Medial Longitudinal Arch Mechanics Before and After a 45-Minute Run

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Background: Medial longitudinal arch integrity after prolonged running has yet to be well documented. We sought to quantify changes in medial longitudinal arch kinematics before and after a 45-min run in healthy recreational runners.

Methods: Thirty runners performed barefoot seated, standing, and running trials before and after a 45-min shod treadmill run. Navicular displacement, arch lengthening, and the arch height index were used to quantify arch deformation, and the arch rigidity index was used to quantify arch stiffness.

Results: There were no statistically significant differences in mean (95% confidence interval) values for navicular displacement (5.6 mm [4.7–6.4 mm]), arch lengthening (3.2 mm [2.6–3.9 mm]), change in arch height index (0.015 [0.012–0.018]), or arch rigidity index (0.95 [0.94–0.96]) after the 45-min run (all multivariate analyses of variance \( P \geq .065 \)).

Conclusions: Because there were no statistically significant changes in arch deformation or rigidity, the structures of a healthy, intact medial longitudinal arch are capable of either adapting to cyclical loading or withstanding a 45-min run without compromise. (J Am Podiatr Med Assoc 104(4): 349-356, 2014)

The human arch is remarkable in its complexity and its ability to optimize the function of the lower extremity during gait. Immediately after the foot contacts the ground, the medial longitudinal arch deforms and absorbs a portion of the kinetic energy of the body through movement of bones and deformation of passive tissues, such as the plantar fascia, ligaments, and tendons, as well as active tissue (ie, muscle). However, energy absorption is counterproductive during propulsion; push-off from a rigid base rather than a compliant one allows for a more efficient transfer of energy to the body. The system complexity is magnified by the changing mechanical properties of the passive tissues at different strain rates and under repetitive loading, which may lead to dynamic creep. Active tissue properties are also affected by repetitive loading through the process of neuromuscular fatigue—the loss of force-generating capability. For example, if plantar foot muscles are fatigued, they no longer provide sufficient force to counter the bending moments experienced in the metatarsal shafts, resulting in higher strains. The changing structure and function of the arch-supporting tissues based on their material properties suggest that biomechanical function may be altered after a prolonged run, when neuromuscular fatigue or creep may become a factor.

Some of these altered functions have been documented. Weist et al and Wu et al found increased peak plantar force and pressure in the medial midfoot region toward the end of moderate- to-exhaustive runs. This finding suggests that either the structures that maintain the arch were unable to do so during fatigue or the forces that work to deform the arch increased during fatigue. Several in vivo studies have observed a plantar pressure increase under the metatarsal heads and a decrease under the toes after fatiguing runs, including a marathon. Nagel et al suggested that this resulted because the toe flexors may have become fatigued. It may also be that the plantar fascia integrity was compromised, as an in vitro study observed that pressure increased under the metatarsal heads and decreased under the toes.
with subsequent plantar fascia release. This shift in plantar pressure was also accompanied by increased strain in the second metatarsal as the fascia was severed. Headlee et al demonstrated that the intrinsic flexor muscles play a role in maintaining the arch; sit-to-stand navicular drop increased by 1.8 mm after these muscles were exercised using sets of 75 repetitions of isometric flexion contractions, so if these same muscles experience fatigue after a long run, increased navicular drop may be observed. These studies suggest that greater arch deformation may occur after running, but it remains to be directly measured.

Different injuries may result if the arch deforms too much, and these injuries are not exclusive to one foot type. As mentioned previously herein, metatarsal strains may increase, possibly leading to metatarsal stress fractures. Greater navicular drop in injured runners versus controls has been observed, although one prospective study found that navicular drop in runners with medial tibial stress syndrome did not differ from that in controls. Plantar fasciitis is thought to be caused by excessive strain of the fascia. Both low- and high-arched runners are associated with an increased risk of plantar fasciitis and metatarsal stress fractures. The prevalence in both foot types may be explained by a more flexible foot during gait, regardless of static height, resulting in increased metatarsal stress fracture. Neuromuscular or passive tissue fatigue may ensue after thousands of impacts from a long run, possibly increasing arch deformation, which may increase the risk of these and other injuries.

Arch deformation (an umbrella term we will use that includes changes in the three-dimensional [3-D] structure of the medial longitudinal arch) after a long run may be greater owing to material fatigue of passive tissues and decreased force production of the arch-supporting muscles, but this has yet to be investigated using 3-D motion capture. Furthermore, most of a recreational runner’s mileage is at a self-selected intensity and not at an exhausting race pace, so it is probable that the biomechanical mechanisms that lead to injury may be present after running a few miles at a low to moderate intensity. Therefore, the purpose of the present study was to evaluate the changes in arch mechanics of healthy runners before and after a 45-min run at a comfortable pace. It was hypothesized that there would be greater arch deformation and decreased arch stiffness after the run.

Methods

Participant Characteristics

Thirty recreational runners (15 men and 15 women) were recruited for this study. Men were taller, had greater mass and body mass index, and ran significantly faster but were similar to women on other characteristics (Table 1). One woman and three men were midfoot/forefoot strikers and the remaining participants were rearfoot strikers, which is within the estimation of shod rearfoot strikers in the running community. Participants were excluded if they had any lower-extremity surgery, deformity, or current pain or wore prescribed foot orthoses. The inclusion criteria included weekly mileage of 16.9 to 80.5 km (10–50 miles) and being capable of running 1,600 m in less than 7.5 min. The experimental procedures were approved by Iowa State University’s institutional review board (Ames, Iowa), and all of the participants gave their written informed consent to participate.

Protocol

Participants visited the laboratory twice. On the first visit, they completed a maximum-effort 1,600-m run, after which we recorded maximum heart rate (HR) and rating of perceived exertion (RPE). Both HR and RPE were collected to have an estimate of effort and neuromuscular fatigue. Seventy percent of their 1,600-m velocity was calculated and used as the speed for the 45-min treadmill run and over-ground running trials during the second visit. Six men and six women were randomly selected for test-retest reliability of the arch deformation measurements. Because participants performed these test-retest trials at visit 1 before the 1,600-m run (to avoid a fatigue effect), we estimated their 1,600-m time to determine the velocity for the running trials. Because of incomplete data, one woman was eliminated from the test-retest data set.

All of the participants completed the same protocol at the second visit (3–14 days later). Retroreflective markers were placed on the right foot (Fig. 1) while participants stood with their weight evenly distributed on a custom-built apparatus for foot measurements. Landmarks included the navicular tuberosity, first metatarsal head, medial calcaneus, dorsum at 50% of total foot length, and posterior calcaneus. The first metatarsal and calcaneal markers were placed 2 cm from the supporting surface, and the medial calcaneal marker was placed 3 and 4 cm anterior from the posterior
calcaneus for women and men, respectively. Foot/ankle markers were circled with a permanent marker so that they could be replaced after the treadmill run. Eight infrared motion analysis cameras (Vicon, Oxford, England), sampling at 200 Hz, recorded marker position, and ground reaction forces were collected simultaneously at 1,000 Hz (AMTI, Watertown, Massachusetts).

Barefoot participants performed three pre–treadmill run conditions. First, a static standing trial was recorded. Navicular height, arch length, and truncated foot length and dorsal arch height (used for arch height index [AHI] calculations) during this standing condition were the baseline references for all of the running trials. Participants then sat on a chair (height: 43 cm, depth: 75% of thigh length) and rested their right foot on the force platform as marker positions were recorded. The seated and standing trials were used to calculate the arch rigidity index (ARI), explained more in the “Variables” section. Finally, participants performed six running trials at 70% of their 1,600-m velocity (no visual targeting of the force platform, within 6% of velocity). Participants used the same foot strike pattern as they used during shod runs. Data were averaged across the six trials for the running condition.

On completing the overground running trials, the reflective markers on the foot were removed, and participants put on their shoes. Treadmill speed was set to 70% of their 1,600-m velocity, and the participants ran for 45 min. Both HR and RPE were recorded immediately after the run, participants removed their shoes, and the reflective foot markers were replaced on the foot in their original locations. Participants then completed the same pre-run conditions but in reverse order (run, sit, stand). For the post-run running trials, participants continuously jogged between trials.

Variables

Reflective marker coordinates were filtered with a fourth-order Butterworth filter using a lowpass cutoff frequency of 16 Hz. Matlab software (version 7.8.0 R2009a; The MathWorks Inc, Natick, Massachusetts) was used to calculate all of the dependent variables. Stance phase data were interpolated to 101 points so that ensemble curves could be created. Medial longitudinal arch mechanics were measured by change in arch length, navicular height, and AHI. Arch length was defined as the 3-D distance between the medial calcaneal and first metatarsal markers. Navicular height was defined as the 3-D perpendicular distance from the navicular marker to the arch length line. Change in navicular height was termed navicular displacement, and change in arch length was termed arch lengthening. Arch lengthening and navicular displacement were expressed as a change from the standing trial, with a positive value representing lengthening and lowering of the arch. Zero would indicate no displacement relative to the standing trial. Peak navicular displacement and arch lengthening during stance were identified for comparison. The pre-run standing reference trial was used for all of the conditions because there were no differences in ground reaction force or any arch measurements in the seated or standing post-run conditions (P > .05).

The AHI was calculated as dorsal arch height at 50% of foot length divided by truncated foot length but in 3-D. Change in AHI was the difference

### Table 1. Participant Characteristics

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age (Years)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>BMI</th>
<th>Weekly Mileage</th>
<th>Running Velocity (m·s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td>20.8 ± 2.1</td>
<td>1.77 ± 0.05</td>
<td>75.6 ± 10.2</td>
<td>24.0 ± 2.6</td>
<td>21 ± 12</td>
<td>3.40 ± 0.27</td>
</tr>
<tr>
<td>Women</td>
<td>21.3 ± 1.9</td>
<td>1.66 ± 0.03</td>
<td>57.5 ± 5.9a</td>
<td>20.9 ± 2.1a</td>
<td>20 ± 10</td>
<td>2.88 ± 0.19a</td>
</tr>
</tbody>
</table>

Note: Data are given as mean ± SD.

Abbreviation: BMI, body mass index (calculated as weight in kilograms divided by the square of the height in meters).

aSignificantly different at P < .05.
between standing and dynamic AHI. Peak change in AHI during stance was identified for comparison. The ARI was the ratio of $AHI_{\text{standing}}/AHI_{\text{sitting}}$, with a value closer to 1.0 indicating a more rigid arch.25

**Statistical Analysis**

All of the statistical tests were completed in SPSS software (version 19.0; SPSS Inc, Chicago, Illinois). Sex was considered an effect modifier because sex differences have been reported.26 A $2 \times 2$ repeated-measures multivariate analysis of variance with $\alpha = 0.05$ was used to detect main effects and interactions between time (pre-run, post-run) and sex (male, female) for the four dependent variables: navicular displacement, arch lengthening, change in AHI, and ARI. If the multivariate analysis of variance was significant for the independent variables or their interaction, the univariate analyses of variance were explored for more detail. To assess the reliability and sensitivity of the measurements to detect a difference, we performed two-tailed repeated-measures $t$ tests for the four dependent variables based on the test-retest data and calculated the minimum detectable change at a 95% confidence level27 and the SEM.

**Results**

Men ran the maximum-effort 1,600 m significantly faster than women, which resulted in a faster mean $\pm$ SD 45-min and overground running velocity (men: $3.40 \pm 0.27$ m·s$^{-1}$; women: $2.88 \pm 0.19$ m·s$^{-1}$). However, mean $\pm$ SD HR (men: 191 $\pm 9$ bpm; women: 186 $\pm 12$ bpm; $P = .65$) and RPE (men: 17.5 $\pm 1.1$; women: 17.3 $\pm 1.7$; $P = .45$) after the 1,600-m run were not significantly different, so values were collapsed across sex. After the 45-min run, HR and RPE were 11% and 20% lower, respectively, than after the 1,600-m run. After the 45-min run, there was an 18% decrease in HR until the first running trial was collected (mean $\pm$ SD, 138 $\pm 17$ bpm). The HR did not significantly change during the overground running trials.

Two male participants were unable to complete the full 45 min (35:20 and 42:25 min). Visual assessment of their data did not reveal a significant difference from other participants, and exclusion of their data did not change statistical significance, so they were included in the analyses.

The $P$ values for the test-retest data were $P = .74$ for arch lengthening, $P = .19$ for navicular displacement, $P = .32$ for change in AHI, and $P = .32$ for ARI. Because the running trials at visit 1 were performed before the maximal-effort 1,600-m run, those 11 participants estimated their 1,600-m time, but running velocity between visits was not significantly different ($P = .78$) (mean $\pm$ SD: estimated, 3.22 $\pm$ 0.99 m·s$^{-1}$; actual, 3.23 $\pm$ 0.36 m·s$^{-1}$). The corresponding minimum detectable change was 1.0 mm for arch lengthening, 2.0 mm for navicular displacement, 0.0057 for change in AHI, and 0.044 for ARI, and the corresponding SEM was 0.45 mm for arch lengthening, 0.89 mm for navicular displacement, 0.0026 for change in AHI, and 0.016 for ARI.

Multivariate analysis of variance results indicated that there was not a statistically significant sex $\times$ time interaction ($P = .65$) or main effects for time ($P = .921$) or sex ($P = .182$). Therefore, univariate comparisons were not pursued, and data were averaged across time and sex. Relative to standing, mean $\pm$ SD navicular displacement during running was 5.6 $\pm$ 2.5 mm (95% confidence interval [CI], 4.7–6.4 mm), arch lengthening was 3.2 $\pm$ 2.1 mm (95% CI, 2.6–3.9 mm), and change in AHI was 0.015 $\pm$ 0.008 (95% CI, 0.012–0.018). Changes in these measurements during the stance phase are shown in Figure 2. Mean $\pm$ SD ARI was 0.95 $\pm$ 0.02 (95% CI, 0.94–0.96). Mean values for men and women before and after the run are presented in Table 2.

**Discussion**

The purpose of this study was to evaluate changes in medial longitudinal arch mechanics before and after a 45-min run at a comfortable pace. The hypothesis that deformation would be greater and arch stiffness would decrease after the 45-min run was not supported.

**Reliability and Measurement Sensitivity**

Arch lengthening was more reliable and sensitive than navicular displacement in quantifying arch kinematics based on the SEM and minimum detectable change values. This may be due to skin movement over the navicular, which has been noted to be larger relative to more distal markers, such as the first metatarsal head.28 Although the minimum detectable change for the dependent variables were all relatively larger than the observed changes post-run, the measurements are sufficiently sensitive and capable of detecting clinically meaningful changes. For instance, navicular drop values in injured populations have been noted to be 2.1 to 3.2 mm greater than those in healthy persons.12-14 Navicular drop measures 2-D vertical change in navicular height as body weight increases by approximately...
0.5 body weight from sitting to standing, so our 2.0-
mm minimum detectable change for navicular
displacement between standing and running (a
\( \geq 1.5 \) bodyweight increase) should be more than
enough to detect meaningful differences. Bandholm
et al\(^\text{12} \) found that the arch of persons with medial
tibial stress syndrome deformed an additional 1.7\(^\circ \)
compared with controls during walking. For the

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Variable} & \text{Men} & \text{Women} \\
\hline
\text{Navicular displacement (mm)} & 5.9 \pm 2.1 & 6.0 \pm 3.5 & 5.2 \pm 1.4 & 5.1 \pm 2.4 \\
& (5.0–6.9) & (4.4–7.6) & (4.3–6.2) & (3.5–6.7) \\
\text{Arch lengthening (mm)} & 3.6 \pm 1.4 & 4.0 \pm 2.4 & 3.0 \pm 1.6 & 2.3 \pm 2.4 \\
& (2.8–4.4) & (2.7–5.3) & (2.2–3.8) & (1.1–3.6) \\
\text{Change in AHI} & 0.015 \pm 0.005 & 0.013 \pm 0.010 & 0.017 \pm 0.005 & 0.016 \pm 0.011 \\
& (0.012–0.017) & (0.008–0.019) & (0.014–0.020) & (0.010–0.021) \\
\text{ARI} & 0.95 \pm 0.020 & 0.94 \pm 0.019 & 0.94 \pm 0.022 & 0.96 \pm 0.018 \\
& (0.94–0.96) & (0.93–0.95) & (0.93–0.96) & (0.95–0.97) \\
\hline
\end{array}
\]

Note: Data are given as mean \( \pm \) SD (95% confidence interval).
Abbreviations: AHI = arch height index; ARI, arch rigidity index.

Figure 2. Ensemble curves for pre– and post–45-min run navicular displacement, arch lengthening, and change in arch height index (AHI). Zero is equivalent to standing values. Positive values indicate lengthening and lowering of the arch.
average arch length of 150 mm, this is approximately 3.1 mm of lengthening, which again is greater than our minimum detectable change of 1.0 mm for arch lengthening during running.

Running Arch Deformation

The observed magnitude of navicular displacement (5.6 mm) was comparable with that in previous studies. Nachbauer and Nigg\textsuperscript{29} placed a marker over the intermediate cuneiform and observed a change in arch height of approximately 4.3 mm in the vertical direction. The difference may be explained by the 3-D measurement used in the present study that captured the medial movement of the bone.\textsuperscript{30} The present values were lower than the 10 mm of movement reported by Ker et al,\textsuperscript{1} but their reference was an unloaded foot for only one male who ran up to 7 m\cdot\text{s}^{-1}, which is much faster than the present mean ± SD running velocities (men: 3.40 ± 0.27 m\cdot\text{s}^{-1}; women: 2.88 ± 0.19 m\cdot\text{s}^{-1}). In addition, mean arch lengthening, which is an approximation of plantar fascia strain, was 2.2% relative to standing, or 4.0% relative to sitting (maximum of 9.4% or 12.8 mm). These values are larger than the maximum lengthening (8.5 mm) and strain (6%) reported by Caravaggi et al\textsuperscript{31,32} during walking, which is to be expected because we measured running, which has higher reaction and muscle forces compared with walking. However, these values are within the range of 9% to 12% during slow walking reported by Gefen,\textsuperscript{33} who used initial heel contact as the reference length.

Effect of Prolonged Running

The moderate running intensity in the present study may explain why we did not observe significant changes. We chose a moderate-intensity running pace to simulate most of the miles run by the participant pool. Previous research has focused on longer or more intense exercise protocols and found significant differences in plantar pressures and bone strain after exercise.\textsuperscript{7,8,34} Running velocity was 3.40 m\cdot\text{s}^{-1} for men and 2.88 m\cdot\text{s}^{-1} for women, post-run RPE was 14 (1 above “somewhat hard”), and most participants said that the treadmill speed was slower than their pace for long runs. The present results lend support for previous research that found no differences in plantar pressures or impulses after a 45-min run\textsuperscript{35} and no significant change in arch height after 3,000 cyclical axial loads of cadaver feet.\textsuperscript{36} Schlee et al\textsuperscript{36} had participants run 45 min at a speed (not reported) corresponding to a lactate concentration of 4 mmol\cdot\text{L}^{-1}, which is above the ventilator anaerobic threshold and near the maximum lactate steady state,\textsuperscript{37,38} so average running velocities in the present study (men: 3.40 m\cdot\text{s}^{-1}; women: 2.88 m\cdot\text{s}^{-1}) were likely slower. However, data from their overground running trials were at 3.5 m\cdot\text{s}^{-1}, similar to the men’s mean velocity. Post hoc correlations were calculated between exertion level (HR and RPE) and post-run arch variables to investigate whether post-run exertion influenced arch mechanics, but no significant correlations were found.

In the present study, it took slightly longer than 3.5 min for the participants to get off the treadmill, remove shoes, replace markers, and begin their post-run running trials. There was an 18% decrease in HR from immediately after the 45-min run to the first successful running trial. These 3.5 min may have likely allowed for some muscle recovery because one study found that isometric force decreased to 67% of baseline after fatiguing the posterior tibialis, but after 2 min of rest, it increased to 80% of baseline.\textsuperscript{39} Therefore, if the passive tissues, neuromuscular system, or cardiovascular system were stressed, recovery may have occurred during the transition from treadmill to overground running trials, possibly contributing to our null results.

Alternatively, other muscles or passive tissues may have compensated for possible fatigue, including the many intrinsic foot muscles. After increased barefoot activity over 4 months, arch length decreased more than 4 mm, which the authors suspected was due to increased intrinsic muscle activity.\textsuperscript{40} Perhaps the participants’ neuromuscular systems also responded to the two bouts of barefoot running trials by contracting more, shortening, and raising the arch. Because muscle activity was not monitored in the present study, changes in activation cannot be confirmed.

Effect of Sex

The ARI was not significantly different between men and women, which contrasts with Zifchock et al,\textsuperscript{26} who quantified arch stiffness slightly differently and found that men in the general population had stiffer arches. However, there was a trend toward greater stiffness in men in the present study before the run.

Interpretation of the results must be considered within the limitations of the study. One limitation is that skin artifact can be of the same magnitude as the changes observed in some individuals.\textsuperscript{28,41} For example, a navicular marker moved an additional
3.4 mm more in the plantar direction when going from standing to 5° everted. However, that study applied markers in nonweightbearing and assessed static orientations only. The effect of skin artifact was minimized in the present study by using a repeated-measures design, applying markers while equal weightbearing during standing, and using this standing position as a reference as opposed to nonweightbearing. However, we are confident that the measured values are reasonable as they agree with previous research, and radiographic evidence has shown that the arch goes through more than 20° of motion and the plantar fascia lengthens 9% to 12% compared with initial foot contact values during walking. Another limitation is that participants ran the 45 min shod but tested barefoot, which may represent slightly different arch deformation than shod running. Arch deformation may have been greater when running barefoot than shod because neuroreceptors indicated a rigid surface, and the arch may have adapted by becoming more compliant. We did not collect electromyography data to support or refute these assumptions.

Conclusions

Medial longitudinal arch deformation was relatively invariant after a 45-min run at a moderate intensity in healthy runners. If the arch-supporting structures were fatigued in this study, then the neuromuscular system must have compensated by recruiting different muscles or altering the forces causing the deformation. Alternatively, the arch-supporting structures may be resilient to the repetitive loading of a nonexhausting run. Future studies should analyze the relationship between arch deformation and both rearfoot motion and tibial rotation and should quantify shod arch deformation to see whether the foot responds differently. Shod analysis more precisely replicates how most runners run and would potentially eliminate the recovery time present in the study. In addition, analyzing arch motion after a more fatiguing run or a longer duration (e.g., a marathon) may reveal significant changes.

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Conflict of Interest: None reported.

References