Heel–toe running: A new look at the influence of foot strike pattern on impact force

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Abstract

Background/Objective: It is important to understand the factors that influence the impact force observed during running, since the impact force is likely to be related to overuse injuries. The purpose of this study was to compare the impact force during running when participants were instructed to use different foot strike patterns: obvious heel strike (Obvious-HS), subtle heel strike (Subtle-HS), midfoot strike (Mid-FS), and fore foot strike (Fore-FS) patterns.

Methods: Participants (n = 10, 25 ± 5.7 years, 70.2 ± 12.1 kg, 174.6 ± 7.2 cm) completed four foot strike patterns while running over ground: Obvious-HS, Subtle-HS, Mid-FS, and Fore-FS. Speed was controlled between conditions (random order). Vertical ground reaction forces were recorded (1000 Hz) along with the impact force, peak force, and stance time for analysis. A repeated measures analysis of variance was used to compare each variable across foot strike instructions, with post hoc comparisons contrasting Obvious-HS to each of the other conditions.

Results: Impact force was influenced by foot strike instructions, with Obvious-HS being greater than Subtle-HS and Fore-FS (p < 0.05) but not different from Mid-FS (p > 0.05). The peak force was not influenced by foot strike instructions (p > 0.05); stance time was longer during Obvious-HS than during Mid-FS or Fore-FS (p < 0.05), but not different from Subtle-HS (p > 0.05).

Conclusion: The unique observation of this study was that impact force was different when participants were instructed to run with either an Obvious-HS or a Subtle-HS at contact. Both these foot strike patterns would have been considered rear foot strike patterns, suggesting that something other than which specific part of the foot strikes the ground initially influenced impact force.

Keywords: Foot strike index; Impact force; Running injuries

Introduction

Running is an activity that continues to grow in participation. For example, there were 25,000 people who completed a marathon in 1976, whereas in 2009 there were 467,000 finishers.1 In 1990, 303,000 people finished half-marathon distance events, whereas in 2009 there were 1,113,000 finishers.1 There are many reasons that people include running in their exercise routine; unfortunately, running has also been associated with a high risk of sustaining an overuse injury.2–4

It has long been considered that the risk of sustaining an overuse injury as a result of running has been associated with the repetitive impact force with each foot strike.2–4 Thus, it has made sense that a wealth of research has been carried out on shoe design. However, there has yet to be a definitive answer to the type of shoe that will prevent running injuries. In any case, there is an abundance of research on factors that influence impact characteristics during running. For example, it is known that changes in speed,5–8 stride length,9,10 running surfaces,7 and running uphill/downhill11 are factors that influence impact force. Likewise, there is also a general

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acceptance that the manner in which a foot initially strikes the ground, or the “foot strike pattern,” is related to the impact magnitude.\textsuperscript{8,12–17}

The part of the foot (or shoe) that contacts the ground first is typically used to define an individual’s foot strike pattern.\textsuperscript{8} Alternatively, if force plate data are available, foot strike patterns can be determined based upon the initial location of the center of pressure within the foot print.\textsuperscript{12} Typical descriptions of foot strike patterns are rear foot (aka, heel–toe) strike, midfoot strike (Mid-FS), and fore foot strike (Fore-FS) patterns.\textsuperscript{12,18} The operational definition of these patterns is based on dividing the foot into thirds (length wise) and then identifying which part of the shoe strikes the ground initially. However, an experimental procedure may include a visual description only of foot strike patterns to ensure that participants are using a particular pattern, and actual foot strike pattern is not quantified.

There is a wealth of published data on the influence of foot strike pattern on ground reaction forces during running, and it is generally expected that when running with a rear foot strike pattern, an impact force will be observed, whereas when running with a Fore-FS pattern, no impact force will be observed.\textsuperscript{12–17,19} However, there is a gap in understanding the influence of how the different ways of striking the ground heel first may influence impact characteristics. Illustrated in Fig. 1 are two examples of foot strikes, both of which would be classified as rear foot strike patterns. Using a simulation model, Gerritsen et al.\textsuperscript{20} reported that for a rear foot strike pattern, a change in foot angle at contact can influence impact forces.

It may be that the classification of rear foot strike pattern does not capture the essence of factors that influence impact forces. Yet there are no data (beyond simulation data) on comparing impact forces during running with different rear foot strike patterns. Therefore, the purpose of this study was to compare the impact force during running when participants were given different instructions on foot strike pattern. Specifically, they were asked to run with an obvious heel strike (Obvious-HS) and a subtle heel strike (Subtle-HS) pattern. This work was extended to also instruct participants to use a Mid-FS and a Fore-FS pattern. Because it was expected that Fore-FS and possibly Mid-FS would not have an impact force, we extended our analysis to peak force (at midstance) and stance time.

Methods

Participants

Volunteer participants (n = 10 males, 25 ± 5.7 years, 70.2 ± 12.1 kg, 174.6 ± 7.2 cm) were physically active and free from any injury that would interfere with their ability to run. Upon reporting to the laboratory, participants reviewed and signed the university-approved informed consent.

Instruments

Ground reaction force data were recorded using a force platform (Kistler, Amherst, NY, USA) mounted flush with the floor in the middle of a 14 m runway. Running speed was determined through the use of infrared photocells (Lafayette Instruments, Lafayette, IN, USA) controlling a timer. The photocells were set up 2.44 m apart, with the force platform approximately in the middle.

Procedures

Prior to testing, participants warmed up on a treadmill (AlterG Anti-Gravity Treadmill PRO 200; AlterG Inc., Fremont, CA, USA), and then the test speed was determined. This was done by having participants self-select a running speed that they felt could be maintained for 30 minutes. The treadmill was set with no elevation gain, and the speed display was hidden from view; no instructions were given to participants regarding foot strike. Participants gave the researcher cues to either increase or decrease speed until the desired speed was reached. The self-selected speed was recorded, the treadmill was stopped, and the process was repeated for a total of three times. The test speed was the average of the three self-selected speeds, with the group averaging 3.1 ± 0.6 m/s.

Each participant completed four overground running conditions. Each condition represented a manipulation of instructions for foot strike patterns. For the first condition, participants were instructed to strike the ground with an Obvious-HS (i.e., rear foot strike pattern). For the second condition, participants were instructed to use a Subtle-HS (i.e., rear foot strike pattern). That is, participants were instructed to still use a rear foot strike pattern by striking the ground first with the heel, but to do so more subtly than during the Obvious-HS condition. Operationally, the kinematic difference between Obvious-HS and Subtle-HS was that the ankle was more dorsiflexed at contact during Obvious-HS. For the third condition, participants were instructed to use a Mid-FS pattern by asking them to land with the sole of their shoe flat on the ground. Finally, for the fourth condition, the participants were instructed to use a Fore-FS pattern by asking them to land with the toe region of the shoe. Participants were shown a video of the different foot strike patterns and were given time to practice the patterns prior to testing. During testing, participants were consistently reminded as to the style of which foot strike pattern they were to use and trials were rejected when the tester visually detected that the target strike pattern was not

Fig. 1. Illustration of two foot strike patterns that are both considered rear foot strike patterns: (A) The obvious heel strike condition and (B) the subtle heel strike condition.
used. Participants wore laboratory-issued footwear (Adidas adiPRENE). Condition order was randomized, and participants were allowed time to rest between trials/conditions, with the total test time being about 1–1.5 hours per participant.

For each condition, participants were asked to complete 10 good trials with a maximum of 20 attempts per condition. A good trial was one that met the following criteria: within ± 5% of the test speed, visually correct foot strike pattern, foot strike on the force platform, and no obvious adjustments in stride to contact the force platform. Using these a priori criteria, five participants achieved 10 good trials for all conditions. Of the other participants, 10 good trials were achieved on two of the four conditions; only one participant achieved less than eight good trials (5 for midfoot and 7 for fore foot) on the remaining conditions (i.e., the other participants achieved 8 or 9 good trials). In all cases, the averages of the good trials were retained for analysis.

Data reduction

Ground reaction force data were normalized to body weight and then the impact force (if present) from the vertical ground reaction force component was recorded. The operational definition of the impact force was a local maximum that occurred within 50 milliseconds of ground contact. One participant was dropped from the analysis entirely because there was an overall absence of impact force for any condition. This resulted in nine participants being retained for analysis. Ground contact was determined as the time of first vertical force > 20 N. Stance time was calculated as the time difference between ground contact and toe off (time of 1st force < 20 N at the end of the stance phase). The peak force (aka F2) was the second maximum vertical ground reaction force that was observed near midstance. This discrete variable was always referred to as the peak force regardless of the magnitude, as compared to the impact force.

Statistical analysis

The dependent variables were impact force, peak force, and stance time. The independent variable was foot strike pattern (Obvious-HS, Subtle-HS, Mid-FS, and Fore-FS). A repeated measures analysis of variance was used to compare each dependent variable among conditions (SPSS version18.0.3; SPSS Inc., Chicago, IL, USA). When the omnibus F-ratio was observed to be significant, post hoc testing was completed such that the Obvious-HS condition was compared with each of the other conditions (i.e., simple effect testing).

Results

Impact force was influenced by foot strike pattern instructions given (Fig. 2; \( p < 0.05 \)), with the impact force during the Obvious-HS condition being greater than that during either Subtle-HS or Fore-FS conditions (\( p < 0.05 \)). There was no difference in the impact force between the Obvious-HS and Mid-FS conditions (\( p > 0.05 \)).

The peak force was not different between conditions (Fig. 3; \( p > 0.05 \)), but stance time was different (Fig. 4; \( p < 0.05 \)). Specifically, stance time during the Obvious-HS condition was not different from that during the Subtle-HS condition (\( p > 0.05 \)), but was longer than the stance time during either Mid-FS or Fore-FS conditions (\( p < 0.05 \)).
Fig. 4. Illustration of stance time when participants were instructed to run with OHS, SHS, MFS, and FFS patterns. Stance time was calculated as the time difference between ground contact and toe off (time of 1st force < 20 N at the end of the stance phase). Stance time was lower during running with FFS versus OHS and during MFS versus OHS (p < 0.05). FFS = fore foot strike; MFS = midfoot strike; OHS = obvious heel strike; SHS = subtle heel strike.

Although we did not quantify the actual foot strike pattern used, the results of our study are in agreement with published literature. For example, the range of impact forces observed in our study are typical for the running speeds (3.1 ± 0.6 m/s) used. Furthermore, using the regression equation \( \text{impact force} = 1.11 + 0.178v \) (where impact force is in “body weight” units and \( v \) is the running velocity in m/s units), the predicted impact force was 1.65 body weight (BW), whereas during Obvious-HS it was 1.68 ± 0.54 BW. Likewise, the shorter stance time during Fore-FS versus Obvious-HS is also consistent with published literature, as is the similarity of peak force between foot strike conditions. Alternatively, we observed that the impact force was not different between Obvious-HS and Mid-FS instructions, which is in contrast with the results of Cavanagh and Lafontune, who qualitatively reported that the impact force was either absent or lower during Mid-FS versus heel— toe running. Arendse et al. reported that the impact force was greater for heel— toe versus Mid-FS running. In that study, participants ran in bare feet, and it is known that impact characteristics (e.g., loading rate) can be influenced while running in bare feet versus shod. Nevertheless, it is possible in the present study that some Mid-FS trials accepted might have tended to be either rear foot or fore foot strike patterns. However, the results of the Mid-FS condition did not fall within a continuum of decreasing impact force between Obvious-HS and Fore-FS, and it is not clear why the magnitude was similar to that of Obvious-HS. To summarize, although we did not quantify foot strike, we selected only trials that visually met the foot strike criteria (i.e., Obvious-HS, Subtle-HS, Mid-FS, and Fore-FS), and the results for each condition are largely in agreement with published data for each foot strike pattern.

It is well understood that impact forces are either entirely absent or greatly reduced when running with a fore foot versus a rear foot strike pattern. In our study, we also observed that the impact force was either absent or greatly reduced when participants were asked to run with a Fore-FS pattern compared to when they were instructed to use a heel strike pattern (i.e., Obvious-HS or Subtle-HS). Specifically, an impact force was observed only about 55% of the time when running with a Fore-FS pattern. Furthermore, when an impact force was observed, it was about 54% less in magnitude than the impact force observed during the Obvious-HS condition. In application, this observation emphasizes that an impact force (albeit of reduced magnitude) can still be observed when using a Fore-FS condition, but the likelihood of an impact force is less than that when any other foot strike pattern is used.

Unique to this study is the comparison of impact forces when participants were given slightly different instructions and asked to run with an Obvious-HS or Subtle-HS pattern. When participants were asked to run with an Obvious-HS, impact forces were about 8% greater than when they were asked to run with a Subtle-HS. The importance of this observation is two-fold: (1) instructions given to participants influence the exact manner in which they run (which influences the impact force) and (2) perhaps using a simple operational definition of rear foot strike, such as striking the ground with the rear-third (or any ratio used) portion of the shoe, does not truly capture the relationship between foot strike pattern and impact force. As Gerritsen et al. demonstrated using a simulation model, a change in foot angle of 1° influenced the impact force by 85 N. Qualitatively, in our study, a strategy to achieve an Obvious-HS was to increase the foot angle (relative to the horizontal). We did not measure the kinematics of the lower extremity, and we do not know the exact mechanism that resulted in a lower impact force for Subtle-HS versus Obvious-HS patterns. In addition to the foot angle mechanism, it may be that the shoe was better designed to absorb the impact energy for a Subtle-HS versus an Obvious-HS. Furthermore, it may have been that the participants changed their running style between conditions such that there was less vertical movement during the Subtle-HS condition. Interestingly, using a simulation model, lower extremity muscle activation, vertical velocity of the foot at contact, and initial angle of the knee all were found to be factors that influenced the impact force. In any case, the importance of our experiment was that it was determined that impact forces were different between foot strike patterns that would have been considered rear foot strike patterns. Future research is needed to better understand the foot strike factors that are directly related to impact forces.

It has long been hypothesized that the repetitive impact nature during running is a causative factor of overuse injuries. This hypothesis highlights the importance of research on the influence of the running shoes on impact forces. Over the past 25 years, many running shoe companies have emerged and, through increased research in shoe design (corporate and academic), have developed a variety of running shoes. The shoe styles of today provide different levels of motion control, stability, cushioning, and performance, for example. Despite advances in shoe technology, it is apparent that runners are still susceptible to overuse injuries. The lack of change in the risk of overuse injuries has led to question whether shoes should be worn at all, and/or whether the foot strike pattern should be a midfoot or fore foot.
versus a rear foot.\textsuperscript{26–29} Regardless of whether or not it makes sense to instruct participants to use a particular foot strike pattern, it is important to recognize that even when they are asked to use a particular foot strike pattern and visually seem to have met the criteria, impact forces (of various magnitudes) can still be observed. Furthermore, it is important to recognize that, from a practical perspective, when someone runs outdoors for training purposes, the runner will likely use a variety of foot strike patterns as he/she starts/stops at intersections, transitions between surfaces (e.g., sidewalk to road), steps up/down a curb, or avoids obstacles, for example. Therefore, a challenge in designing a shoe to minimize the influence of overuse injuries is that the foot strike pattern is not constant during a run.

The results from our study provide further evidence that foot strike patterns influence the impact force when the change in foot strike patterns is extreme (e.g., Obvious-HS vs. Fore-FS). However, the observation that impact forces are lower or less frequently observed when using a Fore-FS pattern does not necessarily mean that runners should run with this pattern. Running with a Fore-FS pattern results in different lower extremity kinematics compared to running with a heel–toe foot strike pattern,\textsuperscript{29} but yet running economy is not different when running with a Fore-FS or a rear foot strike pattern.\textsuperscript{31,32} The observation of similar peak forces combined with changes in stance time between conditions in our study is evidence that running style is different between foot strike patterns. Furthermore, from our experiment, it is clear that the impact force is influenced by factors other than which part of the foot (or shoe) strikes the ground first. Considering the change in kinematics,\textsuperscript{31,32} no change in running economy,\textsuperscript{30} and that impact forces (albeit lower in magnitude) can be observed, it is not clear if the Fore-FS pattern offers any advantages to running performance and/or injury prevention over a heel–toe foot strike pattern.

It is important to note that the participants in this study were not training for any running event and the test speeds tended to be on the low end of the running speed continuum (3.1 ± 0.6 m/s = 8.39 min/mi pace). Since impact forces are influenced by running speed,\textsuperscript{3,6,8} there may be an interaction between running speed and foot strike pattern on impact force. Additionally, the running conditions were rather unique to the participants. However, Williams et al.\textsuperscript{17} reported that habitually rear foot strikers were able to convert to a Fore-FS pattern with very little practice.

**Conclusion**

By instructing participants to run using different styles of rear foot strike patterns (i.e., Obvious-HS and Subtle-HS) as well as with Mid-FS and Fore-FS patterns, we determined that impact forces are influenced by factors other than simply which part of the shoe struck the ground first. That is, even though foot strike patterns were visually considered rear foot strike patterns, the impact force was different when participants used an Obvious-HS versus a more Subtle-HS (albeit still rear foot strike) pattern. Further research is needed to determine the exact mechanism that influences impact forces when foot strike patterns vary within a particular category of foot strike patterns.

**Conflicts of interest**

All authors declare no conflicts of interest.

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No financial or grant support was received for this study. The treadmill used in the study was on loan from AlterG Inc. (Fremont, CA, USA). However, AlterG Inc. did not have any input on study design, analysis or reporting; furthermore, we did not submit any report to them.

**References**


