IMPACT LOADING IN RUNNING

SHOES WITH CUSHIONING COLUMN SYSTEMS

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ABSTRACT

This study evaluated the effects of running shoes with two types of cushioning column systems on impact force patterns during running. Kinematic and ground reaction force data were collected from ten normal subjects wearing shoes with the following cushions: 4-column multi-cellular urethane elastomer (Shoe 1), 4-column thermoplastic polyester elastomer (Shoe 2), and 1-unit EVA foam (Shoe 3). Subjects exhibited significantly lower impact force (p = .02) and loading rate (p = .005) with Shoe 2 (1.84 ± .24 BW; 45.6 ± 11.6 BW/s) compared to Shoe 1 (1.94 ± .18 BW; 57.9 ± 12.1 BW/s). Both cushioning column shoes showed similar impact force characteristics to those of a top-model running shoe (Shoe 3) and improved cushioning performance over shoes previously tested in similar conditions. Alterations in impact force patterns induced by lower limb alignment and running speed were negligible since subjects did not differ in ankle position, knee position, and speed during all shod running trials. Ankle plantarflexion, however, was higher for barefoot running, indicating an apparent midfoot strike. Mechanical testing of each shoe during physiologic, cyclic loading demonstrated that Shoe 3 had the greatest stiffness, followed by Shoe 2 and Shoe 1. Shoe 1 was the least stiff of the two shoes with cushioning column systems yet it displayed a significantly higher impact loading rate during running, possibly due to rearfoot motion alterations induced by the stiffer shoe. This study showed that even in similar shoe types, impact force and loading rate values could significantly vary with midsole cushion constructions. The findings of this study suggest using these newer running shoes may be effective for runners who desire optimal cushioning during running.

INTRODUCTION

During the impact phase of the ground reaction force, the momentum from the decelerating limb rapidly changes as the foot collides with the ground, resulting in a transient force transmitted up the skeleton. In running, these forces can reach magnitudes of up to three times body weight (Cavanagh & Lafortune, 1980). The repetitive transmission of these forces may contribute to degradation and overuse injuries (James, Bates, & Osternig, 1978). Athletic footwear with rearfoot cushioning systems has proven to effectively attenuate impact forces experienced during barefoot heel-toe running (Clarke, Frederick, & Cooper, 1983) and, consequently, been proposed as a mechanism in minimizing overuse injuries (Barnes & Smith, 1994).

In an effort to improve impact attenuation and durability, footwear manufacturers have adapted engineering concepts from other fields to design more effective rearfoot cushions. For example, the *Shox*™ technology developed by Nike, Inc. (Beaverton, OR) incorporates a system of four spring-like columns made up of the same material found in jounce bumpers, which are shock absorbers used to cushion a car's frame. This new cushioning technology was developed based on tuned running tracks and demonstrated greater resiliency than other cushions used in popular running shoes (Valiant et al., 2001). A similar cushioning technology was developed by Iso-Dynamics, Inc. (Cleveland, OH) using a resilient yet stiff elastomer for the midsole columns of a running shoe developed by DaDa Footwear (Los Angeles, CA).

While shoes with these cushioning columns may have undergone rigorous wear and biomechanical testing by their respective manufacturers, no evidence-based research was found in the scientific literature that investigated the effects of these advanced cushioning systems on impact forces or on running kinematics. With these new types of commercially available shoes, a biomechanical assessment may be beneficial for athletes aiming to use such shoes to minimize injuries resulting from repeated impact loading. Therefore, the purposes of this study were to evaluate the effects of two types of running shoes with advanced cushioning column systems on vertical ground reaction force patterns and materials characterization during running, and to compare them to those observed with a shoe constructed using a single rearfoot cushioning unit of viscoelastic foam.

METHODS

Eight male and two female subjects participated in the study after signing informed consent forms approved by the hospital's Institutional Review Board. All subjects were screened with a musculoskeletal exam and were considered healthy, recreational runners (<10 miles per week) with no clinical signs indicating altered gait patterns. The average subject height and body mass were 181 ± 4 cm and 82 ± 4 kg, respectively.

Three commercially available running shoes were evaluated. Shoe 1 (Figure 1, left panel) was constructed with a set of four cushioning columns made of multi-cellular urethane elastomer arranged in an open configuration in the rear midsole (Nike, Inc., Beaverton, OR). Shoe 2 (Figure 1, right panel) had a similar cushioning column system, except each column was built with a thermoplastic polyester elastomer molded into a hollow, bumper-like unit (Iso-Dynamics, Inc., Cleveland, OH). Shoe 3 was manufactured with a single midsole cushioning unit of proprietary ethyl vinyl acetate (EVA) (ASICS Tiger Corporation, Kobe, Japan), considered to be highly durable material (Whittle, 1999). The insole for Shoe 3, a top-model running shoe, was used for both Shoes 1 and 2.

To measure limb position at footstrike, eight visible-red cameras (Motion Analysis Corporation, Santa Rosa, CA) captured coordinate data at a sampling rate of 120 Hz from a cluster-based marker set used to define the pelvis as well as bilateral thigh, shank, and foot segments. For the shod conditions, markers were placed on the heel counter and toe box of each shoe. Three floor-mounted force platforms (OR-6, AMTI, Watertown, MA, USA), with a natural frequency of 450 Hz, were used to sample ground reaction force (GRF) data at 1000Hz. Analog signals were amplified using each platform's associated signal conditioner (MCA-6, AMTI), connected via a 12-bit A/D card to a dual processor computer that was used to simultaneously capture GRF and marker data in real-time.

Following a static calibration trial and a five-minute warm-up period, each subject repeatedly ran barefoot across a 12-meter runway at their preferred stride frequency as motion and GRF data were collected. Three trials, involving complete right foot contact and without visual targeting, were collected for each pair of shoes that were randomly selected by the lab technician.

GRF data was left unfiltered as to preserve the high frequency components that may have indicated the presence of transient forces. Custom software determined the following GRF parameters, as shown in Figure 3: Fz1, peak vertical GRF within 50 ms after footstrike (impact force); Rz1, loading rate of Fz1 calculated from the linear slope between footstrike and the time onset of Fz1; Fz2, minimum vertical GRF; and Fz3, peak propulsive GRF. Using the Orthotrak software (Motion Analysis Corp.), sagittal knee and ankle kinematics were calculated after marker data was smoothed using a low-pass filter at a cut-off frequency of 12 Hz. Knee flexion angle and ankle plantar-dorsi flexion angle at footstrike were selected for subsequent analysis to address the effect of limb position on ground reaction forces.

Each parameter was statistically analyzed using a 4-level repeated measures ANOVA with a *post hoc* Bonferroni-adjusted pairwise comparison test at a significance level of 0.05. To determine the repeatability of each subject's running velocity, the coefficient of variation, which is simply the variance-to-mean ratio, was computed as described by Winter (1984).

In addition to biomechanical testing, a brand-new shoe of each type was randomly chosen for cyclic testing using an MTS 858 Mini-Bionix servohydraulic testing machine (Eden Prairie, MN). The piston actuator of the machine (diameter = 2.5cm) applied loads directly to the center of the rearfoot area in each shoe, simulating the primary weight bearing area of the heel pad. The machine was tuned for high load, high frequency load control prior to testing, which involved a 5 Hz cyclic waveform operating between 10 N and 1400 N of compressive load to approximate the impact loads of 2.5 times the average body weight of the running subjects. Displacement (mm) and load (N) were sampled at 100 Hz for the duration of each test using the TestWare 4.0C software manufactured by MTS. For each test, the last two of 100 cycles were used as data while previous cycles were used to pre-condition the system. Shoe stiffness was measured from the slope of a linear regression between 50 N and 1400 N of the load-deflection curve.

RESULTS

The running velocity as well as the sagittal knee and ankle kinematics had no significant effect on the impact force parameters measured from the shod trials. Mean running velocity across all subjects was 3.23 ± 0.02 m/s. No significant differences in knee flexion angle at footstrike were observed across all running sessions (p = .74). Conversely, subjects exhibited significantly more ankle plantarflexion (p < .001) at footstrike during barefoot running compared to that of shod running, indicating an apparent midfoot strike. As a result, GRF data from the barefoot running trials were not analyzed. Likewise, data for one subject who was observed to be a midfoot striker during all running sessions were removed from the analysis. Ankle flexion at footstrike for the remaining nine subjects did not significantly differ across shod conditions (p = .70).

Differences in impact force parameters across all shoes could only be observed in magnitude (Fz1, p = .04) and loading rate (Rz1, p = .003) values as shown in Table 1. No significant differences in the average minimum vertical (Fz2) or peak propulsive forces (Fz3) were found between shod conditions. *Post hoc* tests revealed that subjects exhibited significantly lower impact forces (p = .02) and loading rates (p = .005) with Shoe 2 compared to Shoe 1, despite the fact that instrumented testing revealed Shoe 2 to have a higher stiffness (124 N mm^{-1}) than Shoe 1 (92 N mm^{-1}) (Figure 3). However, it is worthy to note that the average impact force (Fz1) magnitudes were less than 2.00 BW for all shoe conditions, and the maximum difference in these values between all shoes was .10 BW. Pairwise comparison tests also revealed that GRF parameters for sessions performed in Shoe 3 were not statistically different (p > .10) from those found in sessions with either Shoe 1 or 2, although Shoe 3 had the highest stiffness (137 N mm^{-1}) of all the shoes tested on the instrumented machine (Figure 3).

DISCUSSION

Due to the relatively recent launch of cushioning column shoes, this study represents the first comparative study on the cushioning performances of these new shoes. While there was a statistically significant difference in impact forces (Fz1) between both column-based shoes, the difference in the average magnitude was within a tenth of the average body weight and well within the range found in other popular running shoes that were previously tested using a similar ground reaction force analysis (Hennig, Milani, and Lafortune, 1993). Conversely, loading rates (Rz1) of running trials for both column-based shoes were considerably lower than those previously found with other shoes (Clarke, Frederick, & Cooper, 1983; Hennig, Milani, and Lafortune, 1993), particularly for the thermoplastic column-based shoe (Shoe 2). Such loading rate patterns represent the cushions' capacity to reduce the rate at which the impact shock is transmitted to the lower extremity and perhaps are better indicators of cushioning performance than peak impact forces. The fact that the loading rate of Shoe 2 was significantly less than that of Shoe 1 reinforces previous findings that changes in the foot-ground interface influence loading rates more than they do peak impact forces (Clarke, Frederick, & Cooper, 1983; Lafortune, Hennig, & Lake, 1996). Hence, differences in midsole constructions would appropriately affect impact loading rate, as interpreted by cushioning performance in this study.

Although shoes 1 and 2 were similar in column configuration, the columns in Shoe 2 were constructed with a thermoplastic polyester elastomer material molded into a hollow bumper with a variable wall thickness increasing from top to bottom (Iso-Dynamics, Inc., Cleveland, OH). Shoe 1, on the other hand, was constructed with a system of four rearfoot cushions made up of highly resilient urethane foam with a higher radial thickness than that of Shoe 2 (Valiant et al., 2001). Oddly, instrumented cyclic testing conducted in the present study revealed Shoe 1 to be the softest shoe despite exhibiting relatively higher values of impact force peak and loading rate compared to Shoe 2. This is in contrast to previous findings, which have shown that softer shoes normally exhibit lower impact loading rates (Clarke, Frederick, & Cooper, 1983; Lafortune, Hennig, & Lake, 1996). However, previous instrumented shoe testing was primarily performed using an impact tester (Cavanagh, 1980), which differ from the cyclic testing used in this study. However, it has generally been agreed that instrumented testing does not accurately approximate the *in vivo* loading experienced during running (Cavanagh and Lafortune, 1980). Therefore, the load distribution at the midsole cushioning region during footstrike could be remarkably different to that found during instrumented testing, leading to the observed discrepancies in stiffness and impact force patterns.

Running velocity as well as knee and ankle plantar-dorsi flexion angles at footstrike were highly consistent across all subjects during all sessions. Therefore, any differences observed in the GRF parameters were most likely caused by changes in the foot-ground interface (i.e., shoes) and not by gait adaptations induced by footwear. However, the cushioning column design may have induced changes in normal rearfoot motion, thus potentially affecting the impact forces observed (Perry & Lafortune, 1995). With these systems, only four cushioning units are found in the midsole as opposed to the thousands of closed air cells found in single-unit EVA cushions. Thus, column-based systems behave much like an independent-suspension system, where each column is capable of providing a certain level of cushioning and collectively make up the overall stiffness of the shoe's midsole. Hennig, Valiant, and Liu (1996) concluded that runners who wore harder shoes tend to alter their landing patterns to elicit lower impact forces. Unfortunately due to the lack of a standardized foot model (Areblad et al., 1990), differences in rearfoot motion were not specifically addressed in this study. The potential variations in rearfoot motion combined with the differences in midsole properties between the two constructs could explain the cushioning differences found between the two column-based shoes.

Impact forces during running are of considerable interest because of their potential contributions to overuse injuries (Barnes & Smith, 1994). The new rearfoot cushioning technology tested in this study was first introduced by Nike, Inc (Beaverton, OR) as the *Shox*™ technology, and its development was based on tunable running tracks designed to reduce impact forces (McMahon and Greene, 1979; Valiant et al., 2001). The present study showed that this new technology was in fact highly compliant and comparable to current cushioning systems. However, impact force and loading rate values could vary with midsole material properties as a result of alterations in rearfoot motion and should be addressed in subsequent studies. Nevertheless, both cushioning column-based shoes attenuated impact to a level and at a rate similar to those of a top-model running shoe. For athletes wishing to wear shoes with maximum midsole cushioning, this study has provided relevant information regarding impact loading on shoes with relatively new cushioning column systems.

FIGURE LEGENDS

Figure 1 Cushioning column systems for Shoe 1 (*Shox*™, Nike, Inc., Beaverton, OR) and Shoe 2 (Iso-Dynamics, Inc., Cleveland, OH) pictured on the left and right panels respectively. Shoe 1 is configured with four separate cushioning columns, each constructed with high resilient urethane elastomer. Shoe 2 is configured with four separate cushioning columns, each constructed with thermoplastic polyester elastomer.

Figure 2 Ground reaction force parameters used to evaluate shoe cushioning performance. The impact force, Fz1, is the peak vertical ground reaction force occurring within the first 50 msec following initial contact. The impact loading rate, Rz1, was calculated from the linear slope from initial contact to the onset of Fz1. Fz2 and Fz3 represent the minimum vertical GRF and propulsive GRF, respectively.

Figure 3 Load-displacement curves from instrumented testing of Shoe 1 (solid), Shoe 2 (dotted), and Shoe 3 (dashed). The hysteresis curves represent the loading-unloading cycle effect on each shoe. The amount of displacement during loading represents shoe stiffness, which illustrate a decreasing order of stiffness from Shoe 3 to Shoe 1.

Table 1 Mean (± SD) Ground Reaction Force Parameters while Running with Each Shoe (n=9)

Parameter	Shoe 1	Shoe 2	Shoe 3
F_{z1} (BW)	1.94 ± 0.18*	1.84 ± 0.24*	1.87 ± 0.24
F_{z2} (BW)	1.75 ± 0.15	1.67 ± 0.34	1.74 ± 0.35
F_{z3} (BW)	2.53 ± 0.39	2.55 ± 0.32	2.51 ± 0.37
R_{z1} (BW s^{-1})	57.9 ± 12.1^	45.7 ± 11.6^	58.4 ± 21.3

Note: Ground reaction forces are expressed as percentages of body weight (BW) and loading rate as a percentage of body weight per second (BW s^{-1}).
* denotes a significant difference in impact force observed between shoes 1 and 2 ($p = .02$).
^ denotes a significant difference in loading rate observed between shoes 1 and 2 ($p = .005$).

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