GROUND REACTION FORCES IN RUNNING SHOES WITH TWO TYPES OF CUSHIONING COLUMN SYSTEMS

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The purpose of this investigation was to evaluate the effects of running shoes with two types of cushioning column systems on impact forces during running. Kinematic and ground reaction force data were collected from ten normal subjects wearing shoes with the following cushions: 4-column MPU 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). This study showed that even in similar shoe types, impact force and loading rate values could significantly vary with midsole cushion constructions.

KEY WORDS: impact force, loading rate, impact attenuation, spring-loaded shoes.

INTRODUCTION: It has generally been assumed that running related injuries are, to some degree, caused by excessive peaks in the impact phase of the ground reaction force (James, Bates, & Osternig, 1978; Cavanagh, 1980; Novachek, 1998). During this phase, 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 has been suggested to be a contributing factor in the development of joint degradation and overuse injuries (Radin, Paul, & Rose, 1972; Hreljac, Marshall, & Hume, 1999). Although the foot has internal structures that help attenuate impact loading, athletic footwear with rearfoot cushioning systems have been proven to effectively attenuate impact forces (Clarke, Frederick, & Cooper, 1983). The most common feature in running shoes within the last two decades was in midsole construction, which was usually done as a single cushioning component of sponge rubber or viscoelastic foam (Cavanagh, 1980; Whittle, 1999). In an effort to improve impact attenuation and durability, footwear manufacturers have adapted engineering concepts from other fields to design more effective rearfoot cushioning systems. 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. A similar cushioning technology was developed by Iso-Dynamics, Inc. (Cleveland, OH) and was incorporated in a running shoe manufactured by L&L International, LLC (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 investigates the effects of these advanced cushions on impact forces or on running kinematics. With these shoes commercially available to millions of runners, a biomechanical assessment of these shoes may be beneficial for athletes aiming to enhance performance or minimize injury. 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 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 recruited from the hospital staff and local universities and were labeled as healthy, recreational runners (<10 miles per week) after being screened with a musculoskeletal exam. The average subject height and weight were 181 ± 4 cm and 82 ± 4 kg, respectively. Each subject ran barefoot and in three shod conditions at a speed of 12 km h^{-1} across a 12-meter runway. Three force platforms (AMTI, Watertown, MA) with a natural frequency of 450 Hz were used to collect ground reaction force (GRF) data at a sampling rate of 1000 Hz through a

12-bit A/D converter. To measure limb position during footstrike, eight Falcon cameras (Motion Analysis Corporation, Santa Rosa, CA) captured coordinate data at a sampling rate of 120 Hz from four triads of reflective, spherical markers (2.5 cm DIA) used to define bilateral thigh and shank segments. Markers were also placed on the skin overlying the anterior superior iliac spines, sacrum, heel, and dorsalis pedis. For the shod conditions, markers were placed on the heel counter and toe box of each shoe. Starting position was altered before each session to increase the probability of obtaining three usable trials, defined as one in which the subject's entire right foot cleanly strikes one of the three force platforms while traversing the pathway. Three commercially available running shoes, characterized by midsole cushion type, were tested. Shoe 1 (Figure 1) was constructed with a set of four cushioning columns made of MC urethane elastomer arranged in an open configuration in the rearfoot wedge (Nike, Inc., Beaverton, OR). Shoe 2 (Figure 2) 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). Both spring-loaded shoes were first generation models. Shoe 3 was manufactured with a single midsole cushioning unit of proprietary 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 also used in the other shoes.

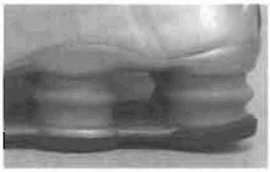

Figure 1. Shoe 1 with MCU elastomer cushioning columns.

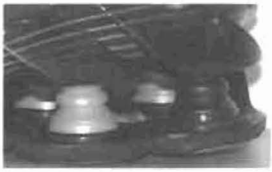

Figure 2. Shoe 2 with polyester elastomer cushioning columns.

In addition to biomechanical testing, each shoe was randomly chosen for cyclic testing using an MTS 858 Mini-Bionix servohydraulic testing machine (Eden Prairie, MN). The machine was tuned for high load, high frequency load control prior to shoe testing. The load control test 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 100Hz 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. Stiffness was measured from the slope of a linear regression between 50 N and 1400 N.

Using the Orthotrak 5.0 software by Motion Analysis Corp., sagittal knee and ankle kinematics were analyzed after marker data was smoothed using a 2nd order Butterworth filter with a cut-off frequency of 12 Hz. A computer spreadsheet was used to determine the following GRF parameters, as shown in Figure 3: F_{z1}, peak vertical GRF within 50 ms after foot contact (impact force); R_{z1}, loading rate of F_{z1} calculated from the linear slope between 0 and the time onset of F_{z1}; F_{z2}, minimum vertical GRF; and F_{z3}, peak propulsive GRF. Each parameter was statistically analyzed using a 4-level RM ANOVA with a *post hoc* Bonferroni-adjusted pairwise comparison test at a significance level of .05.

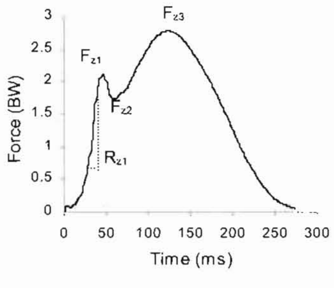

Figure 3. Vertical GRF for the stance phase of a subject running at 3.23 ms^{-1}

RESULTS AND DISCUSSION: Mean running velocity (3.23 ± 0.02 m s^{-1}) across all subjects remained consistent (1% coefficient of variation) for barefoot and shod conditions. Similarly, no significant changes in knee flexion were observed across all running sessions. Therefore, any cushioning effect observed in the GRF parameters could presumably be attributed to changes in the foot-ground interface (i.e., shoes) and not running velocity (Nigg et al., 1987) or knee angle as previously reported (Bobbert, Yeadon, & Nigg, 1992). Conversely, there was an increase in plantarflexion (-3° ± 1°) at footstrike observed in all subjects during barefoot running, indicating an apparent midfoot strike. This observation follows the general presumption that limb posture is used more to control the higher impact forces of barefoot running than it is in walking (Whittle, 1999). Thus, GRF data from the barefoot running trials were not analyzed. Likewise, data were also removed for one subject who was observed to be a midfoot striker during all running sessions.

The mean GRF parameters for heel-toe running in all three shoes are listed in Table 1. No significant differences in minimum vertical (F_{z2}) or peak propulsive forces (F_{z3}) were found. GRF parameters for shoe 3, the only shoe with a single cushioning component that was tested, were not statistically different from those for either shoe 1 or 2. The midsole of shoe 2 was found to be stiffer than that of shoe 1 (Figure 4). Yet, it exhibited significantly lower impact force (F_{z1}) and loading rate (R_{z1}) than shoe 1. This is in contrast to previous findings, which have shown that softer shoes, as defined through instrumented impact testing, exhibit lower impact loading rates (Clarke, Frederick, & Cooper, 1983).

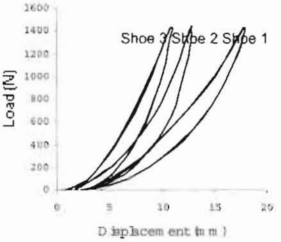

Figure 4. Load-deflection curves from machine testing of shoes 1, 2, and 3.

Table 1. Mean Ground Reaction Force Parameters for Shod Running (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

* *p* = .02; ^ *p* = .005

The discrepancy in the machine tested stiffness and impact attenuation is best explained using a spring-mass model as shown in Figure 5. Shoe stiffness (k) is dependent on how much a midsole cushion deflects under impact loading. With a single, homogeneous cushion as in the one in shoe 3 (Figure 5a), the stiffness is almost exclusively dependent on the material properties of the midsole and insole cushions (i.e., ethylene vinyl acetate or EVA). With cushioning column systems, only four cushioning units are found in the midsole as oppose to the thousands of closed air cells found in EVA cushions. Thus, these column systems behave much like an independent suspension system, where the columns each have a certain amount of stiffness and collectively make up the overall stiffness of the shoe (Figure 5b). It has generally been agreed that machine loading of shoes does not accurately simulate the in-vivo loading experienced during running (Cavanagh and Lafortune, 1980; Novachek, 1998). Therefore, it is highly likely that the columns were each deflecting to different magnitudes during footstrike whereas they were equally compressed during machine loading.

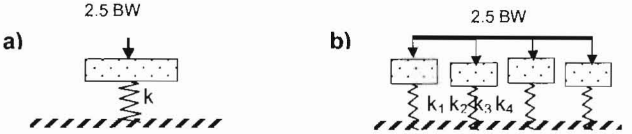

Figure 5. Spring-mass models representing (a) a single EVA cushioning unit and (b) four cushioning columns acting as an independent suspension system.

Because shoes 1 and 2 were very similar in midsole construction, it was unexpected to observe significant differences in impact force and loading rate between them. However, the differences in material and construction between the two column types could have been major factors as they are in single-unit midsoles (Hennig, Milani, & Lafortune, 1993). The columns in shoe 1 were constructed with a urethane elastomer shaped into a solid deformable unit. Conversely, the columns in shoe 2 were made with a thermoplastic elastomer molded into a hollow bumper with a variable wall thickness increasing from top to bottom (Iso-Dynamics, Inc., Cleveland, OH). Such a design is analogous to a spring with two stiffness constants where deflection occurs faster on the top than it does on the bottom. This multi-stage cushioning effect was observed in walking when the relatively lower impact (transient) forces were effectively attenuated at heelstrike (Aguinaldo, Litavish, & Morales, 2002). The overall effect of all four multi-stage columns performing in this manner during impact can explain why shoe 2 exhibited a significantly (p = .005) lower loading rate.

CONCLUSION: This study showed that even in similar shoe types, impact force and loading rate values could significantly vary with midsole cushion constructions. A running shoe constructed with a cushioning system of four multi-stage columns (shoe 2) showed significantly less peak impact force than that observed in another shoe with cushioning columns. Shoe 2 also considerably reduced the rate at which the runner experienced this force. These findings suggest this type of cushioning column system has more shock absorption than the other system. Furthermore, both spring-loaded 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 new relevant information regarding impact loading on shoes with cushioning column systems. However, future studies addressing rearfoot control, stability, and durability of this type of footwear should be conducted before any criteria-based selections can be made.

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