[Physical Therapy]

Effect of Minimalist Footwear on Running Efficiency: A Randomized Crossover Trial

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Background: Although minimalist footwear is increasingly popular among runners, claims that minimalist footwear enhances running biomechanics and efficiency are controversial.

Hypothesis: Minimalist and barefoot conditions improve running efficiency when compared with traditional running shoes.

Study Design: Randomized crossover trial.

Level of Evidence: Level 3.

Methods: Fifteen experienced runners each completed three 90-second running trials on a treadmill, each trial performed in a different type of footwear: traditional running shoes with a heavily cushioned heel, minimalist running shoes with minimal heel cushioning, and barefoot (socked). High-speed photography was used to determine foot strike, ground contact time, knee angle, and stride cadence with each footwear type.

Results: Runners had more rearfoot strikes in traditional shoes (87%) compared with minimalist shoes (67%) and socked (40%) ($P = 0.03$). Ground contact time was longest in traditional shoes (265.9 ± 10.9 ms) when compared with minimalist shoes (253.4 ± 11.2 ms) and socked (250.6 ± 16.2 ms) ($P = 0.005$). There was no difference between groups with respect to knee angle ($P = 0.37$) or stride cadence ($P = 0.20$). When comparing running socked to running with minimalist running shoes, there were no differences in measures of running efficiency.

Conclusion: When compared with running in traditional, cushioned shoes, both barefoot (socked) running and minimalist running shoes produce greater running efficiency in some experienced runners, with a greater tendency toward a midfoot or forefoot strike and a shorter ground contact time. Minimalist shoes closely approximate socked running in the 4 measurements performed.

Clinical Relevance: With regard to running efficiency and biomechanics, in some runners, barefoot (socked) and minimalist footwear are preferable to traditional running shoes.

Keywords: running biomechanics; traditional shoes; minimalist shoes; foot strike; ground contact time

Humans have been running for millions of years, but the modern running shoe was not invented until the 1970s.[11,15] However, in the span of just 4 decades, this novel type of footwear with a heavily cushioned, elevated heel; arch support; and a stiffened midsole ("traditional shoe") has altered running biomechanics and changed the way people run.[14] Investigators contend that because of this shift to traditional running shoes, today, 75% to 80% of shod runners (those wearing shoes) use a rearfoot strike (RFS), which was previously uncommon.[4,7,9] Developed to increase the comfort and safety of running, traditional running shoes have been unable to decrease the incidence of running-related injuries.[13,15,16] In fact, many suggest a link between the persistently high incidence of injuries and the modern traditional running shoe.[13,15,16]

Minimalist running shoes seek to address the shortcomings of traditional shoes. They are distinguished by a less cushioned heel and reduced heel-forefoot offset, greater sole flexibility, and lack of arch support and motion control.[1] Spurred in part by Christopher McDougall's bestselling book, *Born to Run*, many runners are switching to minimalist shoes hoping to run faster and suffer fewer injuries.[12]

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Table 1. Runners' characteristics

Characteristic	Mean ± SD or N[a]
Age, y	16.07 ± 1.07
Height, m	1.76 ± 0.04
Weight, kg	61.14 ± 6.48
Weekly mileage	21.86 ± 9.84
5K pace, min:s	18:44 ± 1:08
Training shoe type	
Traditional	N = 9
Minimalist	N = 5
Barefoot	N = 0

[a]Data available for 14 of 15 subjects.

Several studies have examined the effects of traditional running shoes on running biomechanics, most notably on foot strike.[7,9-11,14] Related studies demonstrate that selected biomechanical factors, including foot strike, ground contact time, stride cadence, and knee angle, influence running efficiency.[3,6,8,11,14] However, there are limited data comparing the impact of the 3 distinct types of running footwear—traditional shoes, minimalist shoes, and barefoot running—on running efficiency (eg, VO_2max or cost of transport).

Accordingly, the first objective of this study was to determine the effect of traditional, minimalist, and barefoot footwear on running biomechanics and efficiency through analysis of foot strike, ground contact time, stride cadence, and knee flexion angle at foot strike. Second, this study sought to establish whether minimalist footwear approximates barefoot running in these 4 measures of running biomechanics.

METHODS

Subjects

The trial protocol was approved by the Anderson Scholars Program at University School. Running biomechanics were measured in 15 male varsity high school cross-country runners, aged 14 to 18 years (Table 1). All subjects were experienced runners, especially at the 5K (5 kilometers) distance, with a mean 5K personal best time of 18:44 ± 1:08 (minutes:seconds) and a mean weekly mileage of 21.86 ± 9.84 mi. Recreational runners and those either injured or recovering from injury were excluded. Data regarding running habits were available for 14 of 15 subjects. Of the 14 subjects, 9 trained in a traditional shoe and 5 trained in a minimalist shoe. Each subject voluntarily provided this preliminary data and agreed to participate in the study of his own volition, giving written informed consent to participate.

Shoes

For each experimental trial, each subject ran in 3 distinct types of footwear: a traditional shoe (with a heavily cushioned heel, arch support, and a stiff sole), a minimalist shoe (lacking these features), and socked (thin socks to prevent blistering). Traditional shoes were the New Balance M880v3 (319 g, 12-mm heel-to-toe drop); minimalist shoes were the New Balance Minimus 10v2 Trail (184 g, 4-mm heel-to-toe drop); socked running was used for the third footwear condition to mimic the natural, barefoot running condition.

Camera and Setup

Each subject completed 3 trials on a Matrix T7xe treadmill. Subjects were filmed using a Nikon 1 S1 camera. The high-speed film rate of 60 fps allowed for clear frames of the subject's lower body at every instance of their gait (Figure 1).

Experimental Protocol

The trial was designed as a prospective, randomized crossover trial. For each subject, the order of footwear trials (eg, traditional, minimalist, socked) was randomly assigned by a computer program. Prior to being tested, each subject warmed-up for 5 minutes on the treadmill in his normal running shoes. Black reflective tape was applied to 3 distinct points on each subject's right leg: the lateral malleolus, the lateral femoral condyle, and the greater trochanter. These 3 points form the flexion angle measured at ground contact for each subject in each type of footwear.

Subjects were instructed to run comfortably in their natural form. Each subject began running at $3.58\ m \cdot s^{-1}$ (average training pace, $3.79\ m \cdot s^{-1}$; a slightly slower pace was chosen to accommodate those runners who trained at a slower pace). The subject acclimated to the pace over the course of 30 seconds. Then, the subject was filmed for 90 seconds, with the camera focused on the foot and ankle for the first 60 seconds (to measure foot strike, ground contact time, and stride cadence) and the entire leg for the final 30 seconds (to measure knee flexion angle). Preliminary studies in 5 subjects revealed that 90-second trials enabled reliable collection of all data points. After the 90-second period terminated, the subject rested for 5 minutes and subsequently repeated the same trial in the second and third types of footwear. Preliminary studies revealed that subjects felt fully recovered within 5 minutes.

Film Review

The film was analyzed for the 4 outcomes using Tracker, a video analysis and physics program.[2]

Definitions of foot strikes from Hasegawa et al[7] were followed for a rearfoot strike (RFS), midfoot strike (MFS), and forefoot strike (FFS). Foot strike was determined at 3 evenly spaced intervals throughout the 60-second film clip. After independent determination of foot strike findings, the reviewers compared data and resolved any discrepancies by an independent subsequent film review.

Ground contact time (GCT) was determined quantitatively in Tracker[2] as the time from initial foot strike to toe-off.[7] GCT was

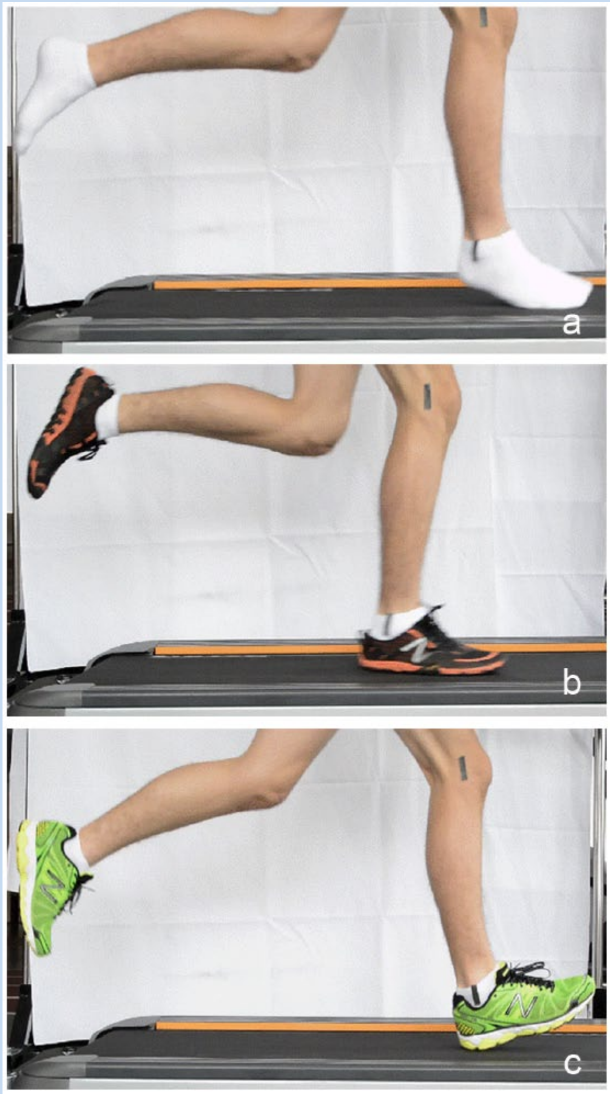

Figure 1. Still frames capturing 3 foot strikes used to determine type of foot strike at ground contact: (a) forefoot strike in socked condition, (b) midfoot strike in minimalist shoes, and (c) rearfoot strike in traditional shoes.

measured 3 times for each footwear trial, and the mean of these 3 measurements was used for comparison.

Stride cadence (SC) was measured in Tracker[2] over a 60-second period. Each foot strike throughout the interval was counted, resulting in the number of foot strikes per minute for each type of running footwear.

Knee flexion angle at ground contact (KA) was measured using Tracker.[2] Three measurements for KA were determined using the reflective tape placed on the right leg. The supplements of these angles (ie, the acute angle formed with the lower leg and the extension of the upper leg past the knee as sides of the angle) were then calculated and used for analysis.[5]

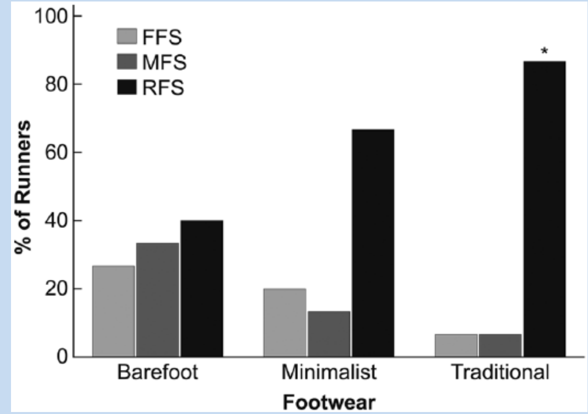

Figure 2. Percentage of runners with each foot strike according to type of footwear. FFS, forefoot strike; MFS, midfoot strike; RFS, rearfoot strike. *$P = 0.03$ vs barefoot and minimalist footwear.

Statistical Analysis

Continuous data are expressed as mean ± standard deviation. Kruskal-Wallis 1-way analysis of variance tests were used to analyze group differences for continuous data. Group comparisons were made using chi-square tests (Fisher exact tests if appropriate). Each runner served as his own control.

Multivariable polytomous logistic regression analysis was used to determine the factor(s) most associated with group differences. With footwear group as the outcome, all biomechanics variables (foot strike, GCT, SC, and KA) were forced into the model (Appendix 1, available at http://sph.sagepub.com/content/by/supplemental-data).

A sample size of 13 runners was necessary to detect a 5% decrease in ground contact time, assuming an average ground contact time in traditional shoes of 270 ± 11 ms (based on preliminary studies), with a 2-sided type 1 error rate = 0.05 and 90% power.

All statistical analyses were performed using SAS (version 9.2; SAS Inc).

RESULTS

Foot Strike

Subjects were more likely to use an RFS in traditional shoes (86.7%) than in minimalist shoes (66.7%) or in the socked condition (40%) ($P = 0.03$) (Figure 2). Conversely, FFS and MFS were more common in the socked condition (FFS, 27%; MFS, 33%) and minimalist shoes (FFS, 20%; MFS, 13%) than in traditional shoes (FFS, 7%; MFS, 7%) (Figure 2).

Ground Contact Time

Mean GCT was the longest in traditional shoes, shorter in minimalist shoes, and shortest in the socked condition ($P = 0.005$) (Figure 3). There was no statistical difference between GCT in minimalist shoes and the socked condition,

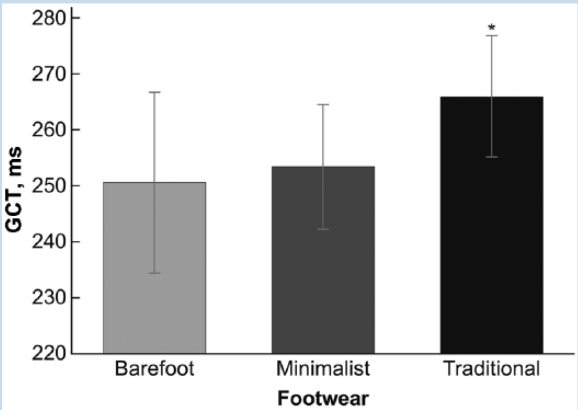

Figure 3. Mean ground contact time (GCT; in milliseconds) according to type of footwear. Error bars represent ±1 SD. *P = 0.005 vs barefoot and minimalist footwear.

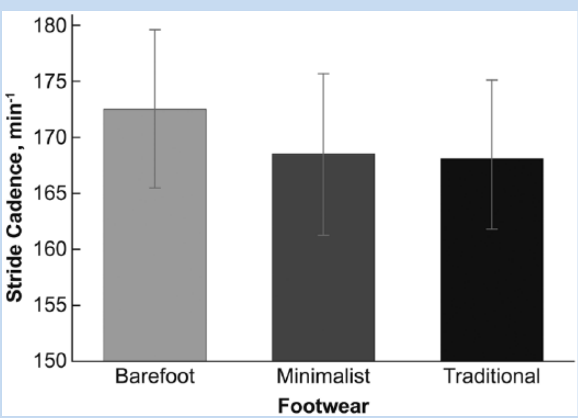

Figure 4. Mean stride cadence (in min^{-1}) according to type of footwear. Error bars represent ±1 SD.

although both did yield significantly shorter GCTs than did traditional shoes (Figure 3).

Stride Cadence and Knee Angle

Both SC and KA tended to decrease as cushioning increased (Figures 4 and 5, respectively). However, there was no significant difference among the groups with respect to SC (P = 0.20) or KA (P = 0.37).

Multivariable Analysis

Considering all running biomechanics simultaneously in a multivariable model, only GCT differed between the 3 groups. With respect to individual comparisons in the adjusted model, GCT in traditional shoes was significantly higher than in both minimalist shoes (P = 0.020) and in the socked condition (P = 0.023).

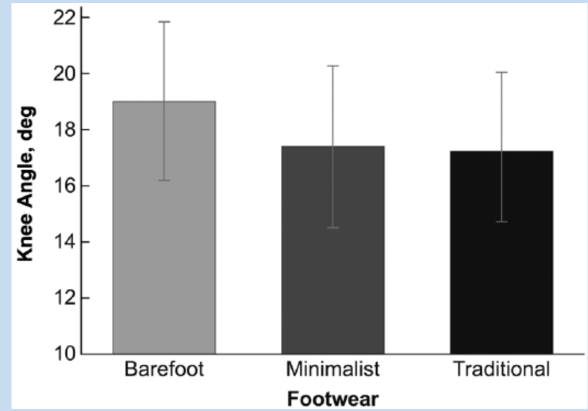

Figure 5. Knee flexion angle at ground contact (in degrees) according to type of footwear. Error bars represent ±1 SD.

DISCUSSION

Compared with traditional shoes, minimalist shoes and barefoot (socked) running facilitated a midfoot or forefoot strike in the group of experienced high school runners. Minimalist shoes and socked running resulted in a shorter GCT than traditional running shoes. Minimalist shoes also approximated socked footwear in all 4 measures of running biomechanics: foot strike, GCT, SC, and KA at ground contact.

Taken together, these findings suggest that minimalist shoes and barefoot running are associated with improved running biomechanics when compared with traditional shoes by certain measures. While we did not measure VO_2max, each of our biomechanical outcome variables has been associated with running efficiency.[5,7,8] Hasegawa et al[7] demonstrated that MFS or FFS leads to increased running efficiency. In addition, a shorter GCT correlates with a higher cadence, which may lead to greater running efficiency.[7] Heiderscheit et al[8] found that increases of 5% to 10% in SC can substantially reduce the loading on the hip and knee joints. Finally, greater flexion can reduce the peak vertical ground reaction force, suggesting that increased KA at ground contact correlates with improved running efficiency.[5] These correlations between biomechanics and efficiency suggest that minimalist shoes and barefoot footwear may improve running efficiency.

The analysis of biomechanical outcomes supports previous work in the field.[7,10,11] Across all trials and regardless of the type of footwear being tested, the majority of runners (64.4%) used an RFS in this study; other studies, conducted both in road races[7,10] and over multiyear periods,[4] suggest this finding. Habitually shod American adults RFS 100% of the time, while habitually barefoot American adults RFS only 25% of the time.[11]

While several studies suggest improved biomechanics and efficiency with barefoot running and/or minimalist footwear,[6,11,13] the question of whether these perceived advantages confer protection from injury remains controversial.[15,17] Running-related injuries have a wide variety of causes, and some question whether changing the biomechanics of running might simply change the pattern of injury. For instance, knee and ankle loading has been studied in different footwear, showing that barefoot and minimalist footwear reduced stress at the knee but increased Achilles tendon forces when compared with traditional shoes.[17] A switch to minimalist footwear has been correlated with the development of foot injuries, most notably metatarsal stress fractures.[16] Several prospective studies suggest improved biomechanics, and possibly also efficiency, with minimalist footwear, but no long-term studies document an impact on running-related injuries.[9,11,13]

This study had several novel features. First, while previous studies have examined different types of footwear, none directly compared the biomechanical impacts of the 3 types of running footwear analyzed in this study. Second, all subjects used the same types of traditional and minimalist shoes, eliminating variability related to shoe models. Finally, this study's experimental protocol enabled each subject to run in each type of footwear, and thus, serve as his own control. Observations in this context enabled us to isolate the impact of footwear on running biomechanics in this select group only.

Limitations

Although 4 indices of running biomechanics were measured, direct measures of running efficiency like VO_2max or cost of transport were not measured. Our sample size was small (15 runners). Because we examined only experienced high school cross-country runners, our findings may not be generalizable to other types of runners (eg, recreational runners or marathon runners) or to other brands or types of running footwear. Furthermore, only male adolescents who are competitive middle-distance runners were tested; their results are probably not representative of the entire population. For the "barefoot condition," runners wore light socks to protect their feet, which could have an impact on biomechanics. Because all testing was performed on a treadmill, these results may not be generalizable to outdoor or track running. Finally, we assessed only the immediate impact of footwear; it is possible that a short-term trial (days to weeks) or longer term trial (months) of different types of running footwear might have greater influence on running biomechanics.

CONCLUSION

This study suggests potential immediate biomechanical benefits of minimalist footwear over traditional, heavily cushioned shoes in adolescent cross-country runners. By improving running biomechanics, minimalist footwear may improve running efficiency and performance.

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