressure (PP) maxima. The study aimed to examine the influence of a standardised fatigue protocol on PP distribution of rearfoot strike runners considering possible test effects and leg asymmetries. 30 male runners volunteered in a laboratory test with repeated-measures after familiarization on the treadmill (11-15 km/h). Isokinetic fatigue protocol included ten sets of six concentric contractions (10 s set break, ω=60°/s). The first force maximum and the peak PP for three foot-regions were tested with an analysis of variance. The plantar flexors (PF) decreased to 52%-62% and the dorsiflexors (DF) to 35-41% of the isometric maximum strength. Maximum of PP under the heel and forefoot decreased to 8.3% and 5.9%, respectively. As hypothesized, the fatigue protocol reduced the performance of DF more intensely which resulted in a muscle imbalance indicating an increased injury-risk. Because of their greater muscle mass and function, PF are more fatigue-resistant during running. The reductions in pressure values may indicate a possible protective strategy to counteract injuries during muscle fatigue. For injury prevention, a strength training of the foot muscles with focus on DF is recommended in addition to running.

**Keywords:** Leg asymmetry; muscular imbalance; Isokinetic; Retest; Treadmill

## INTRODUCTION

During running, the foot is subjected 2 to 3 times the runner's body mass. The muscles of the lower extremities have to provide adequate shock absorption to avoid an over or incorrect loading of the passive musculoskeletal system caused by these forces, e.g. through concentric contraction of the plantar flexors (PF) (26). If the muscles become fatigued, a sufficient absorption of the impact forces is no longer guaranteed, the passive musculoskeletal system is affected and the risk for running injuries increases. This relationship between muscular fatigue and injury risk has already been shown in several studies (2, 5, 8, 13, 28). However, despite numerous studies, it is still unclear how foot loading changes as a result of fatigue. To provide appropriate injury-prophylactic training guidance, the details of changes in foot loading caused by fatigue need to be known. In particular, runners with a history of injuries in the lower extremities have an increased risk for re-injury (19, 20, 39). In this respect, ideally case, running injuries should be prevented before they occur.

Although the number of publications investigating the influence of muscle fatigue on plantar pressure (PP) distribution and increased ground reaction force during running has considerably increased since 2006, the effect of fatigue was not clarified because of the diversity in results. In a meta-analysis on the change of ground reaction force following fatigue, Zadpoor and Nikooyan (44) showed that most studies have focused on the active peak vertical ground reaction force because it reflects the muscular reaction of the collision with the ground. On this, two theories dominate the debate. On the one hand, it is assumed that the ability for an adequate shock absorption decreases with fatigue, whereupon the ground reaction force increases to counteract this effect. On the other hand, a reduction of the ground reaction force is supposed, because the human body has a protective strategy that provokes this reaction to prevent injuries (44).

The meta-analysis included eight studies that determined the active peak of the ground reaction force with force plates before and post fatigue caused by running. Three studies showed a significant decrease (12, 27, 31), while four studies only found minor non-significant changes (8, 11, 36). Another study examined the ground reaction force during running after local muscle fatigue of dorsiflexors (DF) and -invertors of the foot (6). It was found that DF increased non-significantly and the inversion yielded to reduced ground reaction force.

Other studies on ground reaction forces showed also contrary findings. After extreme fatigue following a 24-hours-treadmill-run or an ultra-mountain marathon, Morin, Samozino and Millet17 or Morin, Tomazin, Edouard and Millet18 found significantly decreased ground reaction force of 2.24-times to 2.14-times or of 2.32-times to 2.17-times of the body mass. Quammen et al. (30) compared two different fatigue protocols, where strength tests and sprint as well as the strength tests and a 30-min treadmill run led to a non-significant increase of the ground reaction force.

Contrary findings also exist for the PP-distribution after fatigued-running over different distances (10 km up to marathon or 30-min-run). Some studies found an increase of forefoot loading after fatigued running (3, 42, 43) as well as after local fatigue of PF and DF (29). Inconsistencies were presented for the effect of fatigue caused by running on PP-distribution under the rear-, mid- and forefoot. The results for the rearfoot (RF) showed both significantly increased pressure distribution (41, 42) as well as decreased pressure peaks (1, 3). Some studies found increased values under the metatarsals (3, 25, 41, 42, 43) and under the medial midfoot (41, 42). Other studies found a decrease under the lateral or rather medial midfoot (1, 3). The pressure values under the toes significantly decreased

(10, 25, 29, 42, 43). However, two studies found no differences (3, 41).

Fatigue affects the cadence and step-length during running: the cadence decreases and step-length increases (10, 11) but also minor changes (16) and no changes in cadence (1) were observed. Moreover, treadmill running is characterized by a change in cadence (10, 33, 35, 40). At moderate running speed on the treadmill, reduced step-length and increased cadence were observed compared to natural ground-running (15). Because of the influence of the treadmill on the running movement, the results were discussed controversially (10) Nevertheless, they were accepted by different authors as representative for running investigation (9, 33, 35).

In general, the strength in the two legs is not the same; the jumping leg, in particular, is stronger than the kicking leg and achieves longer distances in jump tests compared to the preferred leg which is used e.g. for kicking a ball. Therefore, the differences in muscle strength are used to classify the legs into the dominant-(jumping)-leg and the preferred (kicking) leg (37). Only few studies exist that describe leg asymmetries during running with biomechanical analysis where no significant differences between the dominant and non-dominant-leg in kinematics of the lower extremities and ground reaction force were found. Neither before nor post fatigue (4, 14).

Controversial results exist for the influence of fatigue on PP-distribution during running for methodological reasons as the studies used different fatigue protocols and foot regions. Moreover, many studies often failed to consider the foot strike patterns, leg dominance, different running speeds and/or repeated measurements. Most studies used exhaustive running (10, 44) without distinguishing which changes demonstrated a direct result of local muscle fatigue. Electromyographic studies of DF and PF of the foot showed that the flexor muscles were active between 50% and 85% of the running cycle and thus, can strongly fatigue (17, 32). It was found that muscular imbalance appeared during running with progressive fatigue because the activity of PF remained constant during the activity whereas that of DF decreased (22).

Aim of the study was to examine the influence of a standard fatigue protocol of PF and DF on PP-distribution under three foot regions of rear foot strikers (RFS) during running at three different speeds during which possible test effects and leg asymmetries as confounding variables were taken into account. It was assumed hypothetically that a local fatigue protocol leads to different reduced muscle efficiency of PF and DF and, that during subsequent running at different speeds reflects comparable changes of PP-distribution under the foot.

## METHODS

### *Study Design*

PP-distribution under the left and right foot before and post local muscle fatigue of PF and DF of the foot was examined in a laboratory study at three different speeds of RFS barefoot on a treadmill. A repeated measures (pre-post design) ANOVA was used whereby the three factors were differentiated in test 1 and 2 (factor: test), left and right leg (factor leg) and standardized protocol, respectively without fatigue (factor: fatigue). Running speed varied between 11, 13 and 15 km/h. The differences in force curves under the feet are used to control for the foot strike pattern and to classify individuals as RFS. Participants were included in the study only when a first passive force maximum appeared.

### *Participants*

Thirty male recreational and athletic runners (body height = 181.1 ± 5.0 cm, body mass = 79.3 ± 9.1 kg, age = 26.9 ± 4.0 years) who ran two to three times per week participated in the study. All runners were healthy, without cardiac and orthopedic restrictions. Participation in the study was voluntary, with participant approval obtained according to the criteria of the Declaration of Helsinki. Before testing, an approval was obtained from the ethics committee of the medical association in Hamburg.

### *Procedures*

Using a test–retest design, each participant completed one training session as well as a pre- and post-test evaluation by the same examiner. During the training session, the participants were familiarized with running on the treadmill, the measuring devices and the testing protocol. The participants' positioning for the strength tests was recorded and the foot strike patterns determined. The post-test evaluation was repeated within 3-7 days after the pre-test evaluation. The treadmill test always started after 10 min of warming-up with increasing running speed up to 15 km/h without pre-exhaustion. This was followed by the standard fatigue protocol for the first leg (strength test) and the running analysis after pre-exhaustion of the same leg. Afterwards, the strength tests as well as the running analysis after pre-exhaustion were conducted for the second leg. Appearance of pre-exhaustion of the leg (left versus right) as well as the running speeds was realized in randomized order.

The running analysis followed immediately after the fatigue protocol on the treadmill. Participants ran only wearing socks to eliminate the influence of shoes. After an adaptation phase for each running speed, the measuring system recorded running cycles for 30 sec. The trained runners completed the running speeds of 11, 13 and 15 km/h - also after local muscle fatigue - without complications.

### *Measuring instruments and variables*

The treadmill (h/p/cosmos quasar – FDM THQ M of Zebris Medical GmbH co., Germany) has a soft, non-slip running surface of 170 x 65 cm and is controlled by the software h/p/cosmos para control. The measuring system consists of a force distribution platform (Force Distribution platform - FDM-T) with capacitive pressure sensors (measuring range 1 - 120 N/cm$^2$, accuracy ± 5%). The 10240 sensors are arranged in a matrix (135.5 x 54.1 cm) and are integrated in the treadmill (1.4 sensors/cm$^2$) with a measuring frequency of 200 Hz.

Reproducibility of the strength test was good to excellent.40 Relative reproducibility reached intra-class correlation coefficient (ICC) for PF or DF during the isometric maximum strength test of 0.96-0.99 or 0.90-0.98, with the fatigue protocol of 0.89-0.97 or 0.87-0.97 as well as with the fatigue index of 0.84-0.96 or 0.76-0.94. Absolute reproducibility was for PF or DF with the isometric maximum strength test 3.1 or 6.4%, with isokinetic fatigue protocol 6.2% or 10.7% as well as with the fatigue index 12.3% or 21.8%.

The degree of asymmetry between left and right foot was identified by the symmetry index (SI) (34) which was defined as:

$$\mathrm{SI} = \frac{(\mathrm{X_R} + \mathrm{X_L})}{0{,}5(\mathrm{X_R} - \mathrm{X_L})} \cdot 100\%$$

With XR for strength or pressure values of the right foot and XL for values of the left foot.

Data analysis was carried out with the treadmill software FDM T version 0.39 of zebris Medical GmbH (2009). By default, the step length, cadence as well as averaged PP maxima were calculated separately for the foot regions rear-, mid- and forefoot as well as the first passive strength maximum of the averaged maximum pressure values of running cycles of 30 s was calculated (Tab. 1 and 2).

***Statistical Analyses***

Data analysis included descriptive statistics (arithmetic mean and standard deviation). Influence of local muscle fatigue, test repetition, leg asymmetry as well as running speed on PP-distribution, cadence and step length while running was tested with a repeated-measures variance analyses (General linear model). Partial eta square ($\eta_p^2$) was used as effect size to determine the amount of solved variance in relation to the total variance. According to Cohen (1992) (7) the following classification was used: small effect, if $\eta_p^2 = 0.08$, medium effect, if $\eta_p^2 = 0.20$ and large effects, if $\eta_p^2 = 0.32$. The LSD-test (least significant difference) examined the significance of the pairwise comparisons. α-level was set at $p \leq 0.05$. Calculations were realized with IBM SPSS 20.0, (Chicago, IL, USA).

**Table 1.** Mean ± standard deviation of the running test, cadence and double step length. *N = 30*

| Test | Leg | Running speed [km/h] | Cadence [1/s] | | Double step length [cm] | |
|---|---|---|---|---|---|---|
| | | | T1 | T2 | T1 | T2 |
| Baseline | Left. right | 11 | 174.9 ± 10.6 | 173.8 ± 12.4 | 210 ± 13 | 211 ± 14 |
| Fatigue | Left | | 175.6 ± 11.6 | 174.8 ± 12.8 | 209 ± 13 | 210 ± 14 |
| | Right | | 176.6 ± 11 | 175 ± 13.3 | 208 ± 13 | 212 ± 20 |
| Baseline | Left. right | 13 | 182.4 ± 11.1 | 182.4 ± 13.7 | 238 ± 14 | 238 ± 17 |
| Fatigue | Left | | 183.7 ± 12.6 | 182.1 ± 13.2 | 236 ± 16 | 238 ± 16 |
| | Right | | 183.4 ± 12.7$^{a}$ | 181.6 ± 13.1 | 237 ± 16 | 239 ± 16 |
| Baseline | Left. right | 15 | 191.6 ± 13.1 | 191.5 ± 14.9 | 261 ± 18 | 261 ± 20 |
| Fatigue | Left | | 193.3 ± 15.8 | 191.6 ± 15.6 | 259 ± 20 | 261 ± 20 |
| | Right | | 191.7 ± 14.3 | 191 ± 15.6 | 261 ± 19 | 262 ± 20 |
| Main effect | | | Test | | Test | |
| Interaction | | | | | | |
| Between groups | | | Running speed | | Running speed | |

**Table 2.** Mean ± standard deviation of the running test, symmetry index (SI), tests of main effect (ME), tests of **i**nteraction (IA), tests of within-subjects effects (speed). *N = 30*

| Test | Speed [km/h] | Leg | First maximal force [N] | | Plantar pressure under the heel [N/cm$^2$] | | Plantar pressure under the midfoot [N/cm$^2$] | | Plantar pressure under the forefoot [N/cm$^2$] | | Step length [cm] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | T1 | T2 | T1 | T2 | T1 | T2 | T1 | T2 | T1 | T2 |
| Baseline | 11 | Left | 1526 ± 257 | 1521 ± 28[b] | 45.1 ± 12.4[b] | 46.9 ± 14.6[c] | 23.3 ± 5.8 | 23.3 ± 6.7 | 42 ± 8.8 | 42.9 ± 10[c] | 105 ± 6 | 106 ± 7 |
| | | Right | 1552 ± 265 | 1551 ± 290 | 42.1 ± 13.2 | 45.4 ± 14.8[c] | 22.7 ± 7.2 | 23.5 ± 6 | 42.9 ± 9[c] | 42.9 ± 7.5 | 105 ± 7 | 106 ± 7 |
| | | SI | 1.7 ± 5.2 | 2 ± 4.9 | -7.5 ± 20.2 | -3.8 ± 10.4 | -3.3 ± 18.5 | 1.3 ± 19.5 | 2.4 ± 20.2 | 1 ± 18.7 | -0.4 ± 2.7 | -0.2 ± 3.4 |
| Fatigue | | Left | 1506 ± 255 | 1515 ± 274 | 42.7 ± 13.3 | 44 ± 15.4[b] | 22.9 ± 4.9 | 24.2 ± 6.1 | 41.3 ± 9.4 | 41.3 ± 9.2 | 105 ± 7 | 105 ± 7 |
| | | Right | 1542 ± 271 | 1538 ± 288 | 41.1 ± 13.9 | 42.3 ± 15.5 | 23.6 ± 5.8 | 23.8 ± 6.5 | 40.7 ± 7.3 | 41.4 ± 7 | 104 ± 6 | 106 ± 10 |
| | | SI | 2.3 ± 7.4 | 1.4 ± 5.8 | -4.7 ± 15.3 | -6 ± 14.7 | 2.3 ± 20.1 | -2.3 ± 20.4 | -0.9 ± 20.5 | 1.2 ± 18.9 | -0.5 ± 3.5 | - 0.8 ± 5.1 |
| Baseline | 13 | Left | 1553 ± 251[b.c] | 1542 ± 272 | 49.1 ± 12 [b. c] | 50.6 ± 14.9 [b. c] | 24.4 ± 6.4 | 23.9 ± 6.9 | 44.7 ± 10 | 45.3 ± 10.4 | 119 ± 7 | 119 ± 9 |
| | | Right | 1599 ± 278[c] | 1572 ± 288 | 46 ± 13 | 48.3 ± 14.7[c] | 23.7 ± 7 | 25 ± 6.5 | 44.6 ± 7.3[c] | 45.1 ± 7.7[c] | 119 ± 8 | 119 ± 8 |
| | | SI | 2.8 ± 5.7 | 1.8 ± 5.5 | -7.4 ± 16.7 | -5.2 ± 8.9 | -3.5 ± 20.5 | 4.8 ± 20.4 | 0.8 ± 19.4 | 0.5 ± 18 | 0.0 ± 2.3 | -0.1 ± 2.3 |
| Fatigue | | Left | 1522 ± 238[b] | 1541 ± 261 | 45.4 ± 13.4 | 47.2 ± 15.8 | 24.2 ± 6 | 24.7 ± 6.2 | 43.9 ± 9.5 | 44.3 ± 9.1 | 118 ± 8[a] | 120 ± 8 |
| | | Right | 1576 ± 278 | 1562 ± 316 | 44.2 ± 15.7 | 46.1 ± 15.5 | 23.8 ± 6.3 | 23.9 ± 6.1 | 43.2 ± 7.4 | 44.1 ± 7.2 | 119 ± 8 | 120 ± 8 |
| | | SI | 3.1 ± 5.6 | 0.4 ± 11.9 | -4.9 ± 20.8 | -2.8 ± 12.7 | -2.2 ± 20.5 | -3.5 ± 18.7 | -1 ± 18.8 | 0 ± 17.1 | 0.3 ± 2.5 | -0.3 ± 2.8 |
| Baseline | 15 | Left | 1583 ± 253 | 1580 ± 269 | 50.8 ± 15.6[b] | 53.7 ± 16[c] | 25.4 ± 6.2 | 26 ± 8.8 | 46.9 ± 10.7 | 47.3 ± 10.3 | 131 ± 9 | 131 ± 10 |
| | | Right | 1601 ± 308 | 1594 ± 318 | 46.8 ± 16.6 | 51.9 ± 16.7[c] | 25.4 ± 6.9 | 25.7 ± 7.2 | 47.7 ± 6.9 | 47.1 ± 7 | 131 ± 9 | 131 ± 10 |
| | | SI | 0.4 ± 10.7 | 0.1 ± 11.1 | -10 ± 20.1 | -4.6 ± 12.9 | -0.6 ± 19.6 | -0.1 ± 26 | 3 ± 18 | 0.5 ± 16.8 | -0.1 ± 2.4 | 0.2 ±1.9 |
| Fatigue | | Left | 1572 ± 241 | 1583 ± 276 | 47.8 ± 14.9 | 50.4 ± 16.4 | 26 ± 5.8 | 25.7 ± 6 | 45.3 ± 9.7 | 46.7 ± 9.4 | 130 ± 10[b] | 131 ± 10 |
| | | Right | 1608 ± 259 | 1619 ± 280 | 47.5 ± 15.9 | 47.8 ± 16.8 | 25.3 ± 6.4 | 25.3 ± 6.6 | 44.9 ± 6.5[a] | 46.4 ± 6.7 | 131 ± 10 | 131 ± 10 |
| | | SI | 2.2 ± 6.3 | 2.3 ± 6.2 | -0.8 ± 13.6 | -7 ± 16.7 | -3.1 ± 22.4 | -2.2 ± 20.4 | 0.1 ± 18.6 | 0 ± 16.5 | 1.2 ± 3.1 | -0.5 ± 2.8 |
| | ME | | Leg | | Fatigue*leg*Test | | | | Fatigue | | | |
| | IA | | | | Fatigue*leg*Test | | | | | | | |
| | Speed | | | | | | | | 0.04 | | | |

Pairwise Comparisons [a] Test 1 vs. Test 2; [b] left leg vs. right leg. [c] baseline vs. fatigue

**Table 3.** Mean ± standard deviation of the strength test, fatigue index = Mean torque of 60 isokinetic contractions /Maximum isometric torque. SI = symmetry index. *N = 30*

| | | Maximum isometric torque [Nm] | | Mean torque of 60 isokinetic contractions [Nm] | | Fatigue index | |
|---|---|---|---|---|---|---|---|
| Muscle group | Leg | T1 | T2 | T1 | T2 | T1 | T2 |
| Plantar flexors | Left | 192.6 ± 38$^{b}$ | 190.5 ± 38.9$^{b}$ | 98.7 ± 28.2 | 98.5 ± 28.1 | 0.52 ± 0.14$^{b}$ | 0.52 ± 0.14$^{b}$ |
| | Right | 154.2 ± 33.7 | 154.1 ± 31.8 | 94.2 ± 30.5 | 92.8 ± 29.2 | 0.62 ± 0.17 | 0.61 ± 0.17 |
| | SI | -22.6 ± 21.7 | -21.3 ± 19.8 | -6.6 ± 24.8 | -7.5 ± 23.7 | 16.13 ± 25.55 | 13.84 ± 24.69 |
| Dorsiflexors | Left | 38.8 ± 7.4 | 38.1 ± 7.3 | 15.5 ± 4.1$^{b}$ | 15.4 ± 4.2$^{b}$ | 0.41 ± 0.1$^{b}$ | 0.41 ± 0.09$^{b}$ |
| | Right | 35.7 ± 10.4 | 35.4 ± 11.2 | 11.8 ± 3.7 | 11.6 ± 3.3 | 0.35 ± 0.12 | 0.35 ± 0.13 |
| | SI | -10.9 ± 26.2 | -10.5 ± 30.5 | -27.7 ± 24.9 | -28.7 ± 21.3 | -16.97 ± 25.33 | -18.15 ± 28.44 |

**Table 4** Variables for the analysis of variance. Fatigue index = mean torque of 60 isokinetic contractions / maximal isometric torque. Effect size (partial eta-squared. $\eta_p^2$). *N = 30*

| Variable | Muscle / foot zone | Effect | df | Mean Square | F | p-value | $\eta_p^2$ |
|---|---|---|---|---|---|---|---|
| Maximal isometric torque | Plantar flexors | Strength | 1 | 41895.5 | 38.5 | 0.00 | 0.57 |
| Fatigue index | | | 1 | 0.3 | 15.5 | 0.00 | 0.35 |
| Mean torque of 60 isokinetic contractions | Dorsiflexors | | 1 | 428.0 | 40.6 | 0.00 | 0.58 |
| Fatigue index | | | 1 | 0.1 | 10.7 | 0.00 | 0.27 |
| Double step length | | Test | 1 | 411.9 | 5.5 | 0.02 | 0.06 |
| Step length | | | 1 | 110.3 | 4.3 | 0.04 | 0.05 |
| Cadence | | | 1 | 150.6 | 2.8 | 0.10 | 0.03 |
| First passive maximum force | Foot | Leg | 1 | 172001.8 | 11.1 | 0.00 | 0.11 |
| Maximal plantar pressure | Forefoot | Fatigue | 1 | 316.4 | 20.5 | 0.00 | 0.19 |
| | Heel | | 1 | 1140.8 | 20.0 | 0.00 | 0.19 |
| | | Leg | 1 | 737.1 | 18.1 | 0.00 | 0.17 |
| | | Test | 1 | 845.6 | 8.5 | 0.00 | 0.09 |
| | | Fatigue*leg*test | 1 | 58.3 | 4.2 | 0.04 | 0.05 |
| | Forefoot | Running speed | 2 | 1281.1 | 3.2 | 0.04 | 0.07 |
| Cadence | | | 2 | 12559.9 | 13.2 | 0.00 | 0.23 |
| Double step length | | | 2 | 117264.3 | 77.9 | 0.00 | 0.64 |
| Step length | | | 2 | 38934.2 | 79.8 | 0.00 | 0.65 |

## RESULTS

Table 4 shows the effects and tables 1, 2 and 3 the means and standard deviations as well as the results of the pairwise comparisons. The strength tests led to a local muscle fatigue with significant differences between left and right leg with a large effect size whereas no significance was found for the measuring-repetition (Tab. 1). Both, the maximum strength as well as the fatigue protocol in test 1 and test 2 revealed higher values for PF and DF of the left leg. As a result of the fatigue protocol, PF decreased to 52%-62% and DF to 35%-41% of the isometric maximum strength. The fatigue coefficient showed a stronger local muscle fatigue of PF of the left leg. In contrast, DF of the right leg were more fatigued (Tab. 2).

Significant effects were found in the test-retest on step length, cadence as well as PP maximum under RF with smaller effect size (Tab. 4). Step length increased while cadence and PP maximum under RF decreased in test 2 (Tab. 1). The local muscle fatigue showed a significant effect on maximal PP under the fore- and RF with medium effect size and lower maximal pressure values after pre-fatigue (Tab. 2 and 4). A significant effect of the leg was found (small effect size) at the first force maximum and PP maximum under RF. The right leg showed higher values at the first force maximum whereas the left leg showed higher maximum pressure values under RF. An interaction of Fatigue*Leg*Test was found for PP maximum under RF (Tab. 4).

With increasing running speed, cadence, step length and the first force maximum as well as PP maximum under the foot regions increased as well. A significant inter-subject effect of running speed was found for step length with high, for cadence with moderate and for PP maximum under the forefoot with low effect size.

## DISCUSSION

The primary aim of the study was to examine the influence of local muscle fatigue of PF and DF on PP-distribution while RFS running at three different speeds as well as taking test repetition and leg asymmetry into account. The isokinetic strength test reproduced the local muscle fatigue very well, so that the same condition was given in the retest. As hypothesized, the results of the strength tests yielded to a less strong local fatigue of PF in comparison with DF with an appearing muscle imbalance. In comparison to other studies (6), the induced muscle fatigue of DF was greater. The reasons for this are the higher strength of PF because of their bigger muscle mass, and its divergent function while running or walking as well as other everyday movements that induce greater stress on PF and thereby exercise their fatigue resistance. As already shown in EMG analyses (22), the arthromuscular ratio for the control of foot motion changed with consequences for the roll-over behavior as well as PP-distribution. A muscular imbalance at the ankle joint as a result of local muscle fatigue was also found for DF by Christina et al. (6) as well as for PF and DF by Kellis and Lissou (17) and can result in an increased injury risk (11, 38).

After local muscle fatigue, a reduction of the first force maximum and PP values under the forefoot as well as under RF were observed. These results coincide with findings of other studies (1, 3, 10, 41, 42, 43,). Lower PP values support the hypothesis of a possible protective strategy to counteract fatigue in injuries (44). The reduction of the first force maximum as well as the maximal pressure values under the heel could be explained by lower landing forces due to a reduced vertical motion of the body’s center of mass, a better shock absorption due to stronger knee flexion (17) and a flat foot strike caused by exhausted DF (6). This also fits the reduced forefoot loading which indicates - with the same running speed and reduced strength ability of PF - a changed strength direction with the foot strike more horizontally. Moreover, the differences in the first passive force maximum with lower values of the dominant-leg support the assumption of an active, flat foot strike with increased shock absorption of this leg, particularly as no difference was observed in step length when comparing both legs.

After local muscle fatigue, no change in cadence and step length was found with same running speed. This was consistent with findings of Alfuth and Rosenbaum (1) who also found no change in cadence. On the contrary, other studies showed a change in step length and cadence after fatigue (18). Others report a decrease of cadence and an increase of step length (11, 10) or an increase of cadence (43).

Asymmetries in strength conditions of the tested runners with higher values of the left leg in the isometric strength maximum as well as the isokinetic strength endurance is due to its dominance as a jumping leg (37). The higher fatigue of DF of the right leg can be explained by a lower strength ability of the non-dominant-leg. On the other hand, the higher relative fatigue of PF of the dominant-left leg could be explained by the index formation of higher maximum strength in the non-exhausted state because even after the fatigue protocol, the absolute strength ability of this leg was higher.

High leg asymmetries observed in the strength tests was reflected in the values of the first force maximum as well as the pressure maximum under RF. However, this was not observed in other values of PP-distribution, step length or related asymmetry index. These differences were found in baseline as well as under the local muscle fatigue. This coincides with findings of Brown et al. (4) who also found no relation between fatigue and leg-dominance while running. They concluded that side differences during fatigued running probably have no relation to leg-dominance which can be supported by the present results.

In the homogeneous group of RFS, the interaction Test*Leg*Fatigue influenced the PP values under RF, i.e. the classification according to the RFS pattern remained constant under all test conditions. But loading under RF was interactively influenced by these factors.

In the three tested speed levels, a comparable influence of the local muscle fatigue on PP values appeared in accordance with the hypothesis on three foot regions, step length and cadence. Although by increasing the running speed, step length, cadence as well as the pressure values all together and in particular under the forefoot increased.

The laboratory tests on the treadmill allow the control of running speed and facilitate the measurement of PP-distribution. On the other hand, the disadvantage of the unusual conditions of the treadmill affecting the running motion may be exists in comparison of test 1 and test 2. The recorded increase in step length and decrease in cadence with the same running speed can be attributed to the insufficient familiarization to the treadmill. The separate familiarization phases of approximately 30 min as well as the 10 min entrance (break) before both tests were not sufficient for an adjustment of step length and cadence. For the given running speed with increasing routine, the cadence decreased and step length simultaneously increased in test 2. In future studies, more time must be given for adapting the running technique to the treadmill. A further limitation was the measurement of PP-distributions as only the vertical force was determined, in comparison to force plates that additionally determine shear forces; however, it did measure and average several running cycles of 30 s. By using the manufacturer's software, a reduction to three foot regions without separating the toes, and a distinction between medial and lateral foot was performed, which limited the comparability with other studies. The evaluation in the strength test focused on the respective maximum only without considering the average torque as well as the work and performance values. Besides, only an angular velocity of 60°/s was tested in a seated position.

## CONCLUSION

As hypothetically expected, it has been shown that the local fatigue protocol with the same number of repetitions lowers the muscular efficiency of DF more than that of PF. This results in a muscular imbalance in the foot indicating an increased risk of injury. As a result of local muscle fatigue in RFS runners, the first passive force maximum as well as the PP values under the rear- and the forefoot decrease for a given running speed within the range of 11-15 km/h. The higher strength abilities of the dominant-leg were related with a low, first passive force maximum as well as with higher PP values under RF during running without fatigue as well as after local muscle fatigue. For testing on treadmills, enough time must be given for getting used to the device. Otherwise, an increase in cadence and decrease in step length while running can be expected. For injury prevention, strength training of the foot muscles with a special main focus on less efficient DF should accompany the running routine.

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