Influence of Maximal Running Shoes on Biomechanics Before and After a 5K Run

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Background: Lower extremity injuries are common among runners. Recent trends in footwear have included minimal and maximal running shoe types. Maximal running shoes are unique because they provide the runner with a highly cushioned midsole in both the rearfoot and forefoot. However, little is known about how maximal shoes influence running biomechanics.

Purpose: To examine the influence of maximal running shoes on biomechanics before and after a 5-km (5K) run as compared with neutral running shoes.

Study Design: Controlled laboratory study.

Methods: Fifteen female runners participated in 2 testing sessions (neutral shoe session and maximal shoe session), with 7 to 10 days between sessions. Three-dimensional kinematic and kinetic data were collected while participants ran along a 10-m runway. After 5 running trials, participants completed a 5K treadmill run, followed by 5 additional running trials. Variables of interest included impact peak of the vertical ground-reaction force, loading rate, and peak eversion. Differences were determined by use of a series of 2-way repeated-measures analysis of variance models (shoe × time).

Results: A significant main effect was found for shoe type for impact peak and loading rate. When the maximal shoe was compared with the neutral shoe before and after the 5K run, participants exhibited an increased loading rate (mean ± SE: pre–maximal shoe, 81.15 body weights/second [BW/s] and pre–neutral shoe, 60.83 BW/s [$P < .001$]; post–maximal shoe, 79.10 BW/s and post–neutral shoe, 61.22 BW/s [$P = .008$]) and increased impact peak (pre–maximal shoe, 1.76 BW and pre–neutral shoe, 1.58 BW [$P = .004$]; post–maximal shoe, 1.79 BW and post–neutral shoe, 1.55 BW [$P = .003$]). There were no shoe × time interactions and no significant findings for peak eversion.

Conclusion: Runners exhibited increased impact forces and loading rate when running in a maximal versus neutral shoe. Because increases in these variables have been associated with an increased risk of running-related injuries, runners who are new to running in a maximal shoe may be at an increased risk of injury.

Clinical Relevance: Understanding the influence of running footwear as an intervention that affects running biomechanics is important for clinicians so as to reduce patient injury.

Keywords: highly cushioned shoes; impact forces; loading rate

Lower extremity injuries have consistently been problematic for runners regardless of footwear. Taunton and colleagues[17,18] reported that over a 13-week training period, 30% of runners incurred a running-related injury, most commonly patellofemoral pain, iliotibial band friction syndrome, and plantar fasciitis. Since the inception of the cushioned running shoe, its fundamental purpose has been to protect the foot in an effort to reduce running-related injuries. Despite significant advances in shoe technology over the past 50 years, the rate of sustaining a running-related injury has remained relatively stable.[11]

Numerous variations of running shoes have been developed to accommodate different types of runners, running styles, and running conditions. Footwear manufacturers have modified the basic components of their running shoe models to accommodate these differences, including midsole cushioning and heel-toe drop. Historically, running shoes fell into 1 of 3 cushioning classifications: (1) neutral, (2) stability, and (3) motion control. In general, individuals with a high amount of pronation were directed to a motion control shoe, those with a moderate amount of pronation

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were directed to a stability shoe, and those with a minimal amount of pronation, or individuals who supinated, were directed to a neutral shoe. Up until the past 7 years, traditional running shoes tended to have a heel-toe drop, which refers to the difference between the heel elevation and forefoot elevation of the midsole, of greater than 10 mm.

In 2009, the minimalist shoe, defined by very little cushioning and heel drop, became popular among runners.[4] Popularity of these shoes spiked largely because their benefits were espoused by shoe manufacturers and authors of popular-press books,[12] who claimed that a lack of cushioning would reduce injuries by promoting a more natural forefoot-strike pattern.[10] However, popularity of minimal shoes has declined, largely due to research suggesting that adopting a forefoot-strike pattern does not decrease injury risk, improve running economy, or reduce the impact peak or loading rate of the vertical ground-reaction force.[6] Research continues to examine how transitioning from a traditional shoe to a minimal shoe influences running style, lower extremity biomechanics, and risk for injury.[7,15,19]

At about the same time that minimal shoe popularity was rising, a company called Hoka One One introduced a highly cushioned "maximal" running shoe, a stark contrast to the minimal shoe. Currently, there is no academic definition of a maximal shoe, but in industry, the defining feature is increased cushioning of the midsole. Since 2010, maximal shoes have slowly gained popularity, with more than 20 variations of maximal running shoes now on the market.

Conceptually, this increase in cushioning is thought to improve shock attenuation and reduce the risk of injury. Anecdotally, runners have expressed in the popular press that maximal running shoes reduce or eliminate running-related pains that often appear several miles into their run. However, despite increased popularity of maximal shoes in the marketplace, no research to date has investigated the effect of a maximal shoe on biomechanical variables associated with injury, including the loading rate and impact peak of the vertical ground-reaction force[2,13,14] and peak eversion of the rearfoot.[14] Therefore, the primary purpose of this study was to examine the effect of a maximal running shoe versus a neutral running shoe on lower extremity running biomechanics before and after a 5-km (5K) run. We hypothesized that the maximal shoe would result in lower vertical impact peak and loading rates, but there would be no change in peak ankle eversion, compared with a neutral shoe. We also hypothesized that the impact peak and loading rate would increase after the 5K run in the traditional neutral shoe but not in the maximal shoe.

METHODS

Participants

Participants were 15 female recreational runners (age range, 23-51 years; mean age, 34 years) who ran a minimum of 15 miles per week and had not run in a minimal shoe for the 6 months prior to the study. Before participating in the study, all participants were running in some form of traditional running shoe, including rearfoot control and

Figure 1. Hoka One One maximal running shoe and New Balance traditional neutral running shoe used in this study.

neutral shoes. All runners considered themselves heel-strikers, which is described as a runner who strikes his or her heel to the ground first when running (vs midfoot-striker or forefoot-striker). We focused on heel-strikers, as it is estimated that 90% of recreational runners have this footstrike pattern.[3,8] In addition, our study required that runners had not had an injury within the past month that limited their running for more than 1 week,[21] were not pregnant, and did not have any neurological or vascular disorders. All participants signed an informed consent document approved by the institutional review board at Oregon State University prior to participation on the first day of testing.

Instrumentation

Kinematic data were collected by use of a Vicon 8-camera 3-dimensional motion analysis system (Oxford Metrics Ltd) at a sampling frequency of 250 Hz. The cameras were interfaced to a microcomputer and placed around a floor-embedded force platform (Advanced Mechanical Technologies Inc). The force platform (1000 Hz) was interfaced to the same microcomputer that was used for kinematic data collection via an analog to digital converter. This interface allowed for synchronization of kinematic and kinetic data.

Procedures

Participants attended the biomechanics laboratory for 2 separate testing sessions, with 7 to 10 days between sessions. For one of the testing sessions, the participants wore a neutral running shoe (New Balance 880: drop, 10.1 mm; heel height, 33.3 mm; forefoot height, 23.2 mm), and for the other testing session, they wore a maximal shoe (Hoka One One Bondi 4: drop, 6.9 mm; heel height, 41.6 mm; forefoot height, 34.7 mm) (Figure 1). The order of shoes worn was randomized across participants. The procedures were the same for each testing session.

Prior to biomechanical data collection, participants' height and mass were recorded. Reflective markers (14-mm spheres) were placed bilaterally over the following anatomic landmarks: the first and fifth metatarsal heads, distal interphalangeal joint of the second toe, medial and lateral malleoli, medial and lateral femoral epicondyles,

greater trochanters, and iliac crests. A single marker was placed on the joint space between the fifth lumbar and the first sacral spinous processes. Quadrads of rigid reflective tracking markers were attached bilaterally to the participant's thigh and leg with a custom adhesive taping system. In addition, triads of rigid reflective tracking markers were placed bilaterally on the heel counter of the shoe. Markers were always placed by the same researcher (J.A.T.), who had several years of biomechanics laboratory experience placing markers. After marker placement, the participant was asked to stand in the center of the calibration area so we could collect a static calibration trial. Once the calibration trial was captured, all markers were removed except those on the quadrads and triads as well as the iliac crest, anterior superior iliac spine, and fifth lumbar/first sacral markers.

The participants completed 5 successful running trials for their dominant leg (defined as the leg they prefer to use when kicking a soccer ball). The participants were allowed 3 to 5 practice trials in order to become familiar with the procedures and instrumentation. For each trial, participants ran toward the force plate from a distance of about 7 m and continued to run for about 3 m beyond the force plate. They were asked to run at a pace that was considered a "natural running pace," and this pace was used for all running trials (before and after the 5K run and during each data collection session). We measured and controlled for their pace by using timing gates placed along the runway. Running trials were considered successful if the participant was able to contact the specified foot entirely on the force plate.

Following completion of the 5 running trials, each participant was taken to a treadmill located in the same laboratory. The participant was asked what her average pace was for a 5K run (in minutes per mile) and was given 2 minutes to warm up on the treadmill at her pace of choice. After the 2-minute warm-up, the treadmill pace was gradually ramped up to the testing pace over a 30-second duration. Once the treadmill pace was set, the participant ran at that pace for the 5K, and all reflective markers remained on the participant during the run. After the participant completed the treadmill run, she was immediately walked back to the capture area in the biomechanics laboratory. At that time, the participant performed 5 successful running trials for the dominant leg as she had done prior to the 5K treadmill run.

Data Analysis

Coordinate data were digitized in Vicon Workstation software (Oxford Metrics Ltd). Kinematic data were filtered by use of a fourth-order, zero-lag, Butterworth 12-Hz, low-pass filter, while kinetic data were filtered with a fourth-order, zero-lag, Butterworth 50-Hz, low-pass filter.[16] Visual3D software (C-Motion Inc) was used to quantify 3-dimensional ankle joint kinematics. Joint kinematic properties were calculated by use of a joint coordinate system approach. Peak eversion angle was defined as the maximum ankle joint angle in the frontal plane during stance phase. The method for calculating average vertical loading rate was consistent with that described by Willy and Davis,[20] which entailed the middle 60% of the vertical ground-reaction force curve from heel-strike to the vertical
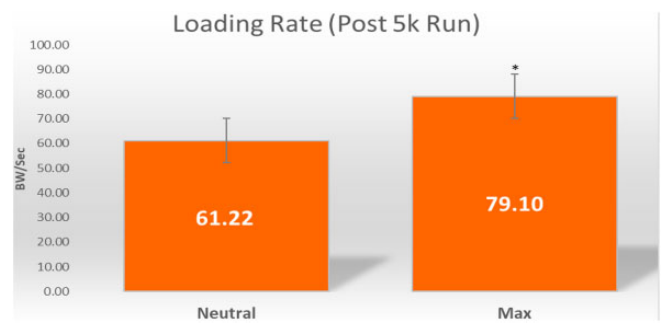

Figure 2. Loading rate comparison between the traditional neutral running shoe condition and the maximal running shoe condition following a 5K run. Error bars represent standard error. A significant difference was found between shoe types, $P \leq .05$. BW, body weight.

impact peak. These calculations were made with custom Excel software (Microsoft Corp).

Statistical Analysis

Variables of interest included the impact peak of the vertical ground-reaction force, loading rate normalized by body weight (BW), and peak ankle eversion. Differences were determined via a series of 2-way repeated-measures analysis of variance (ANOVA) (shoe $\times$ time) ($P \leq .05$). When significant differences were found, post hoc comparisons were made with paired t tests ($P \leq .05$).

RESULTS

Although no significant shoe $\times$ time interactions were found, we noted a significant main effect for shoe type for loading rate and impact peak. When the maximal shoe was compared with the neutral shoe before and after the 5K run, participants exhibited increased loading rate (mean $\pm$ SE: pre–maximal shoe, 81.15 $\pm$ 17.08 BW/s; pre–neutral shoe, 60.83 $\pm$ 12.58 BW/s [$P < .001$]; post–maximal shoe, 79.10 $\pm$ 19.07 BW/s; post–neutral shoe, 61.22 $\pm$ 13.88 BW/s [$P = .008$]) (Figure 2) and increased impact peak (pre–maximal shoe, 1.76 $\pm$ 0.21 BW; pre–neutral shoe, 1.58 $\pm$ 0.14 BW [$P = .004$]; post–maximal shoe, 1.79 $\pm$ 0.21 BW; post–neutral shoe, 1.55 $\pm$ 0.16 BW [$P = .003$]) (Figure 3). No main effect was found for time for loading rate or impact peak. Furthermore, there was no significant difference in peak eversion between shoe types (pre–maximal shoe, 10.92° $\pm$ 3.94°; pre–neutral shoe, 11.1° $\pm$ 3.38° [$P < .001$]; post–maximal shoe, 13.42° $\pm$ 4.84°; post–neutral shoe, 14.6° $\pm$ 3.93° [$P = .008$]).

DISCUSSION

The aim of this study was to examine the effect of maximal running shoes on lower extremity running biomechanics before and after a 5K run compared with neutral running shoes. Despite the popularity of maximal running shoes, we
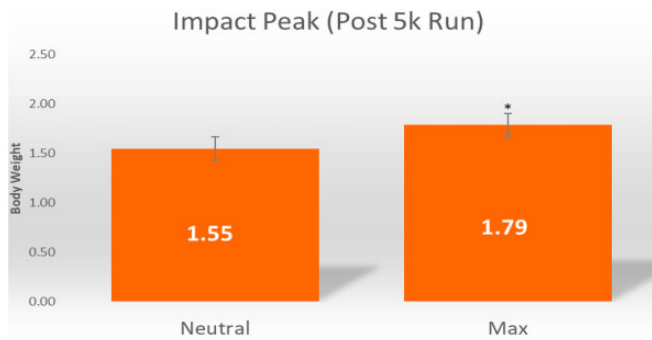
Figure 3. Comparison of impact peaks between the traditional neutral running shoe condition and the maximal running shoe condition following a 5K run. Error bars represent standard error. A significant difference was found between shoe types, $P \leq .05$.
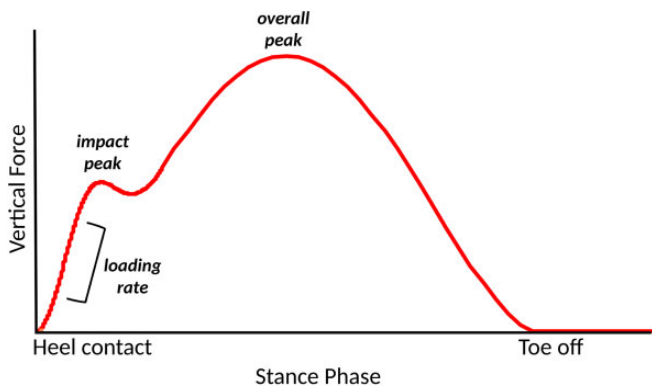

Figure 4. Example of vertical ground-reaction force trajectory for the stance phase of a runner classified as a heel-striker. Key variables of this trajectory are identified.

believe this is the first scientific investigation reported in the literature to make such a comparison. Contrary to our hypothesis, the impact peak and loading rate were greater in the maximal shoe compared with the traditional neutral shoe. No differences were seen in peak rearfoot eversion.

The majority of recreational runners are classified as heel-strikers,[3,8] who generally exhibit two distinct vertical ground-reaction force peaks: an impact peak and an overall peak (Figure 4).[9] The impact peak is of clinical interest, as high impact peaks have been associated with common running-related injuries such as plantar fasciitis and tibial stress fractures.[13,14] Baltich and colleagues[1] examined the influence of midsole cushioning on the vertical impact peak in 93 recreational runners and found that runners exhibited increased vertical impact forces when wearing softer midsole shoes. The investigators suggested that participants either were "bottoming out" in the soft midsole condition or were modifying their lower extremity stiffness. In the post–data collection discussions for the current study, participants reported they could "really feel" the extra cushioning of the maximal shoe, and many reported that the shoes

felt "springy." As such, we doubt that participants were "bottoming out" but rather were relying more heavily on the shoe to attenuate impact forces, which in turn resulted in a higher impact peak. As previously discussed, a higher impact peak could place runners at a greater risk of developing an injury.[13,14] However, it is important to note that the high impact peak occurs with heel-strike and likely causes increased loads to the tibia, calcaneus, and plantar fascia. The increased midsole cushioning likely does not increase loading of the metatarsals; however, we were not able to confirm this under the current study design.

In this study, we found that runners displayed a greater loading rate when wearing a maximal shoe compared with the neutral shoe. A higher loading rate, which represents the slope of the vertical ground-reaction force prior to the impact peak (Figure 4), has been associated with a higher risk of developing a running-related injury.[13,14] Thus, similar to impact peak, higher loading rates in the maximal shoe may place a runner at an increased risk of developing an injury.

We also hypothesized that the impact peak and loading rate would increase after the 5K run in the traditional neutral shoe but not in the maximal shoe. This hypothesis was based on anecdotal reports from recreational runners in the community, who reported "feeling the extra cushion" after 2 to 3 miles into their run. However, we found that the 5K had no influence on the impact peak or loading rate in either shoe condition, indicating that neither a brief accommodation period nor muscular fatigue likely influenced these kinetic variables.

In addition to examining kinetics, we were also interested in whether the maximal shoe influenced peak eversion, since this is another biomechanical variable that has been associated with running-related injuries.[14] The maximal shoe is unique in that it offers a highly cushioned midsole, but manufacturers claim that it also provides a considerable amount of motion control and stability because of its wide rearfoot base of support. The maximal shoe midsole/outsole used in this study was wider than the neutral shoe, particularly in the rearfoot portion of the shoe (maximal shoe: forefoot width, 109 mm and rearfoot width, 96 mm; neutral shoe: forefoot width, 103 mm and rearfoot width, 80 mm). However, our findings revealed no difference in peak eversion between the neutral running shoe and the maximal running shoe condition. Therefore, it appears that there is no difference in the influence of a maximal shoe versus a neutral shoe when participants are running over solid surface in a laboratory setting.

Finally, because recent studies have found that runners, over time and training, may modify their heel-strike pattern to a midfoot- or forefoot-strike pattern when transitioning from a neutral shoe to a minimal shoe,[5] we conducted a post hoc analysis of all running trials to determine whether our participants modified their foot-strike pattern in the maximal shoe condition. This post hoc analysis consisted of viewing all maximal shoe running trials in Vicon software and identifying which portion of the foot hit the force plate first. We found that all participants continued to exhibit a heel-strike pattern across all conditions.

A limitation of this study is that the maximal shoe condition was novel to the participants. The observed differences were not changed by the 5K run; however, we did not assess whether these differences persisted over a greater duration of exposure to the shoe. Allowing runners to gradually transition or adapt to the shoe over a period of several weeks may yield different results. Placing markers directly on the shoes limited our ability to quantify true ankle eversion. In addition, the exclusion of male runners limits our findings to only healthy female runners within the given age range. A final limitation is related to test-retest reliability. Our kinematic model is commonly used in the running biomechanics research reported in the literature; however, this model is most reliable for measuring sagittal plane kinematics. Future studies should examine how runners adapt to running in a maximal shoe over a period of time such as 6 weeks.

CONCLUSION

Runners who were classified as heel-strikers exhibited increased impact forces and loading rate when running in a maximal shoe compared with a traditional neutral shoe. Because increases in these variables have been associated with an increased risk of running-related injuries, runners who are new to running in a maximal shoe may be at an increased risk of injury. Therefore, runners should consider this potential increased risk for injury when switching from a neutral shoe to a maximal shoe; however, further work is necessary to better understand the longer term impact of this type of footwear.

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