The Influence of Muscle Fatigue on Electromyogram and Plantar Pressure Patterns as an Explanation for the Incidence of Metatarsal Stress Fractures

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Background: Stress fractures are common overuse injuries in runners and appear most frequently in the metatarsals.

Purpose: To investigate fatigue-related changes in surface electromyographic activity patterns and plantar pressure patterns during treadmill running as potential causative factors for metatarsal stress fractures.

Study Design: Prospective cohort study with repeated measurements.

Methods: Thirty experienced runners volunteered to participate in a maximally exhaustive run above the anaerobic threshold. Surface electromyographic activity was monitored for 14 muscles, and plantar pressures were measured using an in-shoe monitoring system. Fatigue was documented with blood lactate measurements.

Results: The results demonstrated an increased maximal force (5%, \( P < .01 \)), peak pressure (12%, \( P < .001 \)), and impulse (9%, \( P < .01 \)) under the second and third metatarsal head and under the medial midfoot (force = 7%, \( P < .05 \); pressure = 6%, \( P < .05 \); impulse = 17%, \( P < .01 \)) toward the end of the fatiguing run. Contact area and contact time were only slightly affected. The mean electromyographic activity was significantly reduced in the medial gastrocnemius (–9%, \( P < .01 \)), lateral gastrocnemius (–12%, \( P < .05 \)), and soleus (–9%, \( P < .001 \)) muscles.

Conclusion: The demonstrated alteration of the rollover process with an increased forefoot loading may help to explain the incidence of stress fractures of the metatarsals under fatiguing loading conditions.

Keywords: running; stress fractures; fatigue; electromyography (EMG); pedography; plantar pressure pattern

Bone tissue is subjected to continuous remodeling processes to adjust to the actual loading conditions. Repetitive submaximal stimuli may reduce the individual loading capacity of the bone and lead to structural changes in the regions of maximal stress that may develop into stress reactions. These so-called stress or fatigue fractures account for a high percentage of running-related injuries. With the increasing fitness and wellness movement, the incidence of stress fractures has also affected more recreational athletes. The localization of these fractures depends on the sports activity and is concentrated on the tibia, navicular, and metatarsals in runners. Stress fractures in the metatarsals—predominantly affected are the distal end or shaft of the second and third ray—are also known as marching fractures because they were initially described in military recruits.

Intrinsic biomechanical factors that promote stress fractures are an excessively developed longitudinal arch (ie, a high-arch foot), leg-length discrepancies, and an excessive forefoot varus position. The additional influence of bone density, hormonal factors, and dietary factors underlie the notion of a multifactorial cause of stress fractures. A rapid increase in running mileage of more than 30 km per week has been identified as an additional risk factor. Histologic analyses have demonstrated increased osteoclastic activity and a related increase in microfractures of the trabecular bone. In female runners, the incidence of stress fractures was found to be related to anthropometric factors like calf girth and muscle mass. One of the tasks of the muscles in running activities is to absorb energy during the impact phase to minimize impact forces to the
bony tissue; therefore, a declining force of the muscles during fatigue may cause increased loading.13

In general, central and peripheral fatigue mechanisms can be distinguished. Peripheral fatigue can be determined from the pH level and lactate concentration as a consequence of an insufficient oxygen supply in the capillary blood. The central nervous system tries to delay the fatiguing effects to a certain degree with an increased motivational drive. Central fatigue is reached if this compensatory mechanism fails with continuing activity and the performance decline is caused by musculoskeletal insufficiencies. Local muscle fatigue as a result of intensive exercise can be evaluated with changes in the electromyography (EMG) signals. Reduced EMG activity has been demonstrated in the tibialis anterior and gastrocnemius muscles during fatiguing treadmill running.24 However, it is still unclear how much stress fractures are caused by increased loading of the bony structures during fatigue.11,21,29 To understand the potentially causative factors for the development of stress fractures, the present study investigated the relationship between fatigue-related changes in the muscle activity patterns and plantar loading differences during fatiguing treadmill running.

METHODS

Thirty subjects, 22 male and 8 female runners and triathletes, volunteered to participate in this study and gave their informed consent according to the Declaration of Helsinki. Their health status was confirmed with a sports medical examination. The subjects were free of current or recent injuries and internal problems. The inclusion criterion was regular participation in running activities (Table 1). An average weekly running distance of 60.8 ± 28.2 km revealed that the subjects were above a recreational performance level (up to marathon running). The mean age, body mass, and height were 34.5 ± 8.8 years, 69.6 ± 8.9 kg, and 177.9 ± 8.2 cm. A foot-shape index (minimal midfoot width divided by foot length excluding the toes) was retrospectively determined from Harris mat prints in 20 of the subjects. The values were between −15% and +20% and reflect the range of expected values for a fairly normal population with a distribution between high-arch feet (negative values) and slightly flat feet (greater positive values). During treadmill running, the subjects were allowed to wear their own running footwear (regular running shoes from different brands) to introduce no further change in their customary running conditions as would have been caused by using a uniform testing shoe for all subjects. At least 2 days before the fatiguing run, the subjects performed a maximal running test on a treadmill (Woodway GmbH, Weil am Rhein, Germany) to determine the individual anaerobic threshold according to Simon et al.28 Every 2 minutes, the treadmill speed was increased by 2 km/h. The individual base-level lactate (1.2 ± 0.3 mmol/L) plus 2 mmol/L was used to determine the level of effort and running speed during the fatiguing treadmill run (14.8 ± 1.3 km/h).

After a warm-up run for 8 minutes at a comfortable pace, the individual speed was selected, and the subjects ran at that speed until they could not keep up the speed and had to terminate the run because of fatigue. This was followed by a cool-down run for 6 minutes. Heart rate was monitored throughout the whole experimental period (Polar model S-510, Polar Electro GmbH, Hessen, Germany). The lactate concentration was determined from the capillary blood sampled from the left ear lobe with an enzyme electrode (EBIO plus, Eppendorf AG, Hamburg, Germany). For the EMG and pressure distribution, measurements of at least 20 steps were recorded intermittently every 2 minutes during the exhausting run. Here, we will report the differences between the first measurement after the initial 2 minutes of running and the last measurement before the termination of running.

Plantar pressure measurements were performed with 1 sensor insole worn in the left running shoe between foot/sock and sock liner (Pedar Mobile, Novel GmbH, Munich, Germany). This capacitive system uses flexible insoles with 99 sensors covering the whole plantar aspect. The thickness is less than 2 mm so that the shoe fit was not markedly affected. The unilateral measurements enabled a measurement frequency of 99 Hz. No marked pressure pattern difference between the left and right foot has been described in the literature,31 so this approach does not limit the conclusions.

The insoles were calibrated up to 600 kPa, and pressures could be measured with a resolution of 1 kPa. An excellent reproducibility was reported for the Pedar system.15 Each ground contact caused a trigger impulse that was used for synchronization with the EMG measurements and for the determination of step cycle durations. To attribute the overall foot loading to certain areas of the foot, the pressure patterns were subdivided into 10 regions with a so-called PRC mask (Figure 1) developed by Cavanagh et al.8 The areas of special interest were regions 5 (first metatarsal) and 6 (second and third metatarsal). The following parameters were determined for the whole foot and the selected regions: peak pressure, contact area, contact time, maximum force, and the impulse, that is, the force-time integral. Analyses were performed with the appropriate software (Novel Win, Novel GmbH, Munich, Germany).

The muscle activities were recorded at 1000 Hz with a 16-channel EMG system (Noraxon USA Inc, Scottsdale,
RESULTS

The mean treadmill speed during the fatiguing run was 14.8 ± 1.3 km/h for all subjects at an individually determined exercise level of 2 mmol/L above base lactate (1.18 ± 0.31 mmol/L). Subjects ran at that speed for 13.6 ± 6.5 minutes until they had to terminate the run because of fatigue. The mean lactate level of the whole group was 6.7 ± 1.7 mmol/L and the mean heart rate 184 ± 13 beats per minute (Table 2).

Pedography analysis revealed a significant increase in the peak pressures under the medial midfoot and all forefoot regions \( (P = .01) \) for all subjects. The pressures increased by 11% under the first metatarsal (from 409 to 454 kPa, \( P = .002 \)) and by 12% under the second and third metatarsal (334 to 373 kPa, \( P < .001 \)). The maximal force under the first metatarsal increased by 8.5% to 472 N \( (P < .001) \) and under the second and third metatarsal by 5.3% to 378 N \( (P = .006) \). The contact area became larger only under the first metatarsal by 1% \( (P = .02) \). The contact times in the midfoot and forefoot did not change significantly. The impulse (ie, the force-time integral) increased in all areas of the foot with exception of the lateral heel region (Figure 2, Table 3).

The EMG amplitude of the calf muscles during ground contact was significantly reduced between 16.0% and 21.1% after the fatiguing run (peroneus, \( P < .005 \); soleus, \( P < .007 \); medial gastrocnemius, \( P < .003 \); lateral gastrocnemius, \( P < .003 \)). The amplitudes of the tibialis anterior and the knee extensor muscles of the thigh were not changed. However, in the hamstring muscles the biceps femoris revealed a significantly reduced amplitude \( (P < .03) \). No changes were seen in the remaining hip muscles (Figure 3).

DISCUSSION

The aim of the present study was to evaluate the influence of muscle fatigue on plantar loading patterns with respect to potentially causative mechanisms for stress fractures of the metatarsals. The results of the 30 investigated subjects—a relatively homogeneous group of experienced runners—revealed significant changes in the foot-loading parameters as well as in the muscle activity patterns, predominantly in the calf muscles.

In the present study, only the acute biomechanical changes of foot-loading characteristics and muscle activity patterns were investigated in an intrindividual comparison. The effect of other factors that have been identified in the literature as influencing the predisposition to stress fractures, such as reduced bone density, age, gender, fitness level, nutritional status, and hormonal status, was considered to be negligible. Furthermore, biomechanical parameters such as leg-length differences, high-arched foot structure, and running style may be predisposing factors for metatarsal stress fractures.\(^{17}\)

In the present treadmill running approach, the subjects exercised above their individual anaerobic threshold to complete exhaustion.\(^{28}\) The level of blood lactate reached 6.7 mmol/L and indicated a marked lactic fatigue of the sub-

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Figure 1. Subdivision of the footprint into 10 anatomy-related masks: 1 = medial heel, 2 = lateral heel, 3 = medial midfoot, 4 = lateral midfoot, 5 = first metatarsal head, 6 = second and third metatarsal head, 7 = fourth and fifth metatarsal head, 8 = hallux, 9 = second toe, 10 = lateral toes.
These values reveal that the subjects actually reached a high level of exertion and that the termination of the run was because of peripheral fatigue. The time needed for 10 step cycles (before, 6.78 ± 0.46 seconds; after, 6.81 ± 0.47 seconds) remained constant so that—because of the constant treadmill speed—a constant step length or frequency can be assumed. The average running distance was less than that reported in a previous investigation.

The present results show that the pressure distribution patterns during the fatigued state revealed a significant increase of the peak pressures, maximal forces, and impulses under the forefoot and the medial midfoot. It has previously been reported that a flat foot causes a higher loading of the medial longitudinal arch, whereas a high-arch foot transfers the load to the lateral edge of the foot. However, in the present population the foot-shape index did not reveal a significant correlation to the observed changes in foot-loading characteristics. Previous investigations of the nonfatigued state showed that initial heel contact causes a plantar flexion moment. Throughout touchdown, the heel is slightly supinated, pronates during the stance phase, and returns into supination at pushoff. In the fatigued state, runners use a change in the landing technique as a compensatory strategy, which may cause an external dorsiflexion moment. This adaptational change in forefoot and midfoot loading has been suggested as a potential mechanism for the development of stress fractures. This is in accordance with the present findings, which therefore point toward a potentially detrimental overloading mechanism in fatigued running with decreased calf muscle activity.

The increased forefoot loading under fatigued conditions may be responsible for a disturbed remodeling of the metatarsals, which would increase the likelihood of the development of a fatigue fracture. It has been shown that alterations in the bony structures lead to a rapid increase in the incidence of stress fractures. It is interesting to note that the previously described increased loading under the medial midfoot appears to be due to a more pro-

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base lactate, mmol/L</td>
<td>1.18</td>
<td>0.31</td>
<td>0.75-2.07</td>
</tr>
<tr>
<td>Lactate at termination, mmol/L</td>
<td>6.73</td>
<td>1.71</td>
<td>3.54-11.73</td>
</tr>
<tr>
<td>Lactate after cool down, mmol/L</td>
<td>3.59</td>
<td>1.42</td>
<td>1.78-6.95</td>
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<tr>
<td>Running speed, km/h</td>
<td>14.78</td>
<td>1.30</td>
<td>12.8-17.8</td>
</tr>
<tr>
<td>Running duration, min</td>
<td>13.55</td>
<td>6.48</td>
<td>5.5-26</td>
</tr>
<tr>
<td>Heart rate at termination, beats/min</td>
<td>184</td>
<td>13</td>
<td>158-221</td>
</tr>
</tbody>
</table>

![Figure 2](image2.png)

**Figure 2.** The main significant changes of the plantar loading parameters between the fresh and the fatigued condition in each of the 10 areas of interest. Gray arrows = force time integral; black arrows = peak pressure; white arrows = maximum force.

![Figure 3](image3.png)

**Figure 3.** Differences of the mean EMG amplitudes before and after the fatiguung run. GMX, gluteus maximus; GMD, gluteus medius; TFL, tensor fasciae latae; VM, vastus medialis; VL, vastus lateralis; RF, rectus femoris; ADD, adductor; ST, semitendinosus; BF, biceps femoris; TA, tibialis anterior; LG, lateral gastrocnemius; MG, medial gastrocnemius; PL, peroneus longus; SOL, soleus.
nounced pronation.26 This functional planus foot may be supported by an increased external tibial rotation5 and may be further enhanced by insufficient trunk stability under fatigue.30 It has been shown that the loading is increased especially during the early stance phase,5 which is reflected in the results of the present study.

Although the forefoot loading is increased, the present results did not reveal a decrease in the EMG activity of the tibialis anterior under fatigued conditions. This may be because of the fact that the tibialis anterior is predominantly active during the swing phase and that this phase was not specifically considered in the analysis. Sharkey et al27 explained the increased metatarsal loading by a fatigue-related activity decrease of the flexor digitorum longus. Furthermore, the tibialis posterior appears to play an important role for the support of the longitudinal arch and therefore in fatigue-related changes of forefoot loading. However, because the tibialis posterior is not located in one of the superficial compartments of the shank, EMG measurements can only be performed with indwelling (needle or fine-wire) electrodes, which was not feasible in the current approach. But because several muscles are involved in stabilizing the joints of the foot, it appears rather unlikely that the tibialis posterior is the sole responsible muscle for the support of the foot structure and should therefore be the only causative factor. The EMG activity revealed significantly decreased activity in the fatigued calf muscles, which is in accordance with the results reported in previous investigations.14,24 Unlike the tibialis anterior, the calf muscles are predominantly active during the end of the stance phase. With decreased activity during fatigue—as was shown in the present investigation—the supinatory action of the triceps surae is diminished and the pronation may be more pronounced. This may cause an increased loading under the medial midfoot and forefoot and will therefore affect the push-off force. This mechanism would also reduce the shock-absorbing effect of the muscles during the loading response with an increased loading of the second and third metatarsal and the medial midfoot.10 The effect is supported by reduced activity of the tibialis anterior that revealed a diminished dorsiflexion effect in the swing phase.31 However, it is interesting to note that the contact time of the foot was not affected to a similar degree. This is contrary to the results of another investigation with fatiguing treadmill running using a slower running speed and lower level of exertion.31

Finally, the fatigue-related decrease in calf muscle EMG activity during treadmill running caused a more pronounced forefoot loading, which appeared to be related to a modified rollover process with an increased pronation. This mechanism might help to explain the increased incidence of stress fractures under fatigued conditions. Running shoes should be able to control pronation, especially under fatigued conditions when the stabilizing muscles are losing control over the rollover process. This might help to prevent or at least decrease the likelihood of metatarsal stress fractures during fatiguing running. To develop an optimal protection against overpronation, further research in running shoe design and development appears necessary. Furthermore, the effect of specific training programs on strengthening the stabilizing muscles of the foot should be evaluated. However, according to current understanding, it appears advisable to strengthen not only the agonistic and antagonistic foot/shank muscles but also the trunk-stabilizing muscles. Further research should use comparable technology to address the fatigue problem under aerobic conditions (eg, in marathon running) to investigate and compare the mechanisms during extended exercise with a lower level of exertion.

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REFERENCES