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Research article

Ground reaction force differences between running shoes, racing flats, and distance spikes in runners.

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Abstract
Various shoes are worn by distance runners throughout a training season. This study measured the differences in ground reaction forces between running shoes, racing flats, and distance spikes in order to provide information about the potential effects of footwear on injury risk in highly competitive runners. Ten male and ten female intercollegiate distance runners ran across a force plate at 6.7 $m \cdot s^{-1}$ (for males) and 5.7 $m \cdot s^{-1}$ (for females) in each of the three types of shoes. To control for differences in foot strike, only subjects who exhibited a heel strike were included in the data analysis. Two repeated-measures ANOVAs with Tukey's post-hoc tests ($p < 0.05$) were used to detect differences in shoe types among males and females. For the males, loading rate, peak vertical impact force and peak braking forces were significantly greater in flats and spikes compared to running shoes. Vertical stiffness in spikes was also significantly greater than in running shoes. Females had significantly shorter stance times and greater maximum propulsion forces in racing flats compared to running shoes. Changing footwear between the shoes used in this study alters the loads placed on the body. Care should be taken as athletes enter different phases of training where different footwear is required. Injury risk may be increased since the body may not be accustomed to the differences in force, stance time, and vertical stiffness.

Key words: Footwear, impact, track.

Introduction

During locomotive physical activity, the load on the body can be described by measuring the ground reaction forces (GRF) pushing against the foot. Faster running speeds are primarily achieved as the foot exerts greater forces on the ground (Weyand et al., 2000). During distance running, maximum vertical forces of more than two times body weight are typical (Cavanagh and Lafortune, 1980; Nilsson and Thorstensson, 1989). Over the last three decades, research conducted on GRF during running has examined how these forces affect the body and how factors such as running style, types of surfaces, and footwear may affect GRF (Bobbert et al., 1991; Cavanagh and Lafortune, 1980; Clarke et al., 1983; Cook et al., 1985; De Wit et al., 1996; Divert et al., 2005).

Attenuation of impact force has been a major concern for shoe designers and manufacturers, as one of the primary roles for running shoes is to provide shock absorption (Cavanagh, 1980; Nigg, 1986). Additionally, the weight of the shoe has been reduced to improve performance. Hence, racing flats and spikes have been developed to help facilitate optimal performance (Cavanagh, 1980; Denton, 2005). In comparison to most running shoes, spikes and racing flats have less cushioning and a thinner heel to produce a lighter shoe for competition and training sessions. While competitive footwear has its time and place, it is assumed that this type of shoe should be used with caution and awareness of the possible increased injury risks (Denton, 2005).

Several studies have investigated the reduction of impact force in running shoes, but there is a lack of data on the GRF in competitive footwear. Studies have reported differences in GRF between barefoot and shod running, showing the effects on GRF when the shock absorption of running shoes is absent (De Wit et al., 1996; 2000; Dickinson et al., 1985; Divert et al., 2005). These studies have found significantly increased loading rates and greater vertical impact forces when running barefoot (De Wit et al., 1996; 2000; Dickinson et al., 1985).

The results of studies concerning the relationship between impact forces and increased injury risk have been equivocal. Some investigators claim that greater GRF during running may be associated with increased risk of injury (Gottschall and Kram, 2005; Hreljac et al., 2000; Messier et al., 1995; Milner et al., 2006). Others have not found a positive correlation (Bennell et al., 2004; Crossley et al., 1999), with some even reporting decreased injury occurrence associated with greater GRF (Duffey et al., 2000). If present, differences in GRF between running shoes, racing flats, and spikes, could provide information on potential injury risks (Bus, 2003; Cavanagh, 1980; Frederick et al., 1984; Gottschall and Kram, 2005; Jakobsen et al., 1989).

The purpose of this study was to compare how GRF are influenced while running in running shoes, racing flats, and spikes at a given speed in order to provide meaningful information for future studies towards injury risks and performance benefits that could influence the timing and frequency of the use of competitive footwear in runners. We hypothesized that forces, loading rates, and vertical stiffness would all increase while ground time would decrease among males and females as shoe types progressed from trainers, to racing flats, to spikes.

Methods

Subjects

Twenty members of NCAA Division I distance track teams/cross-country teams, 10 males (21.6 ± 3.0 years; 1.78 ± 0.05 m; 66.3 ± 6 kg; male's US shoe size: 10 ± 0.95) and 10 females (20 ± 1.5 years; 1.69 ± 0.06 m; 57.6

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± 4.8 kg; male's US shoe size: 7.8 ± 1.3) were recruited as volunteers. All subjects competed in the 1500 m through the 5000 m events in track. Each subject completed a short questionnaire about current injury status and signed a consent form approved by the university's institutional review board prior to participating in the study. Only runners who were injury free for at least two months, and had been participating in race-specific training for at least three weeks were included. In addition, subjects underwent an initial screening for foot strike characteristics as described below.

Data Collection

Force Plate

A Kistler force plate (Type 9287BA, serial number 1440145, Amherst, New York, USA) was used for collecting the ground reaction force data. It was imbedded underneath a Mondo SuperX indoor track with an asphalt foundation. The force plate was completely covered by the Mondo surfacing, with no breaks or seams in the track surrounding the plate. The force plate was 90 cm long and 60 cm wide, and was oriented lengthwise in the running direction along the track. Calibration of the force plate took place during manufacturing by the company. The glue under the track surface kept steps prior to or after the measured foot contact from influencing the force measurement. Three orthogonal ground reaction force components were measured by converting an electric charge generated through a piezoelectric force sensor into a voltage via a charge amplifier. A digital signal was then generated from this voltage with a 16-bit analog-to-digital converter. Samples were taken at 2000 Hz with a 50 Hz low-pass Butterworth filter being applied following each trial. A custom software program was developed using Microsoft Visual Studio.NET© (Redmond, WA) to calculate the forces, stance time, and vertical stiffness.

Body weight was measured by having the runners stand on the force plate prior to running the trials. Recorded forces were normalized to the body weights of the subjects. From the force plate data, peak braking and propulsion forces, peak vertical force, stance time, vertical stiffness, loading rate, and peak vertical impact force were calculated. These variables were chosen as the most relevant components based on previous research on GRF during running (Cavanagh and Lafortune, 1980; Keller et al., 1996; De Wit et al., 1996; Nilsson and Thorstensson, 1989). Loading rate was defined as the time rate of change of the vertical impact force between 20% and 80% body weight and had units of BW/s. Stance time was defined as the time that 20 N or more of vertical force was applied to the force plate.

Vertical stiffness was calculated through an optimizing routine matching predicted ground reaction forces to measured ground reaction forces (Hunter, 2003). This method adjusts initial velocity and stiffness until a best fit is found between predicted and calculated vertical GRF. Initial velocity was included in the optimization procedure along with stiffness until a best reproduction of the vertical force was found. In other words, we entered -1 $m \cdot s^{-1}$ as the initial velocity, then adjusted the velocity until a reproduction of ground reaction forces matched the measured ground reaction forces. Thus, one foot strike was sufficient to calculate stiffness.

Shoes

The shoes were the same for all runners, differing only in size (sizes 6-12 in male's shoe size) and consisted of regular running shoes (Nike® Air Pegasus™ 2005), racing flats (Nike® Zoom Waffle Racer™ 2005), and distance spikes (Nike® Zoom Miler™ 2005). The shoes were brand new at the beginning of data collection, and were only used during the data collection. The following information about these shoes was obtained through a telephone conversation with running specialists at the Nike ® Company (personal communication (1-800-595-6453), July 18, 2006). The Air Pegasus™ has a relatively soft midsole, and is neutral in terms of motion control. It is designed to give adequate cushioning and comfort. The Zoom Waffle Racer™ is designed as a lightweight racing shoe for distance runners, and hence has less of the cushioning properties of the Air Pegasus™ as the midsole is much firmer. The Zoom Miler™ is a typical distance racing spike, with no midsole and a very firm outsole made of plastic. There is a thin ethylene-vinyl acetate (EVA) heel wedge for enhanced cushioning, and a sparse rubber outsole covering the heel. As with most racing shoes, the Zoom Waffle Racer™ and the Zoom Miler™ do not provide rearfoot motion control. These shoe characteristics may be important to consider when comparing the results of this study to other studies that may be done in the future.

Running Protocol

Subjects were instructed to come to the track, as if prepared for a normal run or workout. Following their typical warm-up, they began each trial about 25 m before the force plate to allow time to get into a normal running rhythm at the designated pace. Female subjects ran at 4:40 minute per mile pace (5.7 $m \cdot s^{-1}$), and the males at 3:59 minute per mile pace (6.7 $m \cdot s^{-1}$), speeds needed to qualify automatically for the 2007 NCAA Division I Indoor Track National Championships meet. Speed was verified using a photoelectric timing system, with sensors positioned 10 m apart at neck level on both sides of the force plate. Running pace was maintained for at least 5 m after contact with the force plate. Sufficient recovery of at least 60 s easy jogging, walking, and/or standing was allowed between trials.

Data collection took place within the first eight weeks of either the cross-country or indoor track seasons. Since forefoot and midfoot strikers characteristically lack an impact peak, only subjects with a heel strike while running at the speeds used in this study participated. There is limited documented evidence on what proportion of runners are heel strikers at the speeds measured. However, a recent study filmed foot strike patterns for 283 runners during an elite-level half-marathon to determine the proportions of heel strikers, mid-foot strikers, and forefoot strikers (Hasegawa et al., 2007). Results showed that 62% of runners were heel strikers at 5.45 $m \cdot s^{-1}$, a speed comparable to that used for females in the present study. During the initial data collection, 16 out of 20 runners (10 females and 6 males) exhibited a heel strike at

Table 1. Female's means and standard deviations for GRF variables in the three shoe conditions. Data are means (±SD).

	Running Shoes (A)	Racing Flats (B)	Spikes (C)
Peak Vertical Impact Force (BW)	2.47 (.37)	2.54 (.37)	2.77 (.45)
Loading Rate (BW/s)	148 (54)	175 (108)	191 (136)
Stance Time (s)	.167 (.009) ^{B}	.160 (.008) ^{A}	.161 (.008)
Vertical Stiffness (BW/m)	61 (26)	71 (60)	105 (95)
Peak Braking Force (BW)	-.70 (.20)	-.78 (.23)	-.73 (.22)
Peak Propulsion Force (BW)	.54 (.05) ^{B}	.58 (.04) ^{A}	.57 (.05)
Peak Vertical Force (BW)	2.95 (.23)	2.97 (.29)	3.09 (.46)

Superscripts denote a significant difference (p < 0.05) between groups.

the given speeds. Consequently, four additional males who were heel strikers were recruited and tested, giving a total of 20 runners. Forefoot strikers were distinguished by a single peak (only an active peak) on the GRF curve, as compared to the characteristic double peak (impact peak followed by an active peak) associated with heel strikers.

Trials were run in the afternoon on days when the subjects were not training intensively (*i.e.*, "off" or "easy" days). Each subject reported to the track only once, completing all running trials at that time. The order in which the different shoes were worn was randomized. Whichever shoe was randomly selected to be first, all trials were completed in that shoe before running in the next type of shoe. Two trials within 2% of the desired pace were obtained for each shoe condition. Because multiple running attempts were necessary to obtain valid data, the number of trials was chosen in order to keep from introducing variability through possible fatigue. We would like to have had multiple testing days to produce more trials, but were limited due to subjects being in a regimented training program. To control for possible differences between left and right foot strikes, only trials in which the left foot landed entirely on the force plate were valid. Complete foot contact was verified graphically by observing the entire GRF curve generated from a full contact with the force plate; only a partial curve was produced by an incomplete foot placement on the force plate. A research assistant with knowledge of plate location also determined whether the entire foot contacted the plate. Subjects were instructed to modify their starting positions based on where their feet landed in relation to the force plate. The specific location of the force plate was unknown to the subjects to avoid any targeting.

Statistical analysis

The data for males and females were analyzed separately, due to the difference in running speed. Peak vertical impact force (in multiples of body weight (BW)), loading rate (BW/s), peak braking and propulsion forces (BW), peak vertical force (BW), stance time (s), and vertical stiffness (BW/m) from 60 trials for both male and female were subjected to repeated-measures ANOVA and Tukey's post-hoc test ($p < 0.05$) to detect difference between shoe types. All statistical procedures were done using SAS 9.1.3 software.

Results

Subjects ran between 15 and 35 trials to obtain suitable data for each subject. Given the training status of the subject pool, recovery time between trials, and the short duration of each run through, no changes in ground forces due to fatigue were expected. A greater number of trials for each subject would have helped understand the variability between and within subjects, but due to the length of time two good trials with each shoe type took and how limited we were in using collegiate athletes, two was the best we could reasonably expect from each subject.

After adjustments were made for multiple comparisons, peak propulsion force was significantly greater in racing flats than in running shoes (ES = 1.30; F = 4.33, p = 0.028) for females. Stance time decreased significantly in racing flats (ES = 1.13; F = 4.25, p = 0.035), but not in spikes when compared with running shoes. Females had no significant differences in peak vertical impact force, loading rate, peak braking force, peak vertical force, or vertical stiffness (Table 1).

Males had significantly greater vertical stiffness in spikes versus running shoes (ES = 0.82; F = 4.61, p = 0.025). Peak vertical impact force was also significantly greater in both flats (ES = 0.12; F = 8.53, p = 0.011) and spikes (ES = 0.96; p = 0.003) compared to running shoes. Loading rate showed significant increase between the same conditions (ES = 0.96; F = 7.16, p = 0.006 and ES = 0.78; p = 0.021, respectively) as did peak braking force (ES = 0.49; F = 5.78, p = 0.021 and ES = 0.71; p = 0.023, respectively). Peak propulsion force and stance time showed no significant differences between running shoes and flats or spikes (Table 2).

Table 2. Male's means and standard deviations for GRF variables in the three shoe conditions. Data are means (±SD).

	Running Shoes (A)	Racing Flats (B)	Spikes (C)
Peak Vertical Impact Force (BW)	2.36 (.55) ^{BC}	2.96 (.67) ^{A}	3.06 (.48) ^{A}
Loading Rate (BW/s)	151 (47) ^{BC}	247 (73) ^{A}	232 (117) ^{A}
Stance Time (s)	.157 (.013)	.153 (.011)	.151 (.012)
Vertical Stiffness (BW/m)	70 (28) ^{C}	133 (95)	151 (114) ^{A}
Peak Braking Force (BW)	-.67 (.14) ^{BC}	-.88 (.26) ^{A}	-.88 (.21) ^{A}
Peak Propulsion Force (BW)	.52 (.10)	.55 (.10)	.56 (.10)
Peak Vertical Force (BW)	3.16 (.24)	3.46 (.49)	3.44 (.44)

Superscripts denote a significant difference (p < 0.05) between groups.

Discussion

Females

For the females, peak propulsion force was significantly greater and stance time significantly shorter in racing flats than in running shoes. These were the only statistically significant differences found. These findings contrast substantially with the male's results. One interesting finding was that the variability for many GRF parameters was lesser among females. This implies that any potential differences between shoe types for variables other than peak propulsion force and stance time are very small. Since GRF parameters are influenced by running speed (Hamill et al., 1983; Keller et al., 1996; Weyand et al., 2000), the different speeds used for males and females in this study likely account for much of the variance between genders. Because only one speed was used for each gender, further study will be needed to determine other reasons for this discrepancy.

Although the results of this study show a decrease in stance time with competitive footwear, the only significant difference was between female's running shoes and racing flats. However, a decrease in stance time is in agreement with other studies comparing barefoot and shod running, which found total ground-contact time during barefoot running to be significantly lesser than during shod (Dickinson et al., 1985; Divert et al., 2005). The decreased stance time is consistent with the greater GRF measured in flats and spikes, since greater forces would be necessary to maintain a given running speed if ground contact time decreased.

Males

The increased loading rate and peak vertical impact force for the males in the flats and spikes was expected, given similar results from previous studies comparing barefoot and shod running (Dickinson et al., 1985; DeWit et al., 1996; 2000). This can be explained by the smaller heel in flats and spikes, which would increase the acceleration of the foot at impact. Additionally, the relatively little cushioning in the competitive footwear would provide less shock absorption resulting in a greater vertical impact force. The present data support an increase in the initial load and rate of loading at foot strike while running in conditions with less cushioning. While there was a difference in loading rate between shoe conditions, the variability between subjects was quite high. This may be explained by differences in foot strike, particularly when the foot first contacts the ground. Therefore, more needs to be considered besides footwear alone. Additionally, in the attempt to analyze data with such high variability, future research involving group analyses may benefit from doing a multiple single-subject analysis to supplement the group data (Dixon and Kerwin, 2002).

Vertical stiffness increased significantly between running shoes and spikes, but not between running shoes and flats. As with loading rate, variability between subjects was substantial. Differences in anthropometrics, movement patterns, and foot strike (e.g., degree and velocity of pronation; joint angles; limb length; movement within the joints of the foot) upon initial ground contact may help to explain this result.

How limb stiffness adjusts in response to contact surface has been debated among researchers. However, since various methods of calculating stiffness are used across studies, caution is needed when comparing results. De Wit et al. (2000) noted greater leg stiffness in barefoot running compared to shod. Likewise, another study found that softer landing surfaces were linked to significant reductions of initial leg stiffness and amount of impact on the lesser leg (Lafortune et al., 1996). In contrast, Bishop et al. (2006) demonstrated decreased leg stiffness in a harder sole compared with a more cushioned one, maintaining that increased leg stiffness is required in response to softer landing surfaces. In the present study, the increased vertical stiffness among females may be explained by the decreased cushioning in the spikes causing a greater negative vertical acceleration at ground contact. High variability existed among females with regard to vertical stiffness, which limited our ability to detect any differences. These results support other studies that have shown increased stiffness in response to harder landing surfaces.

Peak braking forces were significantly greater in spikes and flats compared to running shoes, whereas peak propulsive forces were not. The increased braking force may be correlated to the greater vertical impact force and loading rate observed with the competitive footwear. Because of the variability between subjects, however, we cannot make definite conclusions about this result. Other studies have also reported braking and propulsive forces to be variable between runners (Cavanagh et al., 1980; Munro et al., 1987). Further research dealing with group data on peak braking and propulsive forces could benefit by running a multiple single-subject analysis on the group data (Dixon and Kerwin, 2002). The results of this study agree with previous reports that peak braking and propulsive forces comprise a relatively small amount of the overall GRF during running (Cavanagh and Lafortune, 1980; Munro et al., 1987; Nilsson and Thorstensson, 1989).

Due to the ambiguity of the female's data, the remainder of this discussion will be focused primarily on the male's results. Peak vertical impact force, loading rate, and stiffness are all related. Although a certain amount of stiffness is required for optimal performance (Arampatzis et al., 1999; McMahon and Cheng, 1990), a greater stiffness may result in increased risk of injury (Butler et al., 2003). Butler et al. (2003) explained that greater leg stiffness is usually correlated to increased maximum forces coupled with smaller lower extremity excursions, which leads to increased loading rates. Previous studies have correlated greater loading rates, peak forces, and the associated lower extremity shock with potential increase in bony injuries (Ferber et al., 2002; Grimston et al., 1991; Radin et al., 1978; Williams et al., 2004). Williams et al. (2004) noticed significantly greater leg and knee stiffness and loading rates in high-arched runners compared to low-arched runners, and found a positive correlation between these variables and the incidence of bony injury (Williams et al., 2004). In the present study, the greater peak vertical impact forces, loading rates, and vertical stiffness found among males while running in spikes and flats suggest a potential increased risk of overuse impact related injuries.

Whether or not greater GRF increase the incidence of injury has been a topic of debate in research. In this study, the amplified loading rate, stiffness, and peak vertical impact force demonstrate that running in spikes and flats produces a greater external load on the body. The initial impact between the foot and the ground is directly transmitted to the leg and can potentially be an influential factor in injury risk (Hewett et al., 1999). In support of this, one prospective study noted the significance of landing forces in jumping and injury at the knee (Hewett et al., 1996). Other studies have reported greater GRF from force plate data in runners with a history of stress fractures (Grimston et al., 1991; Ferber et al., 2002).

By contrast, some studies have not found any statistically significant correlations between GRF and injury occurrence, suggesting other factors to be more vital in the etiology of running injuries (Crossley et al., 1999; Bennell et al., 2004). This lack of consensus has called into question the importance of GRF from an injury perspective. Some researchers have found that muscle activity is tuned in response to GRF in order to minimize soft tissue vibrations (Wakeling et al., 2001). These data support the idea that GRF serves as a signal for the nervous system to tune muscle activity in proportion to the frequency of the impact force. In light of these findings, some researchers consider GRF to be unimportant from an injury perspective (Nigg and Wakeling, 2001).

The body has to deal with increased external forces in one way or another. Many of the studies discussed suggest that greater GRF most likely has some role in injury development, regardless of the question about specific mechanisms. In studies that found no correlation between GRF and injury, there may have been other influential factors that were not accounted for such as bone mineral density, strength of other tissues, training volume and intensity, and movement patterns. In the present study, the increased external loads shown when running in spikes and flats compared to running shoes suggest a potential increase in risk of injury.

In addition to the increased GRF, the need for specificity of training is also an important consideration in deciding upon footwear. Since competitive runners race in flats and spikes, it may be important to do at least some training in these shoes. This is so the body can adapt to the mechanical and physical changes between the shoe types in order to perform optimally. Because the body adapts gradually to increased stresses, the data presented here would support a gradual transition when beginning to wear spikes and flats during training sessions.

Future studies will include body position, joint moment, and joint stiffness data. We were limited in this study by the amount of time we had access to athletes and how many trials we would be able to complete. However, enough trials were completed and subjects used to find significance in many variables. The high variability would likely be decreased in future studies if more subjects were able to be tested on multiple days. The dampening of forces due to the track surface is a small limitation. There is no way around this dampening in the current study since spiked shoes were being worn. However, since all shoe conditions used the same surface, this issue would have similar effects. We expect that some peak forces would be smaller without the track surface covering the plate, but all conclusions would be the same.

Conclusion

Due to the results of this study, the following conclusions are limited to male runners. The GRF experienced during running is significantly increased in competitive footwear compared to regular running shoes. Differences are evident in the larger peak vertical impact force, loading rate, stiffness (in spikes), and peak braking force. These data may be used to better inform competitive runners, coaches, and trainers of possible increased risk of injury when determining the frequency and duration of the use of competitive footwear in training. Based on the high variability within the groups, however, future research in which subjects are analyzed individually could help to strengthen these conclusions.

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Key points

- To determine the differences in ground reaction forces between regular running shoes and competitive footwear, force plate data was obtained from 10 males (6.7 $m \cdot s^{-1}$) and 10 females (5.7 $m \cdot s^{-1}$) for each of three shoe types.
- Data from men and women were analyzed in two separate groups, and significant differences were found for various GRF components between the three types of shoes.
- The significant increases in GRF components in competitive footwear suggest that the body must deal with greater impact forces in these shoes than in running shoes at the same running speed.
- The results from this study warrant the recommendation that runners transition gradually from periods when most or all of their training is done in running shoes to more competitive seasons when more of their training is done in racing flats and spikes.

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