Kinematic and kinetic comparison of running in standard and minimalist shoes

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Running Title: Running in standard versus minimalist shoes

ABSTRACT

Purpose: The purpose of this study was to determine if running in a minimalist shoe results in a reduction in ground reaction forces and alters kinematics over standard shoe running. The secondary purpose of this study was to determine if within-session accommodation to a novel minimalist shoe occurs.

Methods: Subjects were 14 male, rearfoot striking runners who had never run in a minimalist shoe. Subjects were tested while running 3.35 m/s for 10 minutes on an instrumented treadmill in a minimalist and a standard shoe as 3-D lower extremity kinematics and kinetics were evaluated. Data were collected at minute 1 and then again after 10 minutes of running in both shoe conditions to evaluate accommodation to the shoe conditions.

Results: Shoe x time interactions were not found for any of the variables of interest. Minimalist shoe running resulted in no changes in step length ($p=0.967$) nor step rate ($p=0.230$). At footstrike, greater knee flexion ($p=0.001$) and greater dorsiflexion angle ($p=0.025$) were noted in the minimalist shoe. Vertical impact peak ($p=0.017$) and average vertical loading rate ($p<0.000$) were greater during minimalist shoe running. There were main effects of time as dorsiflexion angle decreased ($p=0.035$), foot inclination at footstrike decreased ($p=0.048$) and knee flexion at footstrike increased ($p=0.002$), yet the vertical impact peak ($p=0.002$) and average vertical loading rate ($p<0.000$) increased.

Conclusions: Running in a minimalist shoe appears to, at least in the short-term, increase loading of the lower extremity over standard shoe running. The accommodation period resulted in less favorable landing mechanics in both shoes. These findings bring into question whether minimal shoes will provide enough feedback to induce an alteration that is similar to barefoot running.

Key words: Ground reaction forces, injury prevention, biomechanics, loading rate

INTRODUCTION

Paragraph Number 1: Common running injuries, such as patellofemoral pain, plantar fasciitis and tibial stress fractures have been associated with high impact forces during running.(9, 16, 19, 20, 25) In particular, a high vertical impact peak in the vertical ground reaction force curve and a high rate of rise to this vertical impact peak (vertical loading rate) have been associated with these injuries.(16, 19, 20, 25) The vertical impact force transient is typically seen in runners who strike the ground first with their heel and signifies the end of the passive phase of loading.(1, 6) Thus, it appears that mitigating the forces associated with the passive impact transient should be the focus for reducing the risk of many running-related injuries.

Paragraph Number 2: Various interventions have been suggested to reduce impact forces associated with running. These include the use of cushioned shoes and insoles(4, 5), as well as conscious alterations in running technique, also known as gait retraining.(7, 8, 12, 14, 17, 22, 23) It has been shown that adopting a forefoot or midfoot strike pattern reduces or eliminates the vertical impact peak and reduces the vertical loading rate.(7, 15, 23) Reduction of impact loading may also be accomplished by increasing step rate and reducing step length.(14) A reduction in stride length is often accomplished a strategy of increased knee flexion at foot strike and reduced vertical oscillation of the runner's center of mass.(14)

Paragraph Number 3: Recently, barefoot running has been suggested as a means to reduce impact forces.(1) Habitual barefoot runners tend to strike the ground with a less dorsiflexed foot, often utilizing a mid- or a forefoot strike pattern.(1, 10, 12, 15) It is reasoned that barefoot runners adopt a less dorsiflexed strike pattern because heelstriking while barefoot is painful.(1, 10, 15) In fact, heelstriking while barefoot running results in a very high vertical impact peak and resultant vertical loading rate due to the collision forces between the dense calcaneus and the ground.(15) For many runners, barefoot running may be impractical due to unsafe running surfaces and potential performance limitations.(13). Thus, many runners opt for an intermediate option, a minimalist shoe. Minimalist shoe running may have an even lower metabolic cost compared with standard shoe running.(18) Nevertheless, there is currently a wide variation of shoes that are advertised as “minimal.” All of these shoes are commercially marketed as an alternative to barefoot running.

Paragraph Number 5: Only two studies, to date, have examined the effects of minimalist footwear on kinematic and kinetic parameters of running. Squadrone et al. (2010) examined habitual barefoot runners during three conditions: barefoot, minimalist and standard shoe running.(21) The minimalist shoe used was a 5-toed shoe with a flexible upper, no arch support, a zero drop, no midsole and a 3 mm outersole and the standard shoe was described as a neutral shoe. Using a 2-D kinematic assessment and an instrumented treadmill, barefoot and minimalist shoe running both resulted in a reduction in sagittal plane ankle and knee angle just prior to footstrike compared with standard shoe running. In addition, they reported a reduction in strike index, stride length, and an increase in step rate. also resulted.(21). Finally, the vertical impact peak was found to be reduced in both the barefoot and minimal footwear conditions. However, these authors did not assess vertical loading rate in this study. Further, habitual barefoot runners were the participants. Therefore, their results may be due to long term changes in running mechanics due to barefoot running than any immediate effect of footwear. More recently, Bonacci et al. examined the running mechanics of highly trained runners while running in standard (each runner’s regular training shoe), lightweight (Nike LunaRacer2), minimalist (Nike Free 3.0), and barefoot conditions.(3) The lightweight and minimalist shoe were similar in the amount of cushioning they had. As a result, these two shoes resulted in very similar mechanics to each other. Runners did exhibit a reduced stride length and increased cadence in these two shoes compared to the standard shoe, but most all other variables were similar to standard shoe condition. Neither of these more minimal shoes resulted in mechanics similar to barefoot running. This study underscores the idea that cushioned shoes, even when there is less cushioning than standard shoes, still encourage a heelstrike pattern. The only condition where a plantarflexed position at footstrike was noted was the barefoot one. Bonacci et al. did not report on impact-related forces between the shoe conditions. Understanding the influence of footwear on vertical impact peaks and loadrates is critical, as these forces have been related to running injuries.

Paragraph Number 6: Therefore, the purpose of this investigation was to compare running mechanics between standard neutral cushioned shoes and minimalist shoes in novice minimalist shoe runners. We also sought to determine if runners are able to accommodate to the minimal cushioning in minimalist shoes within a single running session. We hypothesized that runners would increase step rate while decreasing stance time in the minimalist shoes, resulting in a reduction in impact forces when compared with a standard cushioned shoe. An associated decrease in ankle dorsiflexion and increase in knee flexion at footstrike would also be noted in the minimalist shoe condition. We also hypothesized that runners would increase step rate, decrease impact forces and alter their running kinematics to an even greater extent over the course of the run as runners became accommodated to the minimalist shoe.

METHODS

Paragraph Number 7: The data collection protocol and informed consent document were approved by the University of Delaware Human Subjects Research Board. In order to participate, both written and verbal informed consent was obtained from each volunteer. An *a-priori* power analysis was conducted using data from pilot work for this study. Using the variable with the highest standard deviation, ankle dorsiflexion at footstrike, it was revealed that 12 subjects (effect size=0.82, α= 0.05, β=0.20) were required to adequately power this study. To be conservative, we recruited 14 male runners (31.9 km/week ±10.5, 24.8 years of age ±3.2) for this study. In order to qualify, each runner was required to be a habitual shod heelstriker, running at least 10 miles/week, between 18-35 years of age, free of injury over the past 6 months. Habitual strike pattern was self-reported. Each runner was required to be comfortable with treadmill running, defined as a score of at least "8" on a visual analog scale ("0" and "10" corresponding to completely uncomfortable versus completely comfortable, respectively). They also had to be comfortable running at 3.3 m/s. Importantly, each runner was required to be a "novel" minimalist shoe wearer, defined as never having previously run in minimalist shoes. Shoe history was self-reported. We operationally defined a "minimalist shoe" as a racing flat or advertised minimalist shoe. We chose to examine novel minimalist shoe runners in order to capture the true accommodation that may occur during the initial exposure to minimalist shoe running.

Paragraph Number 8: Shoe order was counterbalanced among subjects to avoid a fatigue and learned effect. A Nike Pegasus (Nike, Beaverton, Oregon) served as the standard cushioned shoe and the Nike Free 3.0 served as the minimalist shoe. The Nike Pegasus and Free shoes have heel insole heights of 36.3 mm and 17.6 mm, respectively, as per caliper measurement of size 47 EUR. A MTS QTest 10 Elite load frame (Cary, NC) with a 10 KN load cell was used to measure the stiffness of the heel insole. One shoe from each group was tested once. A compressive preload of 100 N was applied, then the load was increased to 1000 N with a load rate of 400 N/s. Stiffness values of 64.5 N/mm and 88.2 N/mm were determined for the standard and minimalist shoes, respectively. Thus, the standard shoe provided 31% greater cushioning than the minimalist shoe.

Paragraph Number 9: Thirty-five retroreflective markers were attached to the dominant lower extremity to analyze running kinematics (VICON, Oxford, UK). Limb dominance was operationally defined as the leg used to kick a soccer ball. Marker bases were firmly attached to bony landmarks to establish the coordinate systems of the pelvis, thigh, shank, and foot. Marker placement on shoes has previously been shown to overestimate calcaneal movement during running. Therefore, shoe windows were utilized to facilitate marker placement directly on the calcaneus (Figure 1).

Paragraph Number 10: Efforts were made to minimize any potential offsets that could be introduced to the subject models as a result of the different footwear conditions and variability in marker placement. Separate standing calibration trials were taken for each shoe condition utilizing identical anatomical marker placements. This was accomplished by using markers that could easily be separated from their bases, thus leaving the bases in place during the running trials. Once the first run condition was completed, the markers were reattached to their previously mounted bases for the subsequent standing calibration trial. Finally, all tracking markers, including markers mounted directly on the calcaneus, remained in place and unchanged between shoe running conditions.

Paragraph Number 11: For the collection of running trials, subjects ran on an instrumented treadmill (AMTI, Watertown, MA) at 3.35 meters/sec (8 min/mile pace). To fully capture any accommodation to shoe conditions, no warm-up period was allowed. This was accomplished by accelerating the treadmill from a full stop to the test speed using an acceleration rate of 0.2 meters/sec^2 as the subject kept pace. This acceleration rate is modest and was deemed to be a comfortable and attainable acceleration rate by each participant. Data of 5 consecutive strides were analyzed in the first minute of running as soon as the test speed was reached and after 10 minutes of running. Kinematic and kinetic data were collected at 200- and 1000-Hz, respectively. Stance was determined using a threshold of 30 N of the vertical ground reaction force. Once data were collected after the 10th minute, the treadmill was stopped and the shoe condition was changed. Care was exercised to maintain the calcaneal markers in their original positions as shoes were fully unlaced and removed followed by replacing them with the second shoe condition. Anatomical markers were reattached to their previously mounted bases. The second testing session was then commenced and data were recorded in exactly the same manner as described for the first shoe condition.

Paragraph Number 12: Data were then processed using Visual 3D (CMotion, Bethesda, MD). To eliminate any offset introduced into the ankle kinematic data due to the differences in heel height among the two shoe conditions, a virtual foot was created. This was done by subtracting the vertical height of the foot and malleoli anatomical markers in the lab coordinate system to construct the virtual segment. As such, the virtual foot had an inclination (dorsiflexion) angle of 0 degrees during the standing calibration, when referenced to the lab coordinate system. Subsequent foot kinematic calculations were based on the virtual foot referenced to the lab coordinate system and ankle kinematic calculations were based on the virtual foot referenced to the shank segment. Using this virtual foot, a positive angle of the foot inclination angle at footstrike would correspond to a dorsiflexed foot segment at foot strike. An 8- and 40-Hz, lowpass, 4th order, zero-lag Butterworth filters were used to filter the kinematic and kinetic data, respectively. Customized software (LabVIEW 8.0, National Instruments, Austin TX) was used to calculate the following discreet variables: vertical impact peak, average vertical loading rate, dorsiflexion at footstrike, foot inclination at footstrike, knee angle at footstrike, stance length and step rate. The methodology for calculation of average vertical loading rate was done over the middle 60% of the vertical ground reaction force curve from foot strike to the vertical impact peak (Figure 2). (16)

Paragraph Number 13: A series of two-way, repeated analyses of variance (ANOVA) (shoe(2) x time(2)) was utilized to analyze the data ($\alpha \leq 0.05$). When significant differences were found for main effects or the interaction, post hoc comparisons using paired t-tests ($\alpha < 0.05$) were conducted between levels. Mauchly's test of sphericity was utilized to determine if the data met the assumptions of the ANOVA.

RESULTS

Paragraph Number 14: There were no significant shoe X time interactions, and therefore only main effects were assessed. In terms of main effect of shoe-type, no differences were found for step length, step rate, foot inclination angle at foot strike ($p=0.967$, $F=0.002$, $p=0.230$, $F=1.586$, and $p=0.332$, $F=1.014$, respectively) between shoes. However, runners struck the ground with a more dorsiflexed foot ($p=0.025$, $F=6.379$), in more knee flexion ($p=0.001$, $F=13.000$), and with higher vertical impact peak ($p=0.017$, $F=14.902$) and higher average vertical loading rate ($p<0.000$, $F=23.400$) (Table 1) while running in the minimalist shoe. These results did not agree with our hypotheses that runners would land in a less foot inclination and with a less dorsiflexed ankle, experience lower impact forces, and reduce temporospatial measures in the minimalist shoe when compared with the standard running shoe.

Paragraph Number 15: There were no main effects of time for step length or step rate either (p=0.088, F=3.393 and p=0.616, F=0.265, respectively). Significant main effects for time for all kinematic and kinetic variables were found. Runners in both shoe conditions demonstrated reduced foot inclination at footstrike (p=0.048, F=4.763), reduced dorsiflexion (p=0.035, F=5.543) and increased knee flexion at foot strike (p=0.002, F=14.112), yet higher vertical impact peak (p=0.002, F=14.902) and average vertical loading rate (p<0.000, F=91.884) after 10 minutes of running.

DISCUSSION

Paragraph Number 16: We sought to determine if running in a cushioned minimalist shoe results in reduced variables associated with impacts when compared with running in a standard shoe. In addition, we sought to determine if accommodation to running in the minimalist shoe occurs over the course of a 10-minute run. In contrast to our hypotheses, we found that running in the minimalist shoe failed to result in changes in temporospatial parameters, increased average vertical loading rates and vertical impact peaks when compared with running in a standard running shoe. As hypothesized, running in the minimalist shoe resulted in a slightly more flexed knee at footstrike. The runners accommodated to the minimalist shoes in the same manner as to the standard shoes.

Paragraph Number17: The minimalist shoe resulted in a more dorsiflexed ankle and more knee flexion at footstrike compared with standard shoe running. This increased knee flexion may have been a strategy to reduce the impact forces associated with a more dorsiflexed footstrike.(14)

However, this increase in knee flexion was small and apparently insufficient to alter the temporospatial measures nor reduce impact forces during minimalist shoe running.

Paragraph Number 18: It is not clear why dorsiflexion would be increased in the minimal shoe, yet foot inclination was unchanged. Foot inclination was defined as the virtual foot referenced to the running surface whereas ankle dorsiflexion was the foot referenced to the shank segment. Therefore, foot inclination is likely a better indication of foot strike pattern than ankle dorsiflexion angle. Previous work suggests that foot inclination at foot strike is strongly correlated with foot strike patterns.(2) Therefore, we feel that the large (>10°) positive foot inclination angle at foot strike in both shoes indicates a defined heelstrike in the present study. As a large positive foot inclination angle at foot strike was coupled with a stiffer, less compliant minimalist shoe, there was less cushioning between the dense calcaneus and the running surface compared with the standard shoe. Thus, it is not surprisingly then that the minimalist shoe was associated with greater impact loading. Landing on the heel reduces the ability of the ankle to assist in attenuating the loads of impact. High impact loading has been associated with a number of running related injuries.(9, 16, 19, 20, 25) In fact, the average vertical loading rates that we found during minimalist shoe running exceeded the values reported in runners with a history of tibial stress fractures by Milner et al. (78.97 bw/sec, ± 24.96).(16) This is amplified by the fact that the running speed was higher in the Milner study than in the present one (3.7 vs 3.3 m/s) as higher ground reaction forces would be expected at the faster speed. Further justification of this comparison is that there are no differences in impact forces between overground and treadmill running.(24)

Paragraph Number 19: The greater ankle dorsiflexion seen in the minimal shoe was in contrast to the findings of both Squadrone and Bonacci. Squadrone found that habitually barefoot runners in the Vibram five finger shoe landed in plantarflexion compared to dorsiflexion in the standard running shoes.(21) The plantarflexion found in the Vibram five finger shoe was also similar to that of their barefoot condition. However, these runners were habitual barefoot runners and the minimal shoe had no cushioning at all. Bonacci found no difference between the Nike Free 3.0 and the runner's standard shoes, which agrees with our findings.(3) The Bonacci study used a similar shoe to the present study, and runners were given 10 days to accommodate to the shoes. The Bonacci study used a similar shoe to the present study, but runners were given 10 days to accommodate to the shoes which may explain some of the difference. The virtual foot may also at least partially be the source of this discrepancy in dorsiflexion angle between the present work and that of Squadrone and Bonacci. While we accounted for foot angle differences between shoe types, we did not account for differences in shank orientation that may have resulted from the greater heel elevation in the neutral shoe.

Paragraph Number 20: Our results also suggest that a 10-minute accommodation period does not result in more favorable loading mechanics during running in the minimalist shoe. In fact, any changes in mechanics between minute 1 and minute 10 were nearly identical between the two shoe types. Rather than decreasing their impact loading as the runners became accommodated, an increase was found between the two time points in both shoes. While impacts have been noted to increase with fatigue,(11) 10 minutes of running should not have led to fatigue in this group of runners. This may be explained by the fact that the Pegasus may have been an equally novel shoe for the runners as the minimalist shoe. An alternative explanation is that minimizing impact forces is not a criterion of the neuromuscular system during the initial minutes of running.

Paragraph Number 21: When taking the Squadrone, Bonacci and current studies together, the following points can be made. In order to see a change in footstrike pattern that simulates barefoot running, the shoes may need to be as minimal as possible. The shoe in the Squadrone study was simply a thin rubber sole with a flexible upper. It was the only shoe condition of all three studies that resulted in similar mechanics as a barefoot condition. The Squadrone study used habitual barefoot runners who may also do some of their running in minimal shoes.(21) Although the standard shoe condition was the one that was most unfamiliar, runners in the Squadrone study immediately increased their dorsiflexion at footstrike and increased their vertical impact peak. In both the Bonacci and present study, the minimal shoe used was one that still had significant cushioning and allowed for a comfortable heelstrike.(3) In both cases, runners remained as rearfoot strikers in the minimal shoe condition, landing on their heel with greater impact.

Paragraph Number 22: Many runners use these transitional shoes as a way to adopt a barefoot-mimicking running technique, involving minimal plantarflexion and a mild forefoot strike pattern.(15) However, these results suggest that runners should be careful when transitioning to cushioned minimal shoes. While there may be a belief that one will automatically adopt a forefoot or midfoot strike pattern by wearing minimal shoes, both the Bonacci and the present study suggests otherwise. When using one of the vast array of minimal shoes with cushioning, additional gait retraining may be needed in order to train one to land with a midfoot or mild forefoot strike pattern. Based upon previous studies, landing patterns can be altered (7, 8, 14) and with proper feedback and reinforcement, maintained up to 3 months beyond the training period.(7, 8) Whether this alteration is maintained in the long term when using cushioned minimal shoes is yet to be determined.

CONCLUSION

Paragraph Number 23: These results suggest that the minimally cushioned footwear used in the study did not induce result in a transition to a non-rearfoot strike pattern. As runners actually increased their impact loading, these shoes may increase the risk of injury, especially during this early phase of accommodation.

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CONFLICT OF INTEREST

Paragraph Number 27: There are no conflicts of interest among any of the authors of this manuscript.

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Table Captions

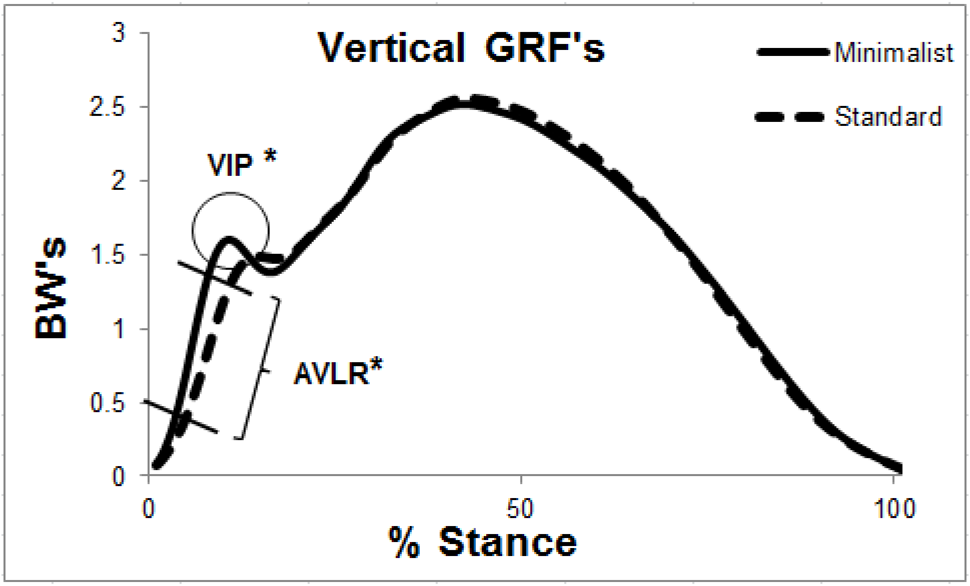
Table 1: Variables of interest. Mean (standard deviation). A more negative knee angle corresponds with a more flexed knee.

Figure Captions

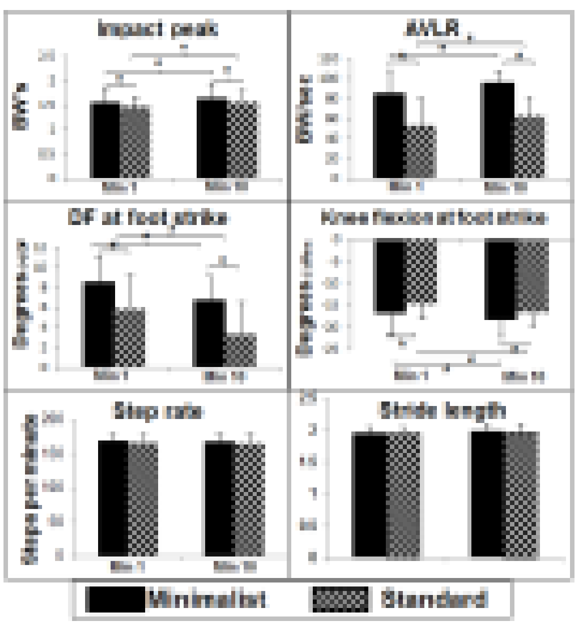
Figure 1: Marker set utilized for collection of motion data. Note shoe windows enabling placement of marker directly on calcaneus.

Figure 2: Ensemble curves of the vertical ground reaction forces (GRF) during Minute 1 of treadmill running in the two shoe conditions. VIP=vertical impact peak, AVLR= average vertical loading rate. *** indicates $p<0.05$**

	Standard shoes Minute 1	Minimalist shoes Minute 1	Standard shoes Minute 10	Minimalist shoes Minute 10
Vertical impact Peak (body weights)	1.44 (0.22)	1.56 (0.27)	1.56 (0.26)	1.64 (0.33)
Average vertical loading rate (body weights/sec)	52.7 (13.2)	85.4 (24.6)	62.9 (19.7)	96.1 (28.7)
Dorsiflexion at footstrike (degrees)	5.9 (3.4)	8.6 (2.6)	3.3 (5.2)	6.8 (2.4)
Knee angle at footstrike (degrees)	-14.5 (4.7)	-16.9 (3.7)	-16.4 (4.0)	-18.2 (3.3)
Stride length (meters)	1.99 (0.084)	1.97 (0.079)	1.99 (0.10)	1.97 (0.11)
Step rate (steps/minute)	169.8 (9.8)	169.7 (10.4)	168.0 (10.5)	168.2 (13.0)



Vertical GRF's
Minimalist
Standard
VIP *
AVLR*
BW's
% Stance
3
2.5
2
1.5
1
0.5
0
0
50
100



Impact peak
AVLR
DF at foot strike
Knee flexion at foot strike
Step rate
Stride length
Minimalist
Standard