Clinical Research

The Impact of the Spartathlon Ultramarathon Race on Athletes' Plantar Pressure Patterns

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Abstract: *More than 90% of injuries in runners are recorded in the lower extremity, equally affecting the regions of the knee, shank, and foot. Stress fractures are responsible for numerous running-related injuries. In the current study, the plantar pressure patterns of prerace, immediately post-race, and 24 hours after long-distance running in the Spartathlon were analyzed to compare foot loading in the respective conditions. Forty-six male participants of the Spartathlon ultramarathon were examined before, immediately after completion of the race, and 24 hours later with plantar pressure measurements during barefoot walking on a capacitive platform. The results revealed a significant increase in the peak pressure and impulse values in the forefoot areas and a decrease under the toes before and immediately after the race. On the contrary, no significant differences were found between the prerace and the 24-hour post-race values. The present findings indicate that the Spartathlon race leads to significant variations in foot-loading characteristics, especially in the peak pressure and impulse values under the forefoot and toe regions. Twenty-four-hour post-race data measurements reveal insignificant differences from the prerace statement, probably because of the restoration of local muscular activity.*

Keywords: adolescent foot problems; forefoot-toe-midfoot; biomechanical abnormalities; gait analysis; podiatric assessment in sports

Recently, the popularity of health-motivated activities as well as competitively oriented events, such as road races with distances between 5 km and the classical marathon distance of 42.2 km, has increased.[1,2] However, the incidence of running-related and overload injuries has also risen.[3]

First, the annual incidence of injuries among runners has been estimated to be between 37% and 56%.[4] More than 90% of injuries in runners are recorded in the lower extremity, equally affecting the regions of the knee, shank, or foot.[5] Bone tissue undergoes continuous remodeling processes to adjust to the actual loading conditions.[6] Repetitive submaximal stimuli may reduce the individual loading capacity of the bone and lead to structural changes in the areas of maximal stress that might develop into stress reactions.[7] These stress fractures are responsible for numerous running-related injuries.[8-10] With increased fitness and wellness activities, more recreational athletes suffer stress fractures.[11]

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Furthermore, sports activity dictates the fracture area, and data indicate that the tibia, navicular bone, and metatarsals in runners are frequently affected.[12] Stress

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fractures in the metatarsals are known as marching fractures because they were initially observed in military recruits.[13]

Spartathlon is a historic ultra-distance foot race (246 km) that takes place every September in Greece.[14] The Spartathlon course is conducted point to point, where elevation ranges from sea level to 1200 m, over tarmac roads, trails, and mountain footpaths. Aid stations can be found every 3 to 5 km, and they supply athletes with food, water, and refreshments. The race is conducted under police and medical supervision throughout its 36-hour duration. Each of the 75 race control points has its distinct time limitations, and should a runner arrive later than the official closing time, he or she will be eliminated from the race.

Various surveys have investigated potential causative factors of stress fractures in runners, but no single factor is responsible for the incidence or frequency of this type of injury.[15-17] Intrinsic factors, such as a high-arch foot, leg-length discrepancies, and an excessive forefoot varus position, may influence the appearance of stress fractures.[8,10,11,17] The additional influence of bone density, hormonal factors, and dietary factors highlights the multifactorial cause of stress fractures.[18,19] Furthermore, excessive exercise of the foot and shank muscles may lead to increased impact forces during landing, which is considered an additional threat to bone integrity.[20-22]

Postexercise variations of plantar pressure patterns have been investigated by other researches and revealed significant differences in foot-loading characteristics before and after running, with postexercise peak pressure and impulse values being increased in the forefoot regions and reduced under the toes area.[3,6] The increased post-race peak pressure under the metatarsal heads points to a load shift from the toes to the metatarsal heads, which may explain the increased incidence of metatarsal stress fractures in long-distance runners.[3] The methodology used in the aforementioned studies employed recordings before, during, and immediately after the race. However, no study has yet examined possible residual effects of an ultramarathon race on the plantar pressure patterns of the participants.

In the current study, the plantar pressure patterns of prerace, immediately post-race, and 24 hours after long-distance running in the Spartathlon were analyzed to compare the foot loading in the respective conditions. The aim of this study was to monitor functional changes of foot loading due to the ultramarathon race and possible residual plantar pressure variations that occur 24 hours after successful completion of the race.

Materials and Methods

Forty-six male participants of the Spartathlon ultramarathon (246 km), which took place in September 2008, were examined before the race, immediately after the completion of the race, and 24 hours later. All athletes volunteered to participate in the current study and gave their informed consent according to the Declaration of Helsinki. Their health status was confirmed by a detailed medical examination. The participants did not suffer any current or recent injuries or health problems and did not present intrinsic factors that could influence the plantar patterns, such as high-arch foot, leg-length discrepancies, excessive forefoot varus position, equines deformity, or varus or cavus foot. The inclusion criterion was successful completion of the Spartathlon race. The mean age of the participants was 44.3 ± 8.2 years, with a range of 30 to 61 years.

The prerace plantar pressure measurements were performed 24 to 48 hours prior to the race. Participants walked barefoot across a plantar pressure platform that was embedded in a soft walkway (EVA-foam, shore 35). Care was taken to ensure that a normal step in full gait was used, with normal walking speed and step length and with the whole foot contacting the platform. After several trials, the starting point was chosen to allow for a 3-step approach. A pressure-sensitive platform with capacitive sensors was used (Footscan USB gait, Scientific Software, sampling rate 300 Hz; RSscan International, Olen, Belgium) for the pressure distribution measurements of the footprint. For the second measurement, the participants were asked to repeat the examination within the first hour after completion. The third measurement was performed 24 hours after the race to examine possible residual plantar effects after the competition, with similar normal gait characteristics for the participants.

For the analysis of the pressure distribution measurements, the footprint was subdivided into 10 areas of interest: medial heel (MH), lateral heel (LH), medial midfoot (MM), lateral midfoot (LM), first metatarsal head (FM), second and third metatarsal heads (2-3M), fourth to fifth metatarsal heads (4-5M), hallux (H), second to third toe (2-3T), and fourth and fifth toes (4-5T). For further analysis, only the left footprints were used to avoid false statistical findings. For the purpose of the current study, the following parameters were determined for the specific areas of interest (FM, 2-3M, 4-5M, H, 2-3T, 4-5T): contact area, contact time, peak pressure, and impulse or force-time-integral. At the retest immediately after the race, the participants' type of running shoe (lightweight, cushion, control, and stability) and any use of orthotic insoles was monitored.

Prior to the official measurements, we conducted a pilot study to establish the reliability of our measurements under similar conditions on 14 adult men of various ages on 2 separate days. The coefficient of variation for the 2 trials was 9% ± 2% for the plantar loading patterns.

For the statistical analysis of the data, differences between the prerace and the 2 post-race measurements were assessed with ANOVA for repeated measures and with a factorial ANOVA for group differences after safeguarding the normal data distribution with the Kolmogorov-Smirnov test. The α level of significance was set at .05 for all statistical procedures with subsequent Bonferroni correction.

Results

Table 1 presents a summary of the anthropometric characteristics of the participants. The age range (30-61 years) indicates that runners of various age

Table 1.

Anthropometric Data of the Runners (N = 46)

Parameter	Mean	SD	Range
Age, y	44.3	8.2	30-61
Height, cm	177.2	8.5	164-192
Weight, kg	69.8	8.3	61-85
Body mass index, kg/m^2	22.3	2	20-26
Shoe size (EU)	41.8	2.2	39-46

Table 2.

Change Pattern for Peak Pressure

Site	Peak Pressure, kPa	
	Before Race to Immediately After Race Change %	Immediately After to 24 h After Race Change, %
MH	+3	−2
LH	+1	−1
MM	−5	−1
LM	−1	−2
FM	+21	−17
2-3M	+19	−15
4-5M	+17	−14
H	−15	+19
2-3T	−37	+56
4-5T	−34	+48

Abbreviations: 2-3M, second and third metatarsal heads; 2-3T, second to third toe; 4-5M, fourth to fifth metatarsal heads; 4-5T; fourth and fifth toes; FM, first metatarsal head; H, hallux; LH, lateral heel; LM, lateral midfoot; MH, medial heel; MM, medial midfoot.

groups participate in this type of ultramarathon, similar to other contests. All participants successfully completed the race. None of the participants declared use of orthotic insoles during the marathon race. In addition, no significant changes were found for the plantar pressure patterns according to the type of running shoe used during the marathon.

Analysis of the plantar loading patterns revealed significant differences ($P < .001$) in the peak pressures (Table 2; Figure 1) under the forefoot regions (metatarsals, hallux, and toes) in the second measurement for all participants. The peak pressure increased by 21% under the first metatarsal (from 296 to 359 kPa), by 19% under the second and third metatarsal (411 to 489 kPa), and by 17% under the fourth and fifth metatarsal (419 to 491 kPa). As far as the hallux and toes regions were concerned, a significant decrease in the peak pressure variable was found for all 3 areas (15% for the hallux, 37% for the second and third toes, and 34% for the fourth and fifth toes). Regarding the third measurement (24 hours after the race), no significant differences were found for the peak pressures in all regions (with regard to the prerace values).

No statistically significant differences were found for the contact area ($P > .05$) in all foot regions, for all 3 repeated measurements. Furthermore, the contact times in the midfoot and forefoot did not change significantly. The only significant difference ($P < .05$) was found in the medial heel, with an increase of 7% (161 to 172 milliseconds). No statistically significant differences were found between the first measurement and the 24-hour post-race values for the variable contact time.

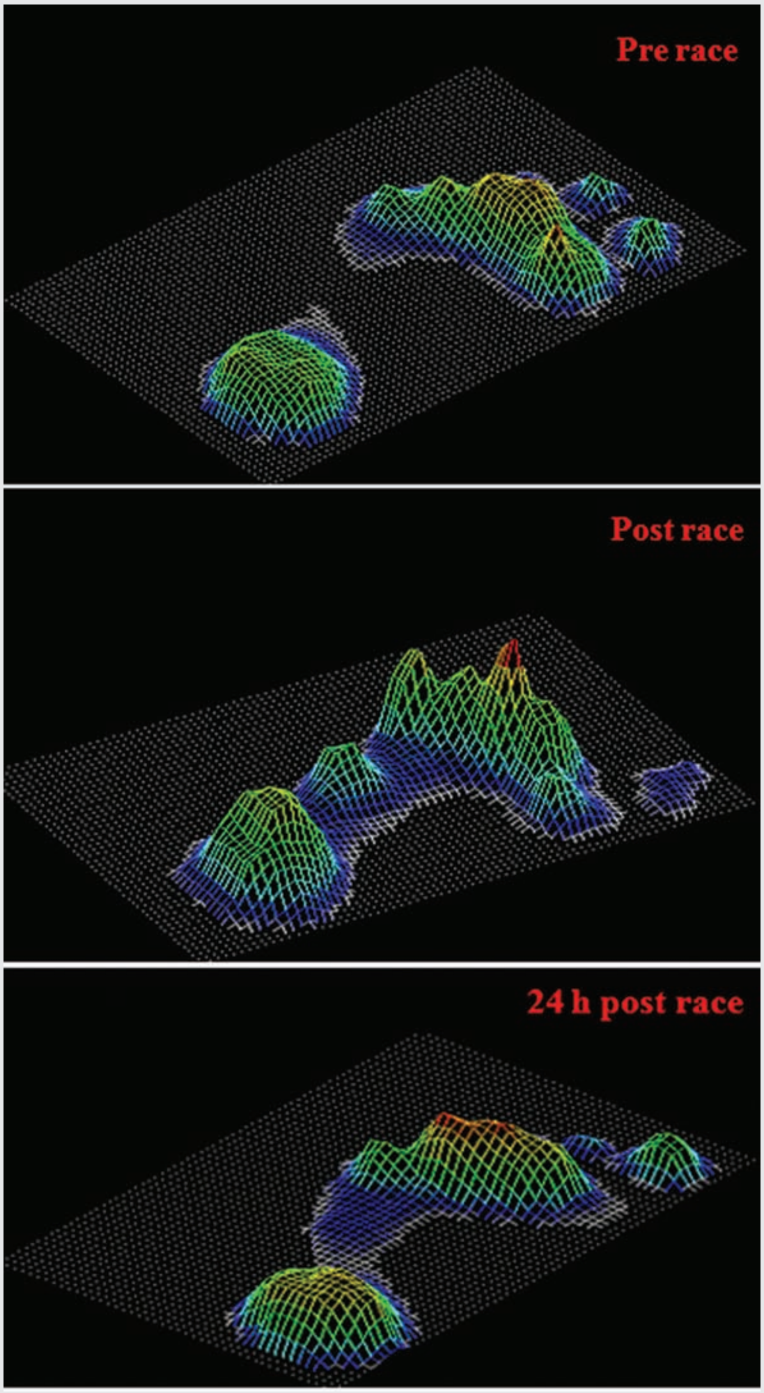
The impulse (force-time integral) varied in all foot areas except the lateral heel region (Table 3). A significant increase of impulse was found in the metatarsals region, while all values decreased significantly in the toes area. Specifically, the total impulse values of the toes area decreased (second measurement) from 45.3 to 35.9 N/s ($P < .05$), while the values of the forefoot areas increased from 136.5 to 144.6 N/s ($P < .05$). The values of the third measurement did not vary significantly from those of the prerace measurement for all foot areas.

Discussion

The aim of our study was to investigate the influence of ultramarathon running on foot-loading characteristics during barefoot walking to indicate the overall impact of fatigue on the plantar pressure distribution. The results of the 46 well-experienced runners revealed statistically significant differences between the foot-loading parameters in the immediately post-race (second measurement) recordings. The innovation of our study was the follow up (third measurement) of

Figure 1.

Plantar pressure distribution of a participant before and after the race (47 years old, body mass index 21.3 kg/m^2).



the runners to investigate possible residual effects of the long-distance race on the plantar pressure parameters 24 hours after the race.

In this research, only the acute changes of foot-loading characteristics were evaluated. The impact of other influencing factors, which have been identified in a literature review, on the predisposition to stress fractures, such as reduced bone density, age, gender, fitness level, running style, nutritional status, and hormonal status, was considered insignificant.[9,11,12] Regarding the type of running shoe used by the athletes, our results did not show any significant difference for the plantar pressure patterns, in accordance with previous research.[3]

For the aim of the investigation, we purposefully used barefoot measurements instead of sensor insoles inside the running shoe to accommodate athletes in real conditions of ultramarathon running. As suggested by current research, sensor insoles are more advantageous for a direct investigation of the tested parameters during running but are affected by external factors, such as the type of running shoe.[3] Barefoot measurements can only indirectly reveal any long-lasting effects and assist in the evaluation of foot-loading characteristics; hence, they are considered an important tool for detecting differences in plantar pressure patterns.

All participants manifested major differences that were reflected in reduced peak pressures and impulses under their toes in contrast to increased peak pressures and impulses under the metatarsal heads at the end of the marathon. As other investigators propose, the load is transferred from the toes to the metatarsal heads, probably because of local muscle fatigue after exercise, which is reflected in the toe flexor muscles.[23-28] Overloading of the metatarsal heads may lead to stress fractures of the metatarsal bones, especially the second and third metatarsals, which are vulnerable because of the discrepancy between bone strength and imposed plantar pressure.[29]

Sharkey et al[30] interpreted the increased metatarsal loading by a fatigue-related activity decrease of the flexor digitorum longus. In addition, the tibialis posterior muscle plays an important role in the support of the longitudinal arch and thus in fatigue-related changes of forefoot loading. But because several muscles participate in the stabilization of the foot joints, it is highly unlikely that the tibialis posterior is the only muscle accountable for the sustenance of the foot structure.[6]

Table 3.

Change Pattern for Impulse

Site	Impulse, N/s	
	Before to Immediately After Race Change, %	Immediately After to 24 h After Race Change, %
MH	+15	−13
LH	+4	−1
MM	+8	−6
LM	+8	−6
FM	+4	−4
2-3M	+7	−6
4-5M	+7	−6
H	−23	+31
2-3T	−18	+20
4-5T	−21	+25

Abbreviations: 2-3M, second and third metatarsal heads; 2-3T, second to third toe; 4-5M, fourth to fifth metatarsal heads; 4-5T; fourth and fifth toes; FM, first metatarsal head; H, hallux; LH, lateral heel; LM, lateral midfoot; MH, medial heel; MM, medial midfoot.

Our findings are in agreement with previous studies. Nagel et al[3] investigated the effects, employing barefoot walking, of a formal marathon race on plantar pressure patterns of 200 male and female runners. Their results revealed significant differences between foot-loading characteristics before and after the race, with post-race peak pressures and impulse values being higher in the forefoot areas and reduced under the toes. Similarly, Weist et al[6] examined fatigue-related variations in electromyographic (EMG) activity and plantar pressure patterns during treadmill running as parameters that bring about metatarsal stress fractures. Their findings demonstrated increased forefoot loading and decreased EMG activity in the medial gastrocnemius muscle, lateral gastrocnemius muscle, and soleus muscle in the fatigue-related conditions.

A justification for the values of the third measurement (24 hours post-race) could be that the local muscles returned to their prerace (prefatigued) condition, with restoration of the local muscle function. In our approach, none of the participants attended a special rehabilitation session after the marathon. An ideal approach to the follow-up of the runners could be the simultaneous examination of the plantar characteristics and EMG activity of the regional involved muscles and the monitoring of possible variations between the findings in athletes who use diverse post-race rehabilitation programs and those who use none.

Future studies could pursue further research on the variations in plantar pressure patterns in post-race conditions related to the time of arrival, anthropometric characteristics, and years of participation (athletic experience) in similar marathon events, and they could monitor possible residual (due to regular running) plantar differences between this type of athlete and the general population.

Conclusion

To summarize, the present findings indicate that the Spartathlon race (246 km) leads to significant variations in foot-loading characteristics, especially in the peak pressure and impulse values under the forefoot and toe regions. Specifically, the loads are transferred from the toe regions to the forefoot, causing a higher bending load on the metatarsal heads. This mechanism could explain the risk for stress fractures of the metatarsals in long-distance runners. Twenty-four-hour post-race data measurements reveal insignificant differences from the prerace measurements, probably because of the restoration of local muscular activity and functionality. FAS

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