Plantar Pressure Changes after Long-Distance Walking

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ABSTRACT

STOLWIJK, N. M., J. DUYSENS, J. W. LOUWERENS, and N. L. W. KEIJSERS. Plantar Pressure Changes after Long-Distance Walking. *Med. Sci. Sports Exerc.*, Vol. 42, No. 12, pp. 2264–2272, 2010. **Purpose**: The popularity of long-distance walking (LDW) has increased in the last decades. However, the effects of LDW on plantar pressure distribution and foot complaints, in particular, after several days of walking, have not been studied. **Methods**: We obtained the plantar pressure data of 62 subjects who had no history of foot complaints and who walked a total distance of 199.8 km for men (n = 30) and 161.5 km for women (n = 32) during four consecutive days. Plantar pressure was measured each day after the finish (posttests I–IV) and compared with the baseline plantar pressure data, which was obtained 1 or 2 d before the march (pretest). Mean, peak, and pressure–time integral per pixel as well as the center of pressure (COP) trajectory of each foot per measurement day were calculated using the normalization method of Keijsers et al. A paired t-test with an adjusted P value was used to detect significant differences between pretest and posttest. **Results**: Short-term adjustment to LDW resulted in a significant decreased loading on the toes accompanied with an increased loading on the metatarsal head III–V ($P < 0.001$). At all stages, particularly at later stages, there was significantly more heel loading ($P < 0.001$). Furthermore, the COP significantly displaced in the posterior direction but not in the mediolateral direction after marching. Contact time increased slightly from 638.5 ± 24.2 to 675.4 ± 22.5 ms ($P < 0.001$). **Conclusions**: The increased heel loading and decreased function of the toes found after marching indicate a change of walking pattern with less roll-off. It is argued that these changes reflect the effect of fatigue of the lower leg muscles and to avoid loading of the most vulnerable parts of the foot. **Key Words:** CENTER OF PRESSURE, LOW-INTENSITY EXERCISE, FOOT INJURIES, BIOMECHANICS

The popularity of long-distance walking (LDW) has increased rapidly in the past decades. It is generally acknowledged that many participants experience pain in the legs and feet after walking such a distance. However, there is not much information available about the basis for these complaints. The only data available are from military recruits and athletes. For example, Almeida et al. (1) showed that almost 40% of the military recruits reported injuries of the lower extremity during basic training, 34% of which were located in the ankle/foot region.

Although the literature is not always consistent, factors such as age, body mass index (BMI), gender, foot wear, training hours, and foot structure are generally thought to be associated with the development of metatarsal stress fractures and lower limb injuries (10,12,18,21,26). Most of these foot problems probably develop because of overloading the foot; therefore, changes in plantar pressure distribution resulting from exercise-related changes in the foot might help to explain why foot problems develop in athletes. Yet, changes in foot kinetics or kinematics during prolonged low-intensity exercise, such as LDW, have hardly been studied (13). The few data available on marching came from a study on short-duration intense walking (2 km), and nothing is known on the effects of long-distance marches (13). Gefen (13) studied the center of pressure (COP) after extensive marching (treadmill march of 2 km at 8 km·h^{-1}) and found that there was generally a lateral displacement of the COP, which they ascribed to a decreased activity of the peroneus longus and the lateral gastrocnemius.

The above data differ from those obtained on running, in which a shift to medial loading of the forefoot has been observed (36). Other differences may also exist. For example, Willson and Kernozek (36) found significantly smaller pressure values under the heel after running, although this has not been observed after short-time marching. Experiments involving exhaustive running have shown that, with the onset of fatigue, plantar pressure distribution and impact forces change (2,3,8,22,35,36). Studies using in-shoe

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measurement systems to measure plantar pressure changes found that fatigue after intense running (30 min) increased peak pressure either under all metatarsal heads and toes (35) or only under metatarsal head II and III (3). Nagel et al. (22) measured plantar pressure during barefoot walking before and after running a marathon and demonstrated that peak pressure under the metatarsal heads II to V increased, whereas the pressure under the toes decreased. It was proposed that increased dorsiflexion in the metatarsophalangeal joints would lead to higher peak pressure and impulse values under the metatarsal heads.

Differences in plantar pressure between walking and running are to be expected, however, because there is a distinct difference in kinetics and kinematics between the two. During walking, one foot or two feet are on the ground at all times, whereas for running, there is an unloaded phase and no double-support phase (29). This difference leads to a substantially higher vertical component of the ground reaction force (GRF) and net muscle moments in each leg for running compared with walking. Furthermore, heel loading in walking can be very different from that in running because the initial contact in running does not always involve the posterior part of the heel (as seen in midfoot strikers or toe runners) (6,27). Hence, it is unclear whether and how the results from studies on running could be extrapolated to LDW.

In view of the paucity of data available on plantar pressure distribution after extensive walking, this study was conducted to measure the plantar pressure of participants of the International Four Day March Nijmegen (IFDMN). On the basis of the available literature, the plantar pressure under the forefoot is expected to increase.

METHODS

Sixty-two participants, 30 men and 32 women, participating in the IFDMN held in July 2008 were included in this study. All subjects were between the age of 35 and 55 yr, had no previous history of foot complaints, and did not use insoles. The women and men walked approximately 40–50 km·d^{-1}, respectively, on four consecutive days (for a total distance of 161.5 and 199.8 km, respectively). Informed written consent was obtained from all subjects. Group characteristics are specified in Table 1, in which difference between men and women was analyzed using a *t*-test for independent samples. This study was approved by the local ethical committee.

TABLE 1. Group characteristics.

n = 62	Men (*n* = 22)	Women (*n* = 28)
Weight (kg)*	88.7 (14.6)	67.6 (9.7)
Length (cm)*	182.2 (7.2)	166.5 (6.5)
BMI (kg·m^{-2})*	26.6 (3.4)	24.4 (3.4)
Age (yr)	43.8 (8.0)	44.8 (5.3)
Sports (h·wk^{-1})[a]	1.8 (2.5)	1.6 (1.7)
Total distance of training (km)	442.9 (228.9)	464.2 (224.8)

[a] Sports other than walking/training for the IFDM.
* Significantly different between both groups at $P < 0.05$.

Plantar pressure measurements were performed during the 2 d before the IFDMN (pretest) and each day after walking (posttests I–IV). The pretest was performed at the research center at the Sint Maartenskliniek in Nijmegen, The Netherlands. The posttest measurements were performed at a location near the finish; thus, it was possible to measure all subjects within an hour of finishing. Plantar pressure distribution was measured during barefoot walking over a pressure plate (RSscan International, Olen, Belgium) with a sensor density of 2.6 cm^{-2} on top of a force plate (Kistler Instruments, Switzerland) at a preferred speed. A total of three trials per foot were measured using the three-step protocol (5). The plantar pressure and force plate data were collected at 500 Hz.

In addition to the plantar pressure data, foot pain was assessed using a questionnaire. Subjects were requested to describe the type of foot pain experienced, if present, and to mark the location of the pain on four different drawings of the left and right feet.

Analysis and statistics. Contact time was used to indicate walking speed and was calculated as the time between heel strike and toe off. Heel strike was defined as the instant that the ground reaction force >5 N, and toe off was when the ground reaction force was <5 N. To test whether there was a difference in contact time between the days, a general linear model (GLM) for repeated measures with day as a factor (4) was used. The Mauchly test for sphericity was used to test whether the variances of each set of data were equal. If sphericity was not met, the Greenhouse–Geisser correction was applied.

Plantar pressure is usually evaluated with pressure or force parameters in predefined areas of the foot. However, this approach has shortcomings as explained earlier by Keijsers et al. (17) and Pataky et al. (24) in the ability to detect small changes in pressure distribution within the predefined areas. Therefore, we opted for a technique that optimally used the data of all sensors and analyzed the plantar pressure per sensor instead of per mask. The parameters of interest were the mean pressure (MP), peak pressure (PP), and pressure–time integral (PTI) per sensor. First the MP, PP, and PTI were calculated for each step per foot for each subject. Subsequently, plantar pressure data were normalized for foot size, width, and foot progression angle according to the method developed by Keijsers et al. (17). After normalization, the plantar pressure of each normalized sensor (pixel) can be compared between trials, days, and subjects. For each subject, the mean MP, PP, and PTI of the three trials per foot per day were computed. The difference in plantar pressure between the days was determined by subtracting the pretest MP, PP, and PTI from those of the posttests. The recent study by Keijsers et al. (17) has demonstrated that the instrumentation used in this study and the normalization procedure have acceptable reliability (intraclass correlation (ICC) ≥ 0.85).

As the analysis of plantar pressure per sensor was only recently developed, there is not yet any consensus about the

best way to treat the large number of sensors in statistical analysis. Therefore, a procedure derived from the analysis techniques used in neuroscience for analyzing EEG signals (19) was used because both fields analyze data consisting of a large number of pixels. The technique involves a nonparametric procedure based on grouping all adjacent sensors that exhibit similar difference in sign (an increase or decrease in MP, PP, or PTI). First, for each measurement day and each parameter (MP, PP, or PTI), each pressure sensor was categorized as being a "decreased" or "increased" sensor. Second, all neighbor sensors with the same difference in sign (the increase or decrease) were grouped. The number of groups for sensors ranged from 3 to 15.

In addition, to take into account the various assessment moments, a paired t-test with adjusted P value for significance was used to detect significant differences in MP, PP, and PTI between the pretest and the posttests. The paired t-test with adjustment of the P value is the most appropriate test for the analysis of these kind of data because it is possible to correct for the number of sensors and the measurement moments. We adopted the strategy of adjusting the P value for the number of groups for sensors as well as for the number of measurement moments by using the general Bonferroni correction (α/N) in advance, in which the N was chosen as the product of the maximum number of groups for sensor (15) and the number of measurement days (4). Hence, the level of significance for this study was set at 0.00083.

In addition, the trajectory of the COP was calculated for each subject per day using the normalization method of Keijsers et al. (17). This trajectory of the normalized COP was calculated, taking the most proximal point of the contour line of 10 kPa for the heel at the onset of stance as the reference. To evaluate the shift of the COP in the mediolateral (ML) and anteroposterior (AP) directions relative to the COP of the pretest for each subject, the COP trajectories were superimposed. Subsequently, the alteration in ML or AP direction of the COP during stance phase was calculated for each posttest. The difference between the pretest and the posttest on day 1 is defined to be the short-term effect of LDW on the plantar pressure. The long-term effect was calculated by subtracting the pretest pressure data from the pressure data obtained during the final posttest.

Finally, to specify foot type, the arch index (AI) was calculated using the equation given by Cavanagh and Rodgers (7) for the pretest and the posttest IV for each subject. The AI is an indicator for foot shape because it is significantly correlated to static navicular height ($r = -0.52$), calcaneal inclination angle ($r = -0.68$), and calcaneal–first metatarsal angle ($r = 0.71$) (20). Differences between pretest and posttest IV were tested using a paired t-test. To test for differences in AI within subjects before and after the march and to test differences between groups (which were to be determined) in relation to the AI, a GLM for repeated measures, with measurement as the within-subjects factor (2) and group as the between-subjects factor (3), was performed.

All data were analyzed using MATLAB 7.3 software (MATLAB; The MathWorks, Inc., Natick, MA). SPSS 12.0 (Chicago, IL) was used to analyze the contact data using the GLM for repeated measures.

RESULTS

In total, 54 subjects completed the IFDMN. Eight subjects did not succeed in finishing the IFDMN, and they were excluded from the study. The reasons for drop out were various and were most often related to private circumstances, loss of motivation, and general health problems; they were not related to foot complaints. Unfortunately, three subjects did not arrive at the site of testing on the last day (because of the large crowd in front of the testing site). Furthermore, pretest plantar pressure data of one subject could not be used for analysis because of technical problems. Therefore, a total of 50 subjects were included in the analysis. Table 1 gives the characteristics of the group per gender. The men in our study seemed to have a significantly higher BMI of 2.2 ± 0.9 $kg{\cdot}m^{-2}$, height of 15.7 ± 1.7 cm, and weight of 21.1 ± 3.4 kg compared with the women.

Contact time. There was a main effect of factor day for contact time, indicating a significant increase in contact time ($F(2.6,252.9) = 143.3$, $P = 0.00$). *Post hoc* analysis revealed that contact time for each posttest was significantly higher compared with the pretest. Mean and SD of the contact times of the total group are shown in Figure 1.

Plantar pressure. After walking for 1 d, MP, PP, and PTI increased significantly under the metatarsal head (MT-heads) IV–V and under the heel. At later stages, MP, PP, and PTI under the heel increased even more, indicated by a significant increase of MP, PP, and PTI under the heel at posttest IV compared with posttest I. In contrast, MP, PP, and PTI under the toes and MT-heads I–II decreased significantly (Fig. 2). As shown in Figure 2, the MP, PP,

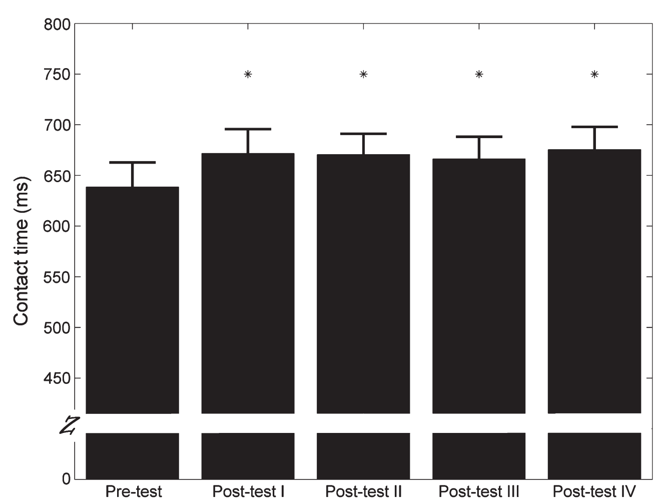

FIGURE 1—Mean contact time (with SD) for the total group for the pretest and posttest. *Significantly different compared with the pretest, $P < 0.001$.

and PTI were similarly affected by the LDW, with exception of the PP under the heel, where the increase was only observed under the distal part of the heel.

COP displacement. The decreased pressure under the toes suggests that the roll-off during stance was less complete after LDW. Superposition of the COP for the pretest and posttest data confirmed that the posttest trajectories ended more posteriorly than the pretest ones (Fig. 3). There was a significant difference of the COP in AP position between pretest and posttest I as well as posttest IV during almost the entire stance phase ($P < 0.001$). This reflects a global posterior shift of the COP.

There was no statistically significant shift of the COP trajectory in the ML direction for the total group. The mean COP displacement of the entire stance phase for the total group after the last walking day compared with the pretest was 0.02 ± 0.31 cm in medial direction. Although the average COP remained relatively stable in the ML direction across the measurement days, several subjects had a larger displacement of the COP. On the basis of this observation, and the fact that it has been found that fatigue of the lower leg muscles can influence the COP trajectory (13,36), subjects with a COP displacement greater than the mean displacement of the total group plus 1 SD (0.33 cm) medially (or laterally) were assigned to the medial ($n = 15$) (or lateral, $n = 14$) group. The remaining subjects were assigned to the neutral group ($n = 71$). As shown in Figure 4, the plantar pressure in the lateral group increased under the heel, metatarsal IV and V, and the lateral part of the midfoot, whereas plantar pressure in the medial group mainly increased under the heel, reflecting the dominant role of the backward shift of the *y* coordinate relative to the medial displacement. Furthermore, in all three groups, the COP displaced significantly in the AP direction ($P < 0.05$).

AI. There was a significant decrease for the total group in AI at posttest IV (0.235 ± 0.04) compared with that at pretest (0.243 ± 0.04) for the total group ($P < 0.001$). To test if there were differences in AI among the medial, neutral, and lateral groups, a simple contrast GLM for repeated measures, with measurement as the within-subjects factor (2) and group as the between-subjects factor (3), was performed. This analysis revealed that there was no main effect for group, indicating no difference among the medial, lateral, and neutral COP groups for the AI score ($F(2,97) = 0.64$, $P = 0.53$). However, there was an interaction effect of measurement × group, which reflected that between the groups at posttest IV, the AI differed. The AI decreased more in the medial group (pretest = 0.24 ± 0.04

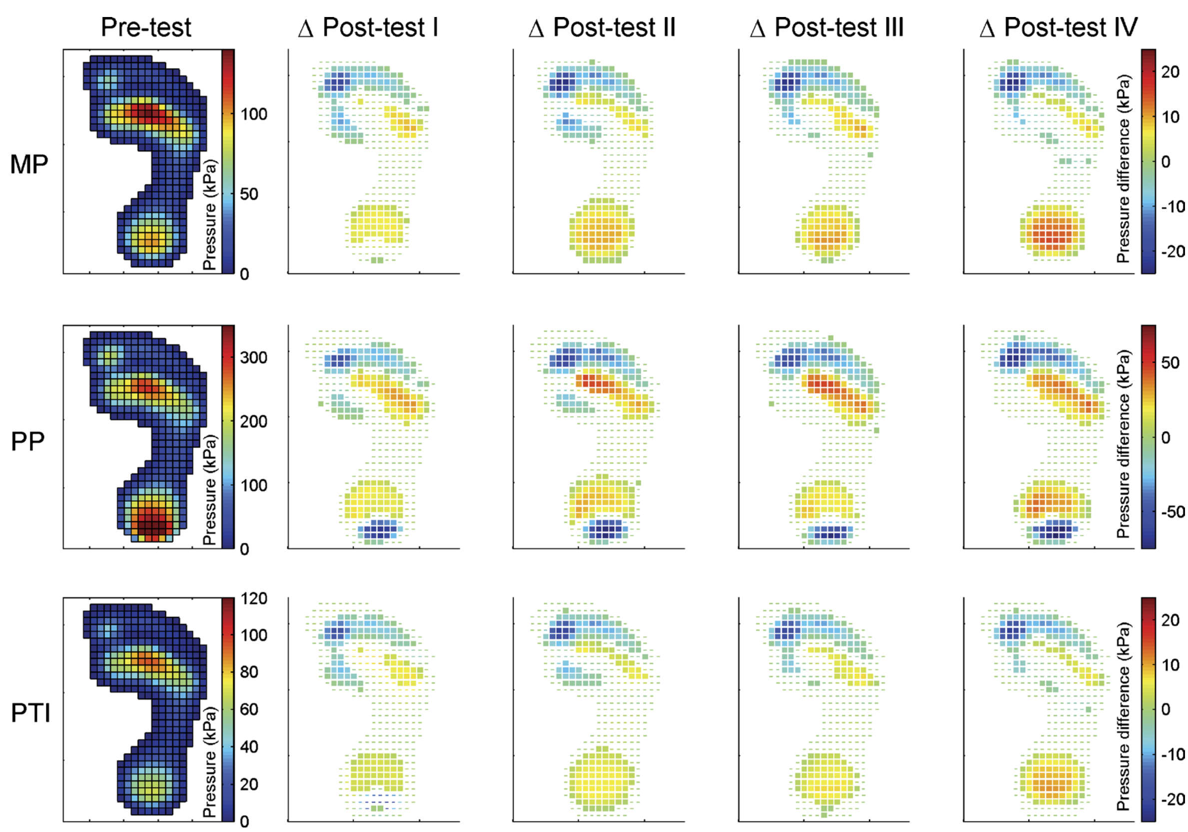

FIGURE 2—MP (*first row*), PP (*second row*), and PTI (*third row*) for each posttest with respect to the pretest. In the pretest (*first column*), the *blue* and *red* indicate the areas of low and high plantar pressure, respectively. For the change at the posttests (*second to fifth column*), the *colored squares* indicate those sensors with significantly different changes in plantar pressure compared with the pretest ($P < 0.00083$). The *small black lines* indicate those sensors without a significantly different change in plantar pressure compared with the pretest. The *color bar* indicates the values of difference in kilopascals.

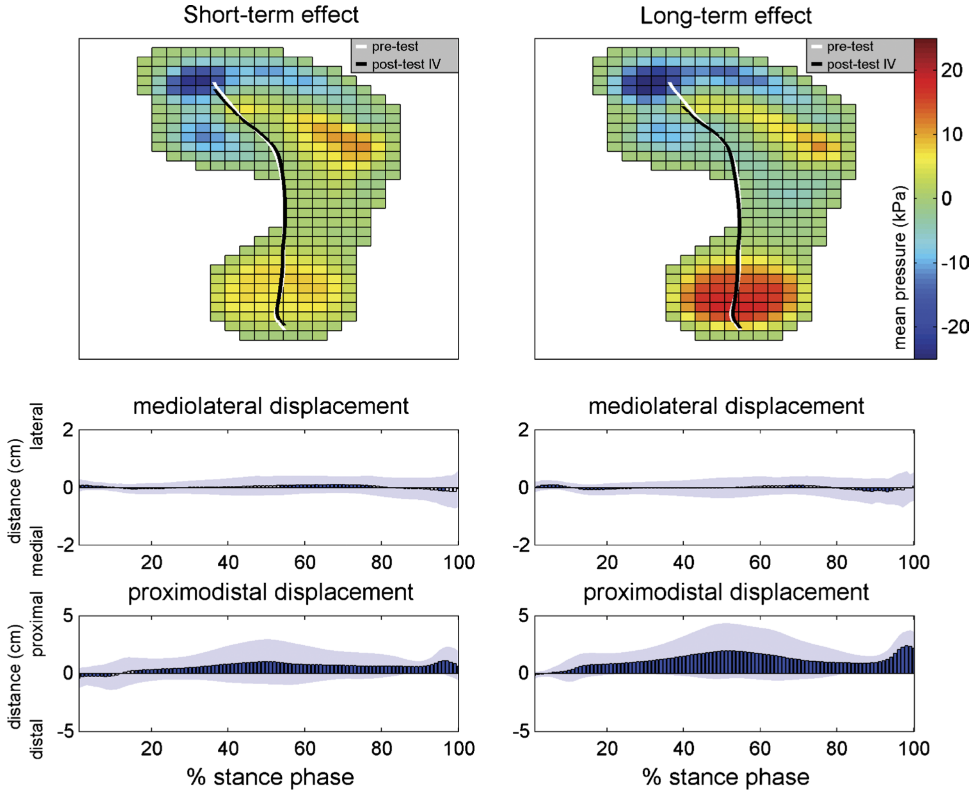

FIGURE 3 —Short-term (posttest I vs pretest) and long-term (posttest IV vs pretest) changes in COP trajectory for the total group in ML and AP directions during stance phase. In the *line graphs*, the *dark blue bars* indicate significant differences ($P < 0.001$) in COP trajectory; the *light blue areas* indicate 1 SD.

vs posttest = 0.22 ± 0.04) than in the lateral (pretest = 0.25 ± 0.03 vs posttest = 0.25 ± 0.02) or neutral (pretest = 0.24 ± 0.04 vs posttest = 0.24 ± 0.04) group.

Development of foot complaints. Foot complaints developed in 88 of the 100 feet included in the analysis. Six subjects (12 feet) did not develop any foot complaints. Of these foot complaints, 26% were "blister-related-problems," whereas the others were forefoot pain (22%), heel pain (7%), or combined forefoot and heel pain (18%). The remaining complaints (27%) were Achilles tendinopathy, ankle joint pain, pain on the dorsum of the foot, and the like. Of the feet that were classified in the medial COP group ($n = 15$), 80% reported forefoot pain compared with 43% in the lateral group ($n = 14$) and 21% in the neutral group ($n = 71$).

Of the subjects who reported forefoot pain in the medial group, seven experienced pain at the plantar aspect of all metatarsal heads (MT-heads I–V), three subjects under MT-heads II–III, and two subjects under MT-heads I–II. The remaining subjects in the medial group reported medial arch pain ($n = 1$), Achilles pain ($n = 1$), and toe blisters ($n = 1$). Thus, 14 of the 15 subjects of the medial COP group developed foot complaints that can be associated with insufficiency of the medial longitudinal column of the foot. The subjects in the lateral group consisted of four subjects with pain under MT-heads I–V, two subjects with pain under MT-heads I–III, one subject with Achilles pain, and one subject with heel complaints. Three subjects reported pain at the medial side of the foot, which shifted toward the lateral side after 2 d of walking. One subject reported pain at the lateral side of the foot only. Only two subjects of this lateral COP group had no foot pain.

DISCUSSION

The present study identified several major changes in plantar pressure distribution and COP displacement related to LDW. Short-term effects can be summarized as a decrease in toe pressure, under the first metatarsal head and hallux, coupled with an increase under the lesser metatarsal heads, similar to what has been observed after long-distance running (3,22,35,36) or short-distance intense marching (13). The most novel finding, however, concerns the long-term effects. Pressure under the heel increased after 1 d of walking and continued to increase during the next 3 d. The literature provided no information indicating that such an increase would take place. Willson and Kernozek (36) found significantly smaller pressure values under the heel after running. Similarly, Nagel et al. (22) did not observe a significant increase of peak pressure under the heel. Weist et al. (35) measured in-shoe plantar pressure during running on a treadmill and found that the forefoot loading increased but not heel pressure. An increase in heel pressure was also not present after short-distance marching.

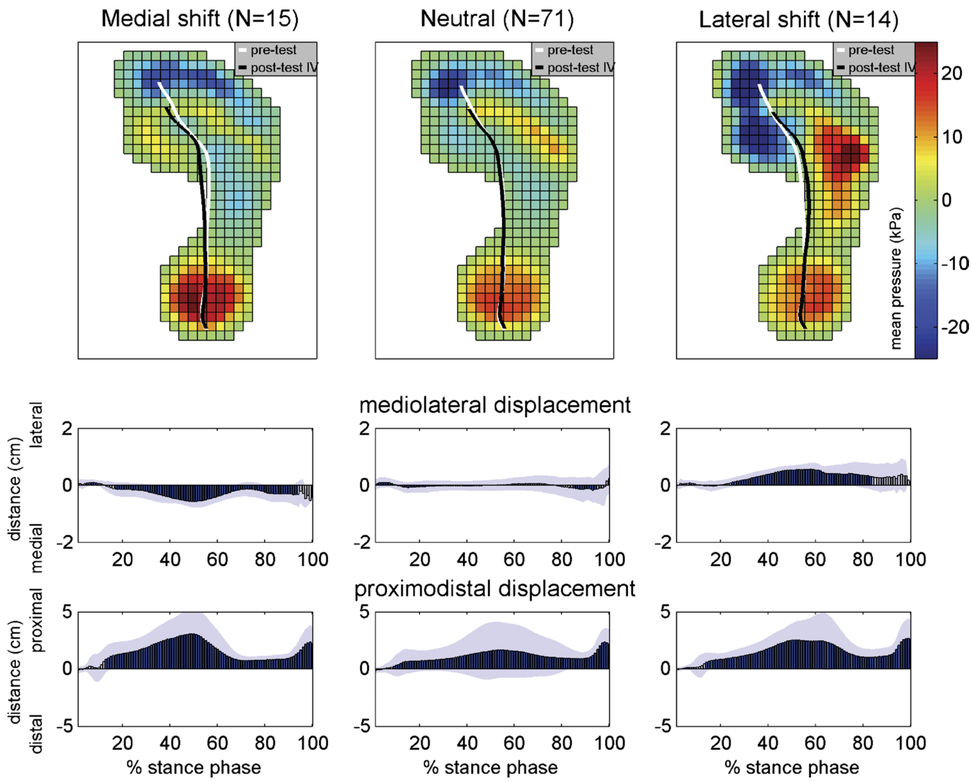

FIGURE 4—Long-term changes (posttest IV vs pretest) in COP trajectory in ML and AP directions during stance phase for the medial, lateral, and neutral COP groups. In the *line graphs*, the *dark blue bars* indicate significant differences (P < 0.05) in COP trajectory; the *light blue areas* indicate 1 SD.

One reason for this difference could be that subjects, to avoid overuse of the forefoot and the risk of incurring forefoot pain (as demonstrated in the present study), adapt their walking pattern in such a way that the pressure under the forefoot is decreased through a relative increase in heel pressure. The fat pad at the heel has excellent shock-absorbing and weight-bearing qualities and is less prone to blisters (9,34). Hence, shifting the load to the heel might be a defense mechanism when forefoot loading becomes problematic. Such an interpretation has been supported by Emborg et al. (11) who studied the effects of repetitive painful stimulation at different sites of the foot during different phases of the step cycle. They found that after stimulations near toe off, withdrawal was primarily accomplished by ankle dorsiflexion, thereby avoiding forefoot pressure. This response to painful stimulation probably differs from that to chronic pain, however. Although forefoot pain was reported by many participants, it was not present in the majority. On the other hand, the shift of pressure to the heel was found to be a general change because it also occurred in participants without any foot complaints and even in participants with heel pain.

Another, more plausible, explanation for this set of findings would be a general one based on a change of walking pattern to accomplish the task of walking these long distances, losing as little energy as possible and/or coping with muscle fatigue. Gefen (13) showed that 10 min of marching on a treadmill is enough to produce fatigue in the tibialis anterior, the extensor hallucis longus, the peroneus longus, and the calf muscles. Yoshino et al. (38) showed that muscle fatigue of the tibialis anterior muscle occurred after 105 min of walking and stated that walking affects the muscles that act at the ankle more than muscles that act at the knee. To compensate for fatigue of the distal leg muscles, one can change the walking pattern in such a way that there is a greater contribution of the proximal, more powerful, muscles. The calf muscles provide damping at touch down, stabilize the knee joint during the stance phase, and are essential for the push-off force at end stance (16,23,27,37). In case of fatigue, more activity of the quadriceps muscles is needed (25) to avoid knee instability, and the propulsion of the leg is provided by the hip extensors, causing increased pressure under the heel as the whole leg is used as a single segment (less knee flexion occurs).

Support for the decreased contribution of the calf muscles also comes from the change in the COP trajectory. The shorter trajectory after extensive walking is consistent with a reduced roll-off and the relatively increased contribution of the heel. The decreased toe participation in the final phase of the stance phase is also in concordance with a reduced roll-off. The absence of toe participation is confirmed by the significant decrease of MP, PP, and PTI under all toes. Decreased activity of the toe flexor muscles has been reported to lead to excessive bending moments of the metatarsals, a transfer of load from the toes to the metatarsals, and the possible development of stress fractures

(2,10,32). Nagel et al. (22), who investigated plantar pressure when walking barefoot before and after running a marathon, also reported the absence of pressure under the toes. They reported a significant decrease of peak pressure under all toes, but they had not investigated the COP trajectory.

The absence of toe participation could also be related to a basic change in posture within the foot, for example, due to a lowering of the arch height (15). The medial longitudinal arch is supported by passive (plantar aponeurosis and ligaments) and active (muscles) structures. The contribution of the active structures is particularly essential in maintaining foot posture during dynamic activities (15); therefore, foot posture is prone to muscle fatigue. The decrease in toe function and the lowering of the arch are associated with a less dynamic use of the foot. The finding in our study that there was a small, but statistically significant, decrease of the AI between the pretest and posttest measurements substantiated this. However, for the population as a whole, there was no ML shift of the COP, which would be expected if a marked lowering of the foot arches occurred throughout the population.

In contrast to the clear AP shift of the COP, there was almost no change in ML direction. In fact, only approximately 25% of the subjects showed a COP that was displaced >0.3 cm in either the medial or the lateral direction. Gefen (13), who investigated COP changes during treadmill marching at 8 $km \cdot h^{-1}$, found a lateral shift of the COP during the stance phase. Gefen et al. ascribed the lateral displacement of the COP to the decreased activity of the peroneus longus and the lateral gastrocnemius muscle (13,14). Because of the decreased activity of these muscles, they stated that it is impossible to counteract the subtalar inversion caused by the tibialis posterior, flexor digitorum, and hallucis longus. For the subjects of the present study who presented a medial displacement of the COP, according to the explanation proposed by Gefen et al., this medial COP displacement might be due to fatigue of the invertor muscles relative to the evertors. However, because muscle activity was not measured in the present study, we are unable to tell whether the ML displacement of the COP is indeed related to muscle fatigue.

The shift in the COP could also be related to the foot shape. Because all participants in this study were healthy volunteers with a foot build within the normal physiological boundaries, it was to be expected that all participants would have a normal medial longitudinal arch. The findings that the mean AI of the total group was within normal range (0.235 ± 0.04) and that, for AI, there was no statistically significant difference among the COP groups support this expectation.

From a pathophysiological point of view, more foot complaints are to be expected in the patients with either a lower or a higher foot arch. Lowering of the foot arch is associated with hyperpronation of the hindfoot, insufficiency of the medial longitudinal arch, less weight-bearing capacity of the first ray, hallux valgus, and forefoot pain. Also, Achilles tendon pain fits into this picture. These feet are generally more mobile along the arch and are more prone to a further decrease in AI. In this study, 14 of 15 participants in the medial COP group reported foot complaints that can be related to the above-mentioned clinical description. This is also supported by the more pronounced AI decrease in the medial COP group.

The shift in COP to one side could be explained by foot pain at the contralateral side of the foot. This would, in our view, particularly be the case for subjects with a lateral COP shift. The present data, however, do not confirm displacement of the COP in the ML direction associated with foot complaint location. Within the lateral COP group, although several different complaints were reported, only three were located at the medial side of the foot. Therefore, it seems that pain avoidance is not a major explanation for any ML COP displacement.

One limitation of the present study could be that walking speed differed before and after the march. The mean contact time changed from 638.5 to 675.4 ms at the end of the march, which corresponds to a change in average walking speed from 1.49 to 1.37 $m \cdot s^{-1}$. However, this was not a major difference, and this would only slightly affect the plantar pressure pattern. Furthermore, the observed changes in pressure cannot be explained by this change in speed. For example, a decrease in walking speed leads to a reduced plantar pressure under the heel (4,24,28,30,31,33). In addition, the increase in PP under MT-heads III–IV for speed alteration similar to that found in the present study would be 1.9 $N \cdot cm^{-2}$ according to Rosenbaum et al. (28), whereas we found an increase of approximately 6 $N \cdot cm^{-2}$ in that area. Hence, it is highly unlikely that the results in the present study could be attributed to the small reduction of walking speed.

In this study, the vertical ground reaction force, measured by the Kistler force plate, was used to calibrate the total pressure measured by the RSscan pressure plate (the sum of the pressure data). Each sensor is calibrated before shipping, but single sensors can change over time, and it was not possible to calibrate single sensors within our research center. Therefore, small changes in sensitivity of the sensors might have been present, which could have influenced the results. However, because of the relatively short interval between the measurements (<1 wk) and the fact that there were no substantial differences between the Kistler and RSscan data, it is to be expected that the RSscan data were correct. Furthermore, an earlier study by Keijsers et al. (17) showed that the instrumentation and method used in this study have good reliability (ICC ≥ 0.85).

Taking all these findings into consideration, we suggest that during walking long distances, the walking pattern is altered, in which there is a decreased roll-off, a decreased toe function, and a shift in the pressure during stance phase to the heel. It seems that the foot is used less dynamically; it is likely that the walking pattern is changed so

that the propulsion is powered by the much stronger proximal muscles located around the knee and hip. This can be primarily the result of muscle fatigue in the distal muscles, but it can also be that, even in well-trained subjects, walking such distances in a normal fashion is simply not possible without developing muscle fatigue. Extensive gait analysis, including muscle activity, with pretest and posttest measurements might further confirm these suggestions.

Finally, from a clinical point of view, it seems sensible to advise participants in long-distance marches, even those without a history of foot complaints, to use insoles to decrease pressure underneath the forefoot and the heel. Furthermore, they would benefit from shoe modalities with adequate shock absorption and support of the roll-off pattern. In subsequent controlled studies, it would be of interest to see whether training or wearing insoles and shoe modifications can prevent foot complaints after LDW and could influence the changes of pressure distribution.

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