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Original article

The effect of shoe type on gait in forefoot strike runners during a 50-km run

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Abstract

Purpose: To observe the relative change in foot-strike pattern, pressure characteristics, surface electromyography (sEMG) recordings, and stride characteristics in forefoot strike runners wearing both minimalist and traditional shoes during a 50-km run.

Methods: Four experienced minimalist runners were enrolled in this study. Each runner ran a 50-km simulated run in both minimalist shoes and traditional shoes. Pressure data, sEMG recordings, and limited 3D motion capture data were collected during the initial 0.8 km and final 0.8 km for each trial.

Results: Three runners in the traditional shoe type condition and one runner in the minimalist shoe type condition demonstrated a more posterior initial contact area (midfoot strike (MFS) pattern) after the 50-km run, which was supported by increased activity of the tibialis anterior in the pre-contact phase (as per root mean square (RMS) values). In addition, in both pre- and post-run conditions, there were increased peak pressures in the minimalist shoe type, specifically in the medial forefoot. Muscle fatigue as defined by a decreased median frequency observed in isometric, constant force contractions did not correspond with our hypothesis in relation to the observed foot strike change pattern. Finally, step rate increased and step length decreased after the 50-km run in both shoe type conditions.

Conclusion: More runners adopted a more posterior initial contact area after the 50-km run in the traditional shoe type than in the minimalist shoe type. The runners who adopted a more posterior initial contact area were more closely associated with an increased median frequency of the medial gastrocnemius, which suggests there may be a change in motor unit recruitment pattern during long-distance, sustained velocity running. The increased peak pressures observed in the medial forefoot in the minimalist shoe type may predispose to metatarsal stress fractures in the setting of improper training.

Keywords: Endurance; Fatigue; Foot-strike pattern; Running; Surface electromyography (sEMG)

1. Introduction

In 1989, Robbins et al.[1] suggested that runners may modify running form based on “impact moderating behavior(s)”. In 2010, Lieberman et al.[2] observed an impact transient, or sudden force of loading at initial contact, among different foot-strike patterns and shod conditions. The reduction of this impact transient in barefoot runners, as well as “minimalist” runners in Vibram Five Fingers, through adaptation of foot-strike pattern has been previously observed by Squadrone and Gallozzi,[3] as well as Divert et al.[4] In addition to a more forefoot strike (FFS) pattern, barefoot or minimalist runners have demonstrated reduced stride length, increased stride rate (or frequency), and decreased contact time.[3–6] In studies in which barefoot or minimalist runners did not alter foot-strike pattern, whether by instruction[5,7] or significant cushioning of the “minimalist” shoe,[6] this same reduction of impact transient has not been observed.

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Aside from barefoot and minimalist runners, another population theorized to benefit from a reduction of impact force are long-distance runners.[8] Laboratory studies, through the implementation of varying fatigue protocols, as well as "in-race" studies, have investigated this theory, most of which have suggested that impact force decreases with fatigue. Gerlach et al.[9] and Willson and Kernozek[10] have demonstrated a reduction in peak force, peak loading rate, peak pressure and pressure time integral under the heel after completion of a fatigue protocol. These findings are similar to the study of Morin et al.[11] during a 24-h treadmill protocol, as well as Millet et al.[12] during an 8500-km run by one runner over 161 days (52.8 km/day). Both "in-race" studies to date, which have been completed in marathon runners,[13] as well as ultramarathon runners,[14] have demonstrated a reduction in impact force.

Possible explanations for the reduction of impact force observed in long-distance runners after fatigue include change in foot-strike pattern and change in stride characteristics. Change in foot-strike pattern during race conditions has been studied previously in a marathon by Larson et al.[15] and an ultramarathon by Kasmer et al.[16] In both studies, more runners utilized a rearfoot strike (RFS) pattern near the middle or end of the race than at the beginning, suggesting that these long-distance runners were more likely to adopt an RFS pattern with presumed muscle fatigue. In the study by Kasmer et al.,[16] non-RFS runners were associated with an increased blood creatinine phosphokinase (CPK) level compared to RFS runners, suggesting that the change in foot-strike pattern from non-RFS to rear foot-strike may be influenced by muscle fatigue of the plantar flexors associated with non-rearfoot striking. Based on the study of Lieberman et al.,[2] who observed a greater impact transient with an RFS, this foot-strike change pattern would not support a decrease in impact force.

Change in stride characteristics following fatigue has likewise been studied. The majority of studies have suggested that step rate increases with fatigue while step length decreases with fatigue, as demonstrated by Willson and Kernozek[10] after a fatigue protocol, by Kyrolainen et al.[17]and Hausswirth et al.[18] after a marathon run, and by Morin et al.[11] after a 24-h treadmill run. The runner in the study by Millet et al.[12] also increased step rate after 161 days and approximately 8500 km. However, in contrast to these studies, Gerlach et al.[9] observed a decreased step rate and increased step length after a fatigue protocol, and Kasmer et al.[16] observed a decreased step rate and step length at the 90.3 km mark of a 161-km run. In the study by Kasmeret al.,[16] the authors also observed an increased number of "shufflers", defined by runners observed to be lacking the double float phase, at the 90.3 km filming site. The authors speculate that a decrease in step length with or without the incorporation of this "shuffling" pattern may reduce the impact force.

To the authors' knowledge, no study has attempted to analyze kinetic characteristics or stride characteristics in the combined setting, i.e., barefoot or minimalist runners after a long-distance run. This study attempted to fill this void by analyzing the kinetic and stride characteristics of runners in minimalist, as well as traditional shoes, both at the beginning and end of a 50-km run.

We hypothesized that experienced minimalist runners would transition from an FFS pattern to a more posterior foot-strike pattern due to plantar flexor muscle fatigue or damage, as previously demonstrated by significantly higher blood CPK values among non-RFS runners compared to RFS runners during an ultramarathon,[16] thus increasing the peak pressure over the heel in both shoe types. Furthermore, we predicted that surface electromyography (sEMG) recordings would demonstrate evidence of fatigue in the plantar flexors, associated with increased work with FFS, supportive of the transition to a more posterior foot-strike pattern. Finally, we hypothesized that stride rate would increase and stride length decrease during the run.

Therefore, the main objectives of this study are to (1) determine the relative change in foot-strike pattern and pressure characteristics in runners wearing both minimalist and traditional shoes after a 50-km run; (2) determine if sEMG demonstrates a fatigue pattern that corresponds to the observed change in foot-strike pattern in both shoe type conditions; and (3) determine the change in stride characteristics in runners wearing both minimalist and traditional shoes after a 50-km run.

2. Materials and methods

2.1. Participants

Four participants were successfully recruited for this study. Each participant met all inclusion/exclusion criteria: male <45 years old or female <55 years old; American College of Sports Medicine (ACSM) criteria for low-risk classification for coronary artery disease (CAD)[19] based on questions from participant's pre-protocol questionnaire; asymptomatic for cardiovascular/pulmonary disease; at least 1 year experience primarily running in minimalist shoes; run greater than 50-km in minimalist shoes within the past 12 months or run greater than 64.4 km (40 miles) per week and have the ability to run 50 km at 2.7 m/s; no injuries within the past 1 year as defined by medical treatment or stoppage of training for greater than 1 week due to injury; no current injury; and have the ability to follow study protocol, including the ability to wear the dynamic measuring system insoles. The study was approved by the institutional review board at Medical College of Wisconsin and each participant provided informed consent prior to enrollment in the study.

2.2. Data collection

Prior to data collection, each runner completed a questionnaire, including demographic information, running history, and injury history (Table 1). Participants were then randomized to either the minimalist shoe (New Balance Minimus Zero Trail; New Balance, Boston, MA, USA), with a heel-toe drop of zero millimeters, or traditional shoe (per runner

Table 1
Information about study participants.

	P1	P2	P3	P4
Demographic information				
Age (year)	31	25	31	25
Gender	Male	Male	Male	Male
Height (m)	1.85	1.78	1.80	1.73
Mass (kg)	88.5	65.8	72.6	63.5
Previous running history				
How long (year)?	25	10	15	10
When first minimalist (year)?	2.5	1	1.5	2
How long primarily minimalist (year)?	2.5	1	1.5	2
Minimalist shoes used	NB Minimus Trail, VFF, Vivo Barefoot	Merrell Sonic Glove	New Balance MT0	New Balance MT0
Current minimalist shoes	NB Minimus Trail, VFF, Vivo Barefoot	Innov-8 155, Merrell Sonic Glove	New Balance MT0	New Balance MT0
Ever received coaching?	N	Y	N	N
Most recent race results				
50 km time	4:51	–	–	–
Marathon time	3:05	–	2:54	–
1/2 Marathon time		1:21	1:34	1:27
Personal best race results				
50 km time	4:38	–	–	–
Marathon time	3:05	–	2:49	–
1/2 Marathon time	–	1:21	1:23	1:27
Current training history				
Days per week	6	6–7	5	5
Miles per week	65	50	35	50
Most recent 50 km (month)	2	–	–	3
Most recent marathon (month)	2	–	1	2
Injury history				
Any muscle aches/pains?	N	N	N	N
Last stoppage of running > 1 week	N	~4 years	N	N

preference) and were instructed to train for 4 weeks solely in the assigned shoe type prior to the initial data collection.

At the initial data collection, each runner received verbal instructions on the protocol. Warm-up was completed by individual preference. Height and body mass were collected. A heart rate monitor (Garmin Forerunner 910XT; Garmin International Inc., Olathe, KS, USA) was attached. Skin near anticipated electrode placement was prepped by shaving any body hair, abrading the skin with sandpaper, and cleansing with alcohol wipes to minimize impedance. Self-adhesive, disposable, Ag/AgCl snap electrodes (Noraxon USA Inc., Scottsdale, AZ, USA, interelectrode distance = 3.8 cm) were placed over the muscle belly according to SENIAM (Surface EMG for Noninvasive Assessment recommendations)[20] on the following muscles of the right leg: gluteus medius, rectus femoris, biceps femoris, anterior tibialis, and medial gastrocnemius. EMG signals were recorded at a frequency of 1500 Hz using a bipolar sEMG recording system (Noraxon USA Inc.). Following placement, each electrode was marked with indelible ink marker, and secured with ACE wraps. A Biodex System 3 Dynamometer (Biodex Medical Systems, Shirley, NY, USA) was used to perform maximum voluntary contractions (MVCs) for hip abduction, knee extension, knee flexion, ankle dorsiflexion, and ankle plantar flexion. Three trials, each 5 s duration, were conducted for each muscle on the dominant side only. Following MVC collection, PEDAR dynamic measuring system insoles (novel GmbH, Munich, Germany) were properly fit into each shoe and calibrated by zeroing each insole while off-loaded. Reflective markers were placed on participant's heel and toe of the right leg. A Vicon T-Series Electromagnetic Motion Tracking System (Polhemus Inc., Cochester, VT, USA) was used to capture the movement of the reflective markers at a sampling rate of 60 Hz for determination of initial contact and toe-off. Each participant completed a 0.8-km treadmill (Landice L8; Landice, Randolph, NJ, USA) run at 2.7 m/s. Heart rate recordings were documented every 0.16 km. Motion capture, PEDAR, and sEMG recordings were collected for 10 consecutive seconds at 0.32-km and 0.64-km distances. Each participant also volunteered a rating of perceived exertion (RPE) score via the Borg RPE index,[21] as well as subjective identification of any specific muscle group(s) that felt "fatigued", at 0.32 km and 0.64 km distances. Following completion of the 0.8-km treadmill run, skin markings were verified and sEMG electrodes were removed, as well as the PEDAR insoles, reflective markers, and heart rate monitor. Each participant then completed a 7-loop, 48.4-km outdoor run at an approximate speed of 2.7 m/s. The runner's course was mapped throughout suburban Milwaukee, Wisconsin, USA, mostly on sidewalks, during late fall (ambient temperature ranged from 0 to 16 °C) with an overall elevation change of approximately 500 m (max elevation of 250 m). Fluid and nutrition replacement was set-up prior to beginning the outdoor run by each individual at one location, which the runner passed on each loop, or seven times, during the course of the run. Following completion of the 48.4-km run, each participant's skin was wiped off with a dry towel and sEMG electrodes, PEDAR insoles, reflective markers, and heart rate monitor were all replaced. Mean time for replacing measuring equipment and starting the treadmill run was approximately 2 min, similar to that reported by Kellis et al.[22] Each participant then completed another 0.8-km treadmill run, with heart rate recordings documented at 0.16-km intervals and motion capture, PEDAR, and sEMG recordings collected at 0.32-km and 0.64-km distances, as well as post-run MVCs, in similitude with pre-50-km run methods. Upon completion, each participant was crossed over to the opposite shoe type and instructed on re-training in the opposite shoe type for 4 weeks. Following crossover and re-training, data collection was repeated for each participant in the opposite shoe type.

2.3. Data processing

Mean PEDAR insole pressure data (inclusive of instant of peak pressure, peak pressure, maximum force, pressure time integral, and contact area) were calculated by PEDAR X software for each runner for each shoe type in both pre- and post-run conditions for each of the 8-foot segments (Fig. 1), as previously defined by Liu et al.[23] Initial foot segment contact was determined by examination of foot pressure patterns using PEDAR X software for each foot of each runner. Initial contact and toe-off were determined for each runner by analysis of the reflective markers, from which mean step rate and mean step length were calculated. The raw sEMG signals were filtered using MATLAB signal processing tool box (The Mathworks, Natick, MA, USA). A Butterworth filter with a low-pass frequency of 20 Hz and high-pass frequency of 400 Hz was applied. The median frequency of the filtered sEMG signal was calculated with custom MATLAB code that utilized MATLAB's power spectral density function for each muscle group sampled in each runner. Custom MATLAB software was utilized to calculate the root mean square (RMS) of the filtered sEMG signal using a 50-ms window for each muscle group sampled in each runner during the following three phases as defined by Kellis et al.:[21] pre-contact (defined as 100 ms prior to initial contact), initial loading response (defined as the 50-ms interval immediately following initial contact), and main loading response (defined as the period between 50 and 200 ms after initial contact).

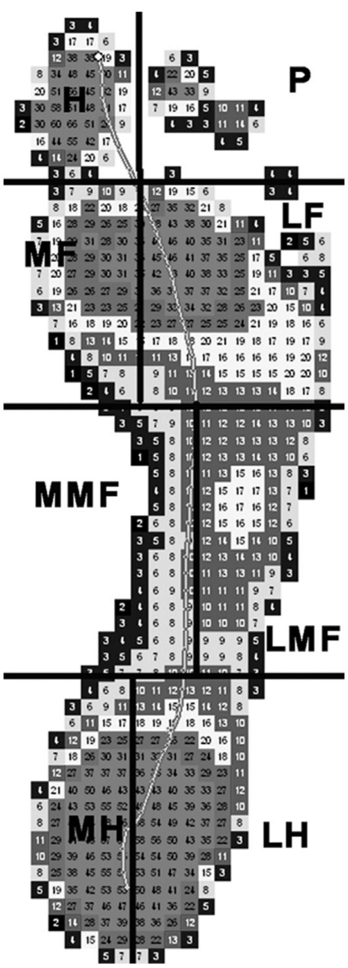

Fig. 1. Insole pressure mapping. MH = medial heel; LH = lateral heel; MMF = medial midfoot; LMF = lateral midfoot; MF = medial forefoot; LF = lateral forefoot; H = hallux; P = phalanges.

2.4. Statistical analysis

Paired t tests were used to compare pressure characteristics, stride characteristics, sEMG data, RPE, heart rate, and body mass among different shoe type and pre- *vs.* post-run condition using R version 2.12 (R Foundation for Statistical Computing, Vienna, Austria). Significance was set at $p < 0.05$.

3. Results

Instant of peak pressure, as a percentage of the gait cycle, and peak pressure are reported by foot segment for each shoe type in both pre- and post-run conditions in Fig. 2. There were no significant differences in instant of peak pressure by shoe type. There were no significant changes in instant of peak pressure between pre- and post-run conditions, except for an earlier instant of peak pressure in the lateral forefoot in the minimalist shoe type and in the hallux in the traditional shoe type in the post-run condition ($p < 0.05$). There was a significantly greater peak pressure in the minimalist shoe type compared to the traditional shoe type in the medial forefoot ($p < 0.05$) and lateral forefoot ($p < 0.01$) in the pre-run condition and in the lateral heel and lateral forefoot in the post-run condition ($p < 0.05$). There was a significantly greater peak pressure in the post-run compared to pre-run condition in the medial heel and lateral heel ($p < 0.05$) in the minimalist shoe type; whereas, there was a significantly lower peak pressure time in the post-run compared to pre-run condition in the lateral midfoot, lateral forefoot, and hallux ($p < 0.05$) in the minimalist shoe type, as well as the medial midfoot ($p < 0.01$) and medial forefoot ($p < 0.05$) in the traditional shoe type. There were no significant differences in contact area by shoe type except in the medial midfoot in the post-run condition ($p < 0.05$), where contact area was smaller in the minimalist shoe type as compared to the traditional shoe type. There was a significantly greater pressure time integral observed in the minimalist shoe type compared to the traditional shoe type in the medial heel post-run ($p < 0.05$), and lateral forefoot both pre- ($p < 0.01$) and post-run ($p < 0.05$). There was a significantly greater pressure time integral in the post-run compared to pre-run condition in the medial heel ($p < 0.05$) in the minimalist shoe type; whereas, there was a significantly lower pressure time integral in the post-run compared to pre-run condition in the lateral forefoot ($p < 0.01$), and hallux ($p < 0.05$) in the minimalist shoe type, as well as the medial midfoot ($p < 0.05$) and medial forefoot ($p < 0.05$) in the traditional shoe type. There was also a significantly greater maximum force between the pre- and post-run conditions in the medial heel in the minimalist shoe type ($p < 0.01$).

Median frequency of the sEMG recordings was reported by foot segment for each shoe type in both pre- and post-run conditions in Fig. 3. There were no significant differences in median frequency in the pre-run compared to post-run

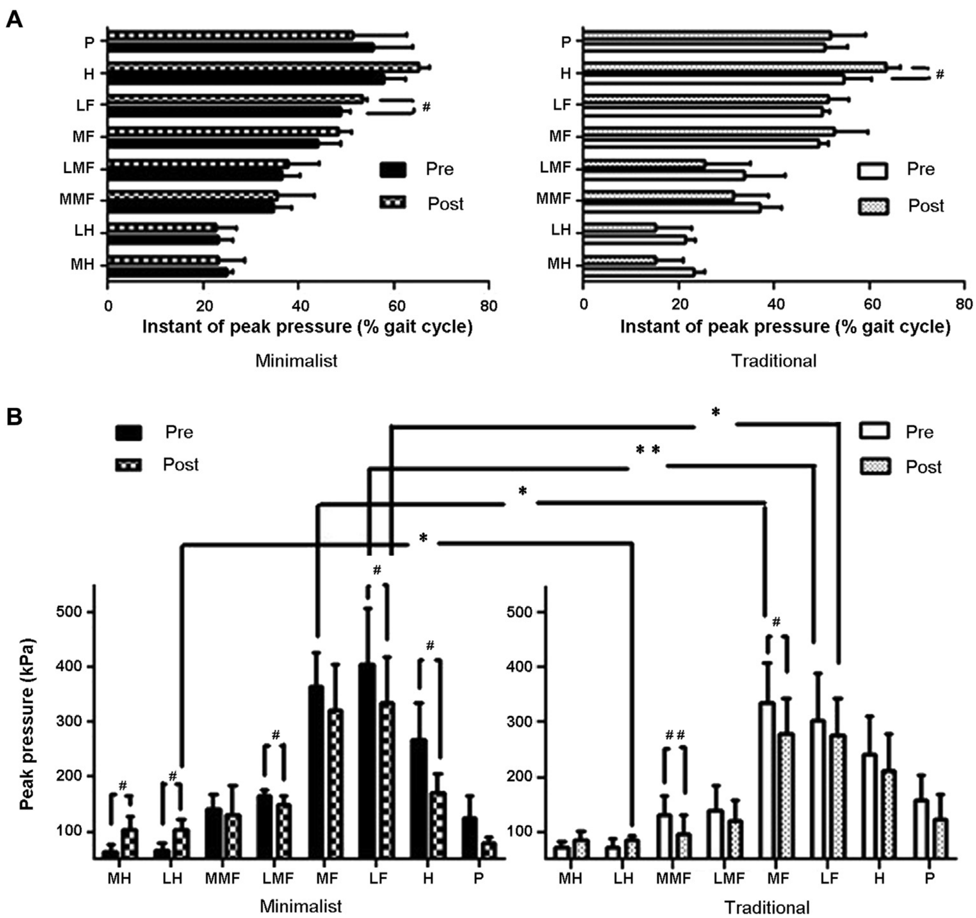

Fig. 2. Instant of peak pressure (% gait cycle) (A) and peak pressure (kPa) (B) by foot segment. MH = medial heel; LH = lateral heel; MMF = medial midfoot; LMF = lateral midfoot; MF = medial forefoot; LF = lateral forefoot; H = hallux; P = phalanges. $^{*}p < 0.05$, $^{**}p < 0.01$, compared between different shoe types; $^{\#}p < 0.05$, $^{\#\#}p < 0.01$, compared between pre- and post-run conditions.

condition, except in the rectus femoris ($p < 0.05$) in the minimalist shoe type, where the median frequency was greater in the post-run condition. There were no significant differences in median frequency by shoe type except in the hip abductor in the post-run condition ($p < 0.05$), where the median frequency was less in the traditional shoe type. During the pre-contact phase, there was a significantly greater RMS value during the post-run condition as compared to the pre-run condition in the tibialis anterior in both shoe types ($p < 0.05$). During the initial loading response, there were no significant differences in RMS values. During the main loading response, there was a significantly greater RMS value in the post-run than the pre-run condition in the hip abductors in the minimalist shoe type ($p < 0.05$), as well as a significantly greater RMS value in traditional shoe type compared to the minimalist shoe type in the tibialis anterior in both pre-

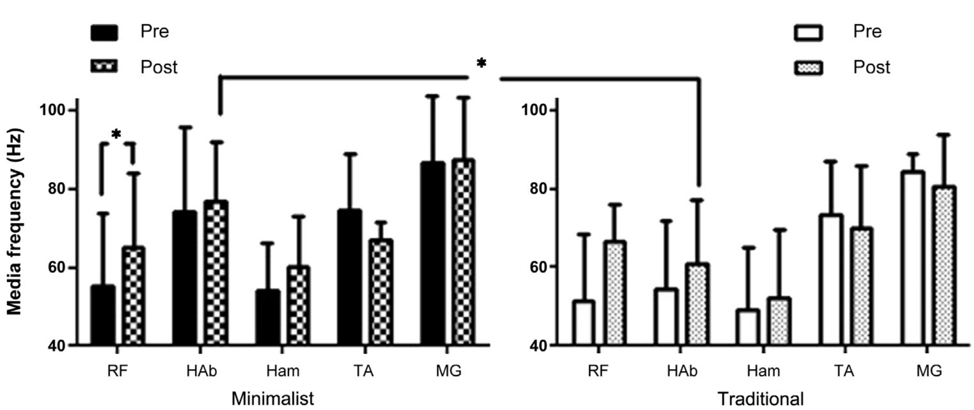

Fig. 3. Median frequency. RF = rectus femoris; HAb = hip abductors; Ham = medial hamstrings; TA = tibialis anterior; MG = medial gastrocnemius. $^{*}p < 0.05$.

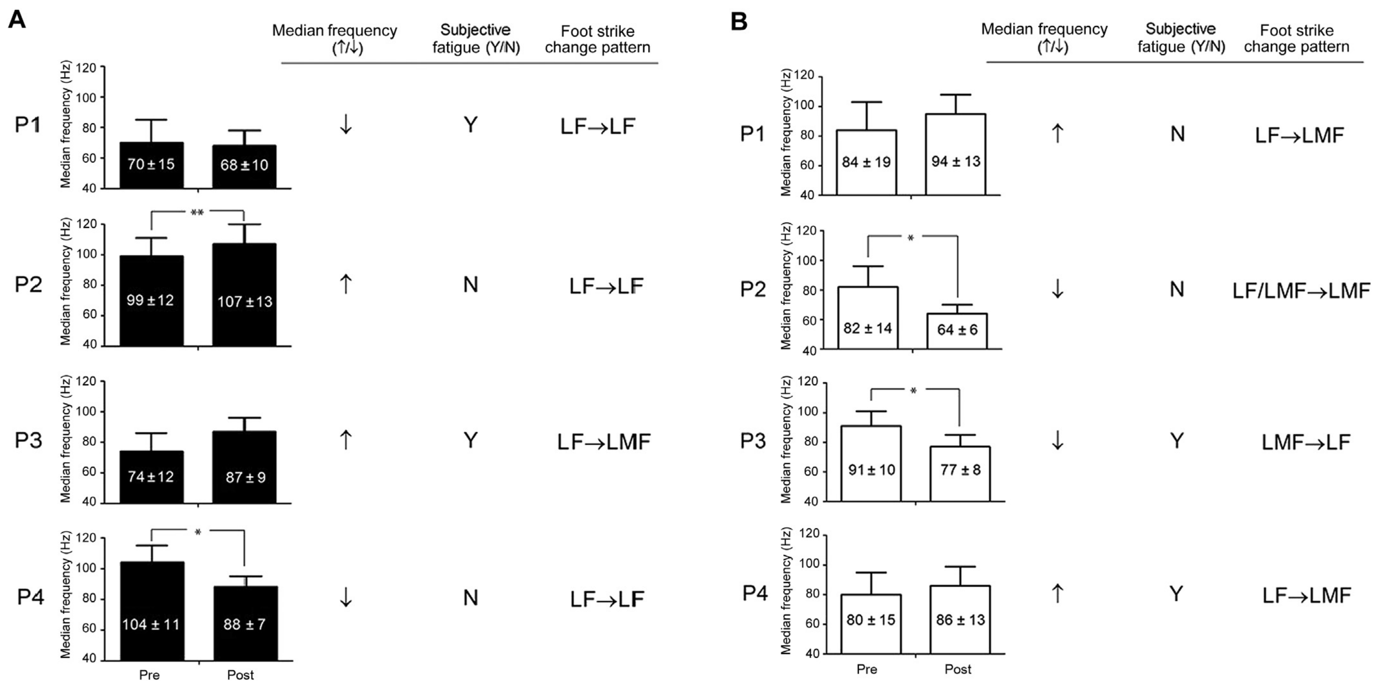

Fig. 4. Median frequency (Hz) of medial gastrocnemius, subjective fatigue, and change in initial foot segment contact (i.e., foot-strike change pattern) by participant in the minimalist (A) and the traditional shoe type (B) conditions. P2 had an asymmetric foot-strike post-run in the traditional shoe type. LF/LMF refers to right foot/left foot. *$p < 0.05$, **$p < 0.01$.

($p < 0.01$) and post-run ($p < 0.05$) conditions. Median frequency of the sEMG recordings of the medial gastrocnemius for individual runners, as well as change in median frequency of the medial gastrocnemius in the pre-run compared to post-run condition, subjective fatigue post-run, and change in initial contact area in the pre-run compared to post-run condition, by shoe type is reported in Fig. 4.

Comparison of step rate and step length by shoe type in pre- and post-run conditions is demonstrated in Fig. 5. RPE values significantly increased between pre- and post-run conditions in both minimalist ($p < 0.05$) and traditional ($p < 0.05$) shoe types. Heart rate also significantly increased between pre- and post-run conditions in both shoe types ($p < 0.05$). Body mass reduction ranged from 0.4 to 3.6 kg per runner, averaging between 1.4 and 3.4 kg per runner, but did not represent a significant difference between pre- and post-run conditions in either shoe type. RPE, heart rate, and body mass did not vary significantly by shoe type in either the pre- or post-run conditions. Two of the four runners reported fatigue in the gastrocnemius in the post-run condition in minimalist shoe type; two of the four runners also reported fatigue in the gastrocnemius in the post-run condition in the traditional shoe type.

4. Discussion

As initially hypothesized, experienced minimalist runners did alter gait pattern between pre- and post-run conditions, as previously observed by Larson et al.[15] and Kasmer et al.[16] The observed foot-strike pattern from an FFS to a more posterior-footstrike (MFS) was more common among runners in the traditional shoe type. There were four runners who demonstrated a shift in initial contact area from lateral forefoot to lateral midfoot after the 50-km run: one runner (both feet) in

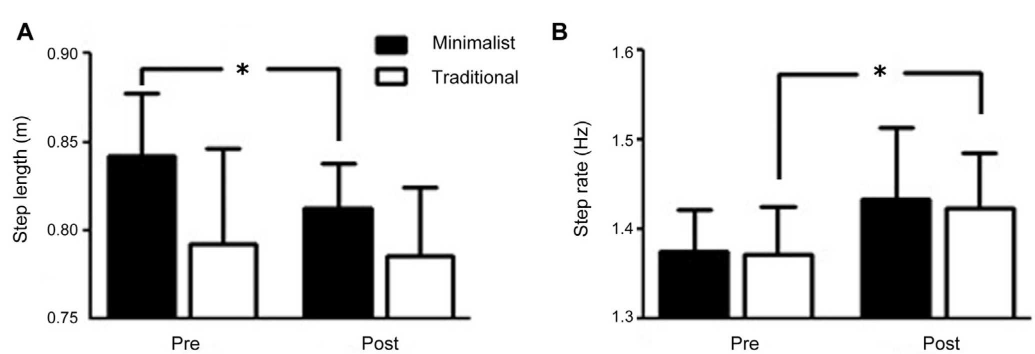

Fig. 5. Comparison of step length (A) and step rate (B) by shoe types. *$p < 0.05$.

the minimalist shoe type condition and three runners (2 runners both feet, 1 runner 1 foot) in the traditional shoe type condition (Fig. 4). The observed foot-strike change pattern was further supported by the increased muscle activity, as per the observed increased RMS values, during the pre-contact phase in the tibialis anterior in both shoe type conditions post-run compared to pre-run, similar to previous results of Cheung et al.,[24] as well as a trend noted by Kellis et al.,[22] suggesting a more dorsiflexed foot preparatory to initial contact. Of note, given the traditionally accepted foot-strike classifications as described by Lieberman et al.,[2] this shift in initial contact area represents a shift from an FFS classification to an MFS classification, but not an RFS classification.

The observed foot-strike change resulted in an increased peak pressure, pressure time integral, and maximum force under the heel. These findings were only significant in the minimalist shoe type, suggesting that when foot-strike pattern was altered, even if not noted by a clear differentiation from FFS to MFS, the resultant increased peak pressure, pressure time integral, and maximum force were more pronounced in the minimalist shoe type. This finding suggests that the driving etiology of the change in foot-strike pattern may not be impact force, but another variable, such as muscular fatigue, which will be discussed later. The increased peak pressure under the heel (significant in the minimalist shoe type) post-run is contrary to previous studies of Gerlach et al.[9] and Willson and Kernozek[10] that noted decreased peak pressure under the heel. The likely explanation was the contradictory change in foot-strike pattern. In this study, most runners either changed from an FFS to an MFS or maintained an FFS both pre- and post-run. In the previous studies, as documented by Gerlach et al.,[9] the foot-strike change pattern was likely a more dorsiflexed RFS to a less dorsiflexed RFS. Thus, the change pattern in this study is in the opposite direction of the change pattern of previous studies, resulting in the exact opposite direction of change in peak pressure under the heel.

In addition to pre- and post-run differences in peak pressure, there was a significantly greater peak pressure in multiple foot segments observed in the minimalist shoe compared to the traditional shoe, namely the lateral heel, as well as the medial and lateral forefoot. This existed in two foot segments in the pre-run condition and two foot segments in the post-run condition. This finding is consistent with a well-known complication of transitioning to a minimalist shoes, specifically metatarsal stress fractures, as initially described by Giuliani et al.[25] and more recently Ridge et al.[26] Thus, the finding of increased peak pressure, specifically in the medial forefoot, in the minimalist shoe type, combined with an inadequate transition time to allow for bone remodeling, muscle fiber adaptations, and neuromuscular reprogramming may predispose minimalist runners to an increased risk of metatarsal stress fractures.

The proposed etiology for the observed change in foot-strike pattern was muscle fatigue, specifically muscle fatigue of the plantar flexors, based on work by Kasmer et al.[16] in ultramarathon runners. This work demonstrated significantly higher CPK values among non-RFS runners compared to RFS runners after a 161-km run, likely a result of the eccentric loading of the plantar flexors seen in an FFS pattern and absent in an MFS or RFS pattern.[8,10] Thus, it was hypothesized that in addition to observing a change in foot-strike pattern after a 50-km run, we would likewise observe fatigue in the gastrocnemius, specifically by an observed decrement in median frequency in the sEMG recordings pre- to post-run.[27,28] However, there was no decrement in median frequency observed from pre- to post-run condition in either shoe type condition observed in the combined data of all four runners.

Further investigation of median frequency of the medial gastrocnemius, subjective fatigue, and foot-strike change pattern by individual runner by shoe type is displayed in Fig. 4. When examining our data on an individual basis, our hypothesis that each foot-strike change from forefoot to midfoot would be supported by a corresponding decrease in median frequency (and *vice versa*) between pre- and post-run was not supported. In fact, each runner who did change foot-strike pattern from forefoot to midfoot was associated with a trend toward an increased median frequency. However, to the authors' knowledge, there have only been two such "long-distance" running protocols examining median frequency of various muscles during prolonged, constant speed running,[24,29,30] in which one study[30] demonstrated an increase in median frequency of the rectus femoris, biceps femoris, anterior tibialis, and medial gastrocnemius during a constant speed, 30-min treadmill run. Wakeling et al.[30] suggested the findings are the result of a change in the motor unit recruitment pattern during sustained submaximal activity, specifically that runners may increase recruitment of fast-twitch fibers and de-recruit slow-twitch muscle fibers in a time-dependent manner in order to generate the power output necessary to maintain a constant speed. In the present study, each trial in which the runner changed foot-strike pattern from an FFS in the pre-run condition to an MFS in the post-run condition (P3 in the minimalist shoe type; P1 and P4 in the traditional shoe type) was accompanied by a trend toward an increase in median frequency of the medial gastrocnemius after the 50-km run. This finding was consistent with the fatigue pattern demonstrated in the experiment of Wakeling et al.,[30] suggesting that a similar change in motor unit recruitment pattern may be contributing to the change in median frequency observed in the present study. Thus, muscle fatigue of the gastrocnemius, as well greater muscle damage, as observed as significantly greater CPK values among non-RFS runners than RFS runners after a 161-km ultramarathon, may contribute to the change of foot-strike pattern in long-distance runners. However, further investigation is warranted to support this theory, as well as alternative explanations that may contribute to the findings in the present study.

Our final hypothesis, i.e., that step rate would increase and step length would decrease in the post-run condition in both shoe types was consistent with our findings, as well as with previous studies, namely a high-intensity, relatively short distance fatigue protocol,[10] a marathon distance,[17] and ultramarathon distances.[11,14]

As expected, the completion of a 50-km run resulted in a significant increase in RPE between pre- and post-run conditions, consistent with a previous ultramarathon distance study of Martin et al.[31] Of the four runners that subjectively identified post-run gastrocnemius fatigue (1 runner in both shoe types, 1 runner in only the minimalist shoe type, and 1 runner in only the traditional shoe type), two runners demonstrated an increased median frequency and altered the initial contact area from lateral forefoot to lateral midfoot. The other two runners that subjectively identified post-run gastrocnemius fatigue demonstrated a decreased median frequency and did not alter initial contact area between lateral forefoot and lateral midfoot. In addition, heart rate elevations were observed consistently between pre- and post-run conditions, within expectations for an endurance-type event. Heart rate was between 116 and 150, or 59%−77% of estimated maximum heart rate, as determined by 220 − age. Of note, each runner experienced a reduction in body mass over the 50-km run for each trial, between 0.4 kg (0.6%) and 3.6 kg (4.3%), within the range of findings observed in a recent study of marathon runners, where mean body mass reduction was 2.2% ± 1.2%.[32]

5. Conclusion

This study analyzed both kinetic and stride characteristics of runners in minimalist, as well as traditional shoes, both at the beginning and end of a 50-km run through the collection of pressure data, sEMG recordings, and limited 3D motion capture data. Of significance, the runners in this study who adopted a more posterior initial contact area after the 50-km run were those more closely associated with muscle fatigue of the gastrocnemius as defined by the theory of Wakeling et al.,[30] which may accompany long-distance, sustained velocity running. In addition, peak pressures were significantly greater in the minimalist shoe type, specifically in the medial forefoot, which may predispose to an increased risk of metatarsal stress fractures in the setting of improper training.

Due to the limited study size of only FFS runners, the ability to generalize to all runners of varying foot-strike patterns must be cautioned. Additional studies are necessary to (a) validate the observed findings of altered gait pattern, pressure data, and stride characteristics as a result of fatigue in both shoe type conditions; (b) further investigate the applicability of the isometric, constant force contraction theory in a dynamic, endurance exercise, such as running; and (c) further investigate the proposed theory of change in motor unit recruitment etiology observed during sustained, submaximal activity, such as endurance running.

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