



2007-06-15

Ground Reaction Force Differences Between Running Shoes, Racing Flats, and Distance Spikes in Runners

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GROUND REACTION FORCE DIFFERENCES BETWEEN RUNNING SHOES,
RACING FLATS, AND DISTANCE SPIKES IN RUNNERS

by

Suzanna Logan

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Exercise Sciences

Brigham Young University

August 2007

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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As chair of the candidate's graduate committee, I have read the thesis of Suzanna Logan in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

GROUND REACTION FORCE DIFFERENCES BETWEEN RUNNING SHOES, RACING FLATS, AND DISTANCE SPIKES IN RUNNERS

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Master of Science

To measure the differences in ground reaction forces between running shoes, racing flats, and distance spikes, twenty intercollegiate distance runners ran across a force plate at 6.7m/s (for males) and 5.74m/s (for females) in each of the three types of shoes. In order to control for differences in foot strike, only subjects who had a heel strike were included in the data analysis (N=16). Repeated-measures ANOVA and Tukey's post-hoc test ($p<0.05$) revealed loading rate and impact peak to be significantly increased in the flats and spikes compared to running shoes. Stiffness in spikes was significantly higher than in running shoes. Stance time in spikes and flats was decreased. These results can be used to better inform competitive runners, coaches, and trainers of the risks and performance benefits when determining the frequency and duration of the use of competitive footwear in training.

ACKNOWLEDGMENTS

Thank you, Iain for so much help and good advice. You were very supportive and helpful through this project. You are awesome!

Thank you to all my committee members for the good feedback and helpful advice.

Thank you, track and cross-country members who participated as subjects. You guys were great!

Thank you, James for the support and for a listening ear.

Thank you, Sandy for answering all my questions and helping me meet the format requirements.

Thank you, Mom and Dad, and Jim and Siu for your support.

Thank you, Grandpa Gordon. This might not have been possible if it weren't for your help.

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

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ABSTRACT

To measure the differences in ground reaction forces between running shoes, racing flats, and distance spikes, twenty intercollegiate distance runners ran across a force plate at 6.7m/s (for males) and 5.74m/s (for females) in each of the three types of shoes. In order to control for differences in foot strike, only subjects who had a heel strike were included in the data analysis (N=16). Repeated-measures ANOVA and Tukey's post-hoc test ($p<0.05$) revealed loading rate and impact peak to be significantly increased in the flats and spikes compared to running shoes. Stiffness in spikes was significantly higher than in running shoes. Stance time in spikes and flats was decreased. These results can be used to better inform competitive runners, coaches, and trainers of the risks and performance benefits when determining the frequency and duration of the use of competitive footwear in training.

Keywords: ground reaction forces, shoes, running, impact

Word count: 3,208

INTRODUCTION

During locomotive physical activity, the load on the body can be described using ground reaction forces (GRF), or the forces of the ground pushing back on the foot. The GRF components are equal in magnitude and opposite in direction to the forces the foot applies to the ground. Faster movement speeds are primarily achieved as the foot exerts greater forces on the ground (Weyand, Sternlight, Belizzi, & Wright, 2000). During distance running, vertical GRF of more than two times a person's body weight are typical (Cavanagh & Lafortune, 1980; Nilsson & Thorstensson, 1989). Research conducted on GRF during running over the last two decades has looked at how these forces affect the body, and how different factors such as running style, types of surfaces, and footwear may affect GRF (Cavanagh & Lafortune, 1980; Clarke, Frederick, & Cooper, 1983; Cook, Kester, & Brunet, 1985; De Wit, DeClercq, & Aerts, 1996; Divert, Mornieux, Baur, Mayer, & Belli, 2005).

Attenuation of GRF 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, especially for competitive runners, 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 looked at the reduction of GRF 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, which shows the effects on GRF when the shock absorption of running shoes is absent (De Wit *et al.*, 1996; De Wit, De Clercq, & Aerts, 2000; Dickinson, Cook, & Leinhardt, 1985; Divert *et al.*, 2005). These studies have found significantly increased loading rates and greater vertical impact peaks with barefoot running in comparison to shod (De Wit *et al.*, 1996; De Wit *et al.*, 2000; Dickinson *et al.*, 1985).

The effect of external impact forces on increased injury risk in running has shown mixed results in research. Some studies claim that higher GRF during running may be associated with increased risk of injury (Gottschall & Kram, 2005; Hreljac, Marshall, & Hume 2000; Milner, Ferber, Pollard, Hamill, & Davis, 2006; Messier *et al.*, 1995). Other studies have found no correlation (Bennell *et al.*, 2004; Crossley, Bennell, Wrigley, & Oakes, 1999), or even decreased (Duffey, Martin, Cannon, Craven, & Messier, 2000) injury occurrence associated with higher GRF. Depending on the differences of GRF between running shoes, racing flats, and spikes, information on potential injury risks could be provided (Bus, 2003; Cavanagh, 1980; Frederick, Clarke, & Hamill, 1984; Gottschall & Kram, 2005; Jakobsen, Krøner, Schmidt, & Jensen, 1989).

The purpose of this study is to compare how GRF are influenced while running in running shoes, racing flats, and spikes at a given speed, and therefore provide meaningful information on possible injury risks and performance benefits that could influence the timing and frequency of the use of competitive footwear in runners.

METHODS

Subjects

Twenty members of NCAA Division I distance track teams/cross-country teams, 10 males (age (years): 21.6 ± 3.0 ; height (inches): 69.9 ± 2.0 ; weight (lbs.): 141.5 ± 0.45 ; men's shoe size (US): 10 ± 0.95) and 10 females (age (years): 20 ± 1.5 ; height (inches): 66.4 ± 2.5 ; weight (lbs.) 126.9 ± 10.6 ; men's shoe size (US): 7.8 ± 1.3) were recruited as volunteers. All subjects were on the cross-country team and competed in the 1500 m through 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 and had been training regularly for at least three weeks were included. Weight and height of each subject was measured at the time of data collection prior to running the trials.

Data Collection

Running Protocol

Subjects were instructed to come to the track, prepared as if for a normal run or workout. 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. Running pace was maintained for

at least 5 m after contact with the force plate. Sufficient recovery (at least 45 seconds) was allowed between each trial, and consisted of easy jogging, walking, and standing.

Female subjects ran at 4:40 minute per mile pace (5.74 m/s), and the males at 3:59 minute per mile pace (6.7 m/s), which were determined from the speeds needed to automatically qualify for the 2007 NCAA Division I Indoor Track National Championship 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.

Two trials within 2% of the desired pace were obtained for each shoe condition. Only trials in which the left foot landed entirely on the force plate were valid. 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.

The trials were run on days when the subjects were not training intensively (*i.e.*, “off” or “easy” days). All trials were run in the afternoon. Data collection took place within the first eight weeks of the cross-country season.

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 is imbedded underneath a Mondo SuperX indoor track with an asphalt foundation, and is covered with the same texture and surface as the rest of the track. Calibration of the force plate took

place during manufacturing by the company. All three dimensions of force were measured and recorded for further analysis.

Before each data collection, a few practice trials were done to verify the appropriate function of all instruments. All ground reaction force parameters were recorded through a laptop computer that converts the force plate signal from voltage to force. Recorded forces were normalized to the body weights of the subjects by dividing force by body weight.

From the force plate data, peak braking and propulsion forces, peak vertical force, stance time, vertical stiffness, loading rate, and peak impact force were calculated. These variables were chosen as the most relevant components based on previous research on GRF during running (Cavanagh & LaFortune, 1980; De Wit, et al., 1996; Keller, Weisberger, Ray, Hasan, Shiavi, & Spengler, 1996; Nilsson & Thorstensson, 1989). Forces were normalized to body weight. Loading rate was defined as the amount of force in body weights per second between 20% and 80% of the impact peak. Vertical stiffness was calculated through an optimizing routine matching predicted ground reaction forces to measured ground reaction forces (Hunter, 2003). Stance time was measured during the time that 20 N of force or greater was applied to the force plate.

Shoes

The shoes were the same for all runners, differing in size only (sizes 6-12 in men'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.

Statistical Analysis

In order to control for differences in foot strike, only subjects who had a heel strike were included in the data analysis (N=16). Forefoot or midfoot strikers characteristically lack an impact peak. Impact peak (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) were subjected to a repeated-measures

ANOVA and Tukey's post-hoc test ($p < 0.05$). All statistical procedures were done using SAS 9.1.3 software.

RESULTS

Of the GRF variables subjected to the repeated-measures ANOVA, impact peak and vertical stiffness showed significant differences ($p < 0.05$). Before statistical adjustment for multiple comparisons, loading rate and stance time were also significantly different between groups. After the adjustment, the increased loading rate between running shoes and spikes approached significance ($F=3.46, p=0.057$). Additionally, the decrease in stance time ($F=3.46, p=0.083$) approached significance between running shoes and flats, and a p -value of 0.068 between running shoes and spikes. Impact peak was significantly different between running shoes and both flats ($F=9.47, p=0.0495$) and spikes ($p=0.0004$), whereas vertical stiffness was only significantly different between running shoes and spikes ($F=6.12, p=0.0041$; Table 1). Peak propulsion forces were significantly different between flats and running shoes after adjustment ($F=4.01, p=0.045$), and were approaching significance between spikes and running shoes ($p=0.059$). Peak braking forces between running shoes and flats and between running shoes and spikes also approached significance after adjustment ($F=3.12, p=0.092$ and $p=0.096$). Peak vertical force was not significantly different between any of the shoe types ($F=2.17$). There were no significant differences between flats and spikes for any of these variables before or after adjusting for multiple comparisons. See Table 1 for a summary of these statistics.

DISCUSSION

The increased loading rate and impact peak in the flats and spikes was expected, given similar results from previous studies comparing barefoot and shod running (DeWit *et al.*, 1996; DeWit *et al.*, 2000; Dickinson *et al.*, 1985). This increase is explained by the smaller heel in flats and spikes, which would affect the negative acceleration of the foot at impact. Additionally, the relatively little cushioning in the competitive footwear would provide less shock absorption on impact resulting in a greater 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.

Vertical stiffness increased significantly between training shoes and spikes, but not between training shoes and flats. This was in part due to a large amount of variability among subjects. How limb stiffness adjusts in response to contact surface has been somewhat debatable 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 higher leg stiffness in barefoot running compared to shod. Likewise, another study noticed that softer landing surfaces were linked to significant reductions of initial leg stiffness and amount of impact on the lower leg (Lafortune, Hennig, & Lake, 1996). In contrast to these results, Bishop, Fiolkowski, Conrad, Brunt, and Horodyski, (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 might be explained by the decreased cushioning in the spikes causing a greater negative vertical acceleration

at ground contact. These results support other studies that have shown increased stiffness in response to harder landing surfaces.

Although loading rate and stance time were significantly different between shoes before adjusting for multiple measures, they approached significance after the adjustment. This suggests there may be an increased rate of force loading and decreased stance time in spikes and flats compared to running shoes. These differences could possibly be more evident with a larger sample size.

The lower stance time in competitive footwear is in agreement with other studies on barefoot versus shod running, which found total ground-contact time during barefoot running was significantly lower than that for shod (Dickinson *et al.*, 1985; Divert *et al.*, 2005). The significance of decreased stance time is mostly from a performance standpoint, as shorter stance times have been correlated with higher running speeds (Cavanagh & Lafortune, 1980; Munro, Miller, Fuglevand, 1987; Weyand *et al.*, 2000). Our data support the idea that spikes and flats may enhance performance.

Peak braking and propulsion forces were approaching significance between shoe types, except for peak propulsion between running shoes and racing flats, which was significant. Because of the variability between subjects, however, we cannot make definite conclusions about this result. In agreement, other studies have reported these forces to be variable between runners (Cavanagh *et al.*, 1980; Munro *et al.*, 1987). Braking and propulsion forces comprise a relatively small amount of the overall GRF during running, as illustrated in the present data as well as in previous studies (Cavanagh & Lafortune, 1980; Munro *et al.*, 1987; Nilsson & Thorstensson, 1989). In our study, we

expected running shoes to attenuate the braking and propulsive forces compared to flats and spikes. Although a decrease was observed, the differences were minimal.

Impact peak, loading rate, and stiffness are all related. Although a certain amount of stiffness is required for optimal performance (Arampatzis *et al.*, 1999; McMahon & Cheng, 1990), too much stiffness may result in increased risk of injury (Butler, Crowell, & Davis, 2003). Butler *et al.* (2003) explain that higher leg stiffness is usually correlated to increased peak forces coupled with smaller lower extremity excursions, which leads to increased loading rates. Previous studies have correlated higher loading rates, peak forces, and the associated lower extremity shock with potential increase in bony injuries (Ferber, McClay-Davis, Hamill, Pollard, & McKeown, 2002; Grimston, Engsborg, Kloiber, Hanley, 1991; Radin, Ehrlich, Chernack, Abernethy, Paul, & Rose, 1978; Williams, McClay-Davis, Scholz, Hamill, & Buchanan, 2004). Williams *et al.* (2004) noticed significantly higher 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 higher peak forces, loading rates, and vertical stiffness while running in spikes and flats suggests a potential increased risk of injury.

Whether or not enhanced GRF increases the incidence of injury through increasing the load on the body has been a topic of debate in research. In this study, the amplified loading rate, stiffness, and impact peak demonstrate that running in spikes and flats produces a greater external load on the body. The initial impact between the foot and the ground are directly transmitted to the leg and can potentially be an influential

factor in injury risk (Hewett, Lindenfeld, Riccobene, & Noyes, 1999). In support of this, one prospective study noted the significance of landing forces in jumping and injury at the knee (Hewett, Stroupe, Nance, & Noyes, 1996). Although Hewett *et al.* (1996) looked at forces in jumping, it does suggest relationship between GRF and injury. Further, other studies have reported greater GRF from force plate data in runners with a history of stress fractures (Ferber, *et al.*, 2002; Grimston *et al.*, 1991).

On the other hand, some studies have found no correlation between GRF and injury occurrence, suggesting other factors to be more vital in the etiology of running injuries (Bennell *et al.*, 2004; Crossley, Bennell, Wrigley, & Oakes, 1999). This 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, Tscharnner, Nigg, & Stergiou, 2001). These data support the idea that GRF serve 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 & Wakeling, 2001).

The body has to deal with increased external forces in one way or another. Many of the studies discussed above show that greater GRF most likely plays some role in injury development, regardless of the debate about the specific mechanisms. When no correlations were found between injury and GRF, other factors such as: bone mineral density, strength of other tissues, training volume and intensity, and movement patterns may have introduced much of the variability not accounted for. 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 shoes 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.

One limitation of this study is that there was only one running speed, which was relatively fast. This prevents the direct comparison of these results to running in the same shoes at different speeds. Based on studies between GRF and running speed, it would be expected that the GRF reported here would be greater at faster running speeds and lesser at slower running speeds (Munro *et al.*, 1987; Weyand *et al.*, 2000). However, because the speed selected in the present study is a common training pace for collegiate athletes and other competitive runners these results are directly applicable to these populations.

Another limitation is in the number of attempts it took for subjects to complete two valid trials in each shoe type. It took about 25 attempts to obtain suitable data for each subject. However, some subjects completed the trials in around 15 attempts while others took about 35. Because the subjects were trained distance runners and because adequate time was given between running attempts, this difference between subjects was not expected to affect the data.

In conclusion, the GRF experienced during running is significantly increased in competitive footwear compared to regular running shoes. The differences are evident in the larger impact peak, loading rate, and stiffness (in spikes), as well as in the shorter stance time. This data may be used to better inform competitive runners, coaches, and trainers of possible increased injury risks and performance benefits when determining the frequency and duration of the use of competitive footwear in training.

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Table 1. Means and standard deviations for GRF variables in the three shoe conditions.

	<u>Running Shoes (A)</u>	<u>Racing Flats (B)</u>	<u>Spikes (C)</u>
Impact Peak (BW)	2.34 ± 0.44	2.66 ± 0.71	2.90 ± 0.51
Loading Rate (BW/s)	151.87 ± 56.9 ^{BC}	206.48 ± 113.3 ^A	213.93 ± 131.8 ^A
Stance Time (s)	0.162 ± 0.010	0.156 ± 0.008	0.156 ± 0.010
Vertical Stiffness (BW/m)	63 ± 26.4 ^C	101 ± 77.3	138 ± 106.7 ^A
Peak Braking (BW)	-0.70 ± 0.17	-0.823 ± 0.26	-0.822 ± 0.23
Peak Propulsion (BW)	0.56 ± 0.06 ^B	0.60 ± 0.053 ^A	0.60 ± 0.060
Peak Vertical Force (BW)	3.01 ± 0.25	3.16 ± 0.50	3.23 ± 0.49

Superscripts denote a significant difference ($p < 0.05$) between groups. Numbers are mean ± SD.

Appendix A
Prospectus

Chapter 1

Introduction

Over the last 20 years, many researchers have studied the ground reaction forces (GRF) produced during running. These forces increase dramatically with running speed, which presents an important consideration in terms of the overall load on the body. GRF as high as two to three times a person's body weight are characteristic of distance running speeds (Cavanagh & LaFortune, 1980; Nilsson & Thorstensson, 1989). There is rampant literature on the impact of ground reaction forces on the running body, and how different factors including running style, surface, and equipment may attenuate or accentuate those forces (Cavanagh & LaFortune, 1980; Clarke, Frederick, & Cooper, 1983; Cook, Kester, & Brunet, 1985; De Wit, DeClercq, & Aerts, 1996; Divert, Mornieux, Baur, Mayer, & Belli, 2005).

The attenuation of GRF 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, 1986a). However, performance is also an important issue for running shoe designers, which also motivates manufacturers to decrease the weight of the shoe. Hence, racing flats and spikes have been developed to help facilitate optimal performance (Cavanagh, 1980; Denton, 2005). In comparison to most training shoes, spikes and racing flats have less cushioning and a thinner heel in order to produce a lighter shoe for the enhancement of performance during competition and training sessions.

Some running shoe professionals look disapprovingly on racing flats and spikes. J.D. Denton (2005), a well recognized writer and expert on running shoes states that “while it’s good that shoe product managers consider weight when building the next midsole miracle, sometimes they go anorexic on us” (p. 78). Denton agrees that competitive footwear has its time and place for competitive runners, but stresses that this type of shoe should be used with caution and awareness of the risks.

While several existing studies have looked at the reduction of GRF in running shoes, there is a lack of quantitative data on the shock absorbing qualities of competitive footwear. Some studies have been done on the differences in GRF between barefoot and shod running (De Wit, et al., 1996; De Wit, De Clercq, & Aerts, 2000; Divert, et al., 2005). Although the comparison between barefoot running and the use of racing flats or spikes is not straightforward, it does begin to show the effects on GRF when the protection and shock absorption of running shoes is absent. Particularly, the loading rate of the vertical ground reaction force increases dramatically with barefoot running in comparison to shod (De Wit, et al., 1996; Dickinson, Cook, & Leinhardt, 1985).

The significance of this study is in providing information on how different types of foot wear influence impact forces. The effect of impact forces on increased injury risk in running has shown mixed results in research. Some studies show evidence to support that higher GRF during running may be associated with increased risk of injury (Gottschall & Kram, 2005; Hreljac, Marshall, & Hume 2000; Messier et al., 1995; Milner, Ferber, Pollard, Hamill, & Davis, 2006), while others have found no difference (Bennell et al., 2004; Crossley, Bennel, Wrigley, & Oakes, 1999), or even a decrease in

injury in runners with higher GRF (Duffey, Martin, Cannon, Craven, & Messier, 2000). Depending on the differences in components of GRF between different types of footwear, useful information could be provided in determining the frequency and duration of the use of competitive footwear (Bus, 2003; Cavanagh, 1980; Frederick, Clarke, & Hamill, 1984; Gottschall & Kram, 2005; Jakobsen, Krøner, Schmidt, & Jensen, 1989).

The purpose of this study is to quantitatively evaluate the differences in ground reaction force characteristics produced between wearing running shoes, racing flats, and distance spikes. The ultimate objective is to provide information to athletes, recreational runners, coaches, and athletic trainers that may influence the transition to the use of competitive footwear in the early season, as well as the overall amount of training done in the shoes.

Hypothesis

At a given running speed, peak propulsive, braking, and vertical ground reaction forces and the corresponding impulses are greatest while wearing distance spikes, followed by racing flats, and lastly training shoes.

Null Hypothesis

At a given speed, there is no difference in propulsive, braking, and vertical ground reaction forces or the corresponding impulses between conditions of wearing training shoes, distance spikes, and racing flats.

Assumptions

1. Each subject will be screened for injury prior to participation in the study.

2. The subjects will have been participating in their regular training schedule for at least three weeks prior to the time of data collection.
3. The subjects will be warmed up adequately before running their trials.
4. The shoes used for this study will be identical except for size (none will be affected by manufacturing defect).
5. The shoes will retain their original shock absorbing capabilities throughout the course of the data collection.

Operational Definitions

Ground reaction forces (GRF): the force exerted from the ground on an individual during the stance phase of running; can be normalized and reported in multiples of body weight.

Shore: the standard measure of material hardness among shoe manufacturers; values range from 0-100 (100 being the hardest); can be classified as either A or D, which distinguishes the system of values used to declare the hardness (Nigg, 1986b).

Running shoes: also called training shoes; shoes meant for regular running (that is, not designed specially for racing).

Delimitations

1. The participants are current or former NCAA Division I intercollegiate distance runners between the ages of 18 and 24 years.
2. The participants have been practicing a regular running training schedule for at least three weeks prior to data collection and are injury free.
3. Only one make and model of each type of shoe will be studied.

4. The running surface will be limited to the Mondo, indoor track at Brigham Young University, Provo, UT.

Limitations

1. Subjects may not accurately report their injury or training status.
2. The shoes may undergo shock absorption reductions throughout the data collection process.

Chapter 2

Review of Literature

Much of the existing literature on ground reaction forces in running does not talk about the effects of shoes. Some of this literature will be presented in the first part of this review to provide an understanding of how different aspects of running can increase GRF prior to talking about the influences running shoes can have on GRF. For example, running speed, anatomical characteristics, foot strike, and fatigue have all been shown to have significant effects on GRF. Knowledge about how these and other variables affect the high impact forces of running has helped shape the development of training and competition running shoe designs over the years. Following this discussion, literature on shoe components that influence GRF will be presented, as well as findings on barefoot running.

Ground Reaction Forces and Running Speed

It is well established that all components (*i.e.*, medio-lateral, antero-posterior, and vertical) of the GRF increase with running. A strong correlation exists between running speed and the GRF produced. Weyand, Sternlight, Belizzi, & Wright (2000) demonstrated that faster top running speeds are due to a greater transmission of force from the muscle to the ground rather than to increased frequency of limb movement. This information agrees with the idea that faster running depends mostly upon stride length increases, and less upon stride frequency. Hence Weyand et al. state that “At any speed, applying greater forces in opposition to gravity would increase a runner’s vertical

velocity on takeoff, thereby increasing both the aerial time and forward distance traveled between steps” (p. 1991).

Running speed enhances the magnitude of force curve parameters, while the relative timing of force curve events remains the same during the stance phase (Hamill, Bates, Knutzen, & Sawhill, 1983; Munro, Miller, & Fuglevand, 1987; Nilsson & Thorstensson, 1989). GRF data therefore, should be compared across studies only when the speeds are similar. With increasing speeds, the vertical component of the GRF increases the most, with the antero-posterior and medio-lateral parts amplifying relatively little (Nilsson & Thorstensson, 1989).

Vertical GRF

The vertical component of GRF appears to be the least variable across studies, and the magnitude values reported are generally in agreement (Cavanagh & LaFortune 1980; Keller et al., 1996; Munro et al., 1983). In distance running, vertical GRF as high as three times a person’s body weight are not uncommon (Cavanagh & LaFortune, 1980; Nilsson & Thorstensson, 1989). Vertical GRF have several descriptive factors such as loading rate, impact maximum, relative minimum, active peak (or “thrust” peak), average vertical GRF, change in vertical velocity, and decay rate. Moreover, this component is affected by numerous external variables which include body mass, mass distribution, running style, area of foot-ground contact, shoe and surface properties, as well as foot mechanics (Keller et al., 1996; Nigg, 1986a).

Nilsson and Thorstensson (1989) found the magnitude of the active peak to be directly related to the increase in running speeds, growing from 1.2 times body weight (b.w.) at 1.5 m/s to 2.6 b.w. at 6 m/s. In another study, Munro et al. (1987) showed greater GRF in all of the vertical GRF variables including the loading rate, impact peak, relative minimum, thrust (active) peak, average vertical GRF and change in vertical velocity. The active peak significantly increased with running speed from 2.5 b.w. at 3 m/s to 2.8 b.w. at 5 m/s (Munro et al., 1987). Similarly, Keller et al. (1996) showed an increase of the active peak of vertical GRF from 1.15 b.w. at 1.5 m/s to about 2.5 b.w. at 5 m/s. They also state that the greatest variation seen in vertical GRF is in the transition from walking to running, or around 2.5 to 3 m/s, and that the increase of the vertical thrust maximum force was linear until about 4 m/s (about 50%-60% maximum speed of their subjects), after which it became relatively constant. The nonlinearity at higher speeds, they say, is in contrast to other studies, which found the maximum thrust peak to increase linearly from 3 m/s all the way to 6 m/s (Keller et al., 1996; Munro et al., 1987).

Antero-posterior GRF

The antero-posterior forces are typically separated into braking (posterior) and propulsive (anterior) phases, although some studies report a peak-to-peak value rather than report the anterior and posterior forces separately (Munro et al., 1987; Nilsson & Thorstensson, 1989) (Figure 1).

During running, this component of the GRF comprises a small amount of the total impact forces in comparison to the vertical part. Nilsson and Thorstensson (1989) found linear increases with running speed from 0.13 times body weight at 1.5 m/s to 0.5 b.w. at 6 m/s. In another study, Munro et al. (1987) reported the braking impulse of the antero-posterior GRF to increase with running speed, from -0.15 b.w. at 3 m/s to -0.25 b.w. at 5 m/s and the propulsive impulse from 0.14 to 0.25 at the same speeds. They divided each subject's body weight over the entire stance time to normalize the braking and propulsion impulses.

Medio-lateral GRF

In distance running, the medio-lateral element contributes the least to the overall GRF, and has been found to be the most variable (Cavanagh & Lafortune 1980; Keller et al., 1996). However, although the graphical representations of medio-lateral data are not consistent, literature that has reported values for this component agree that the value is quite small in comparison to the vertical and antero-posterior forces (Cavanagh & Lafortune, 1980; Hamill et al., 1983; Munro et al., 1987). A study in which runners only ran at 4.5 m/s, showed the mean peak-to-peak medio-lateral force to be equal to merely 9% of the vertical and 26% of the antero-posterior components (Cavanagh & Lafortune, 1980). Furthermore, Nilsson and Thorstensson (1989) found the peak-to-peak medio-lateral force increased from 0.12 b.w. at 1.5 m/s to 0.28 b.w. at 6 m/s. Munro et al. (1987) state that across studies, research results demonstrate no clear relationship in the medio-lateral GRF and running speeds reporting the overall averages to range from 0.04

b.w. to 0.25 b.w. in the medial direction and from 0.06 b.w. to 0.31 b.w. in the lateral direction.

Foot Strike and Anatomical Effects on GRF

The ways in which the foot and the ground interact can have meaningful effects on certain aspects of the GRF during running. Several studies exhibit marked differences in force curve patterns between forefoot and midfoot versus rearfoot strikers. While there is considerable controversy seen across studies in the effects of foot strike on the antero-posterior and medio-lateral data, there is general consensus upon the nature of the vertical component, which is the dominant factor in GRF.

Foot strike and vertical GRF

Studies have consistently shown a double peak vertical impact curve associated with heel-strike in running (Cavanagh & Lafortune, 1980; Lees, Lake, & Klenerman, 2005; Munro et al., 1987; Nilsson & Thorstensson 1989) (Figure 2). The first sharp peak, known as the impact peak, characteristically has a high frequency, and occurs in the first part of the stance phase. The subsequent peak, often referred to as the active (thrust) peak, is of lower frequency and is usually seen about halfway through the stance phase (Munro et al., 1987).

Cavanagh and Lafortune (1980) demonstrated that at 4.5 m/s, rearfoot strikers exhibited a double peak vertical component, the rapid initial peak reaching about 2.2 b.w. early in the stance phase, and the second peak rising more slowly to the maximum force

of 2.8 b.w. The data for the midfoot group, however, did not show the fast rising first peak (Cavanagh & LaFortune, 1980). In consensus, Nilsson and Thorstensson (1989) also noted a characteristic double peak for rearfoot striking runners, which was not seen among the forefoot runners.

Additionally, Munro et al. (1987) also provide supporting evidence for the impact peak characteristic of heel striking, noting the occurrence of the impact peak between the first 6% and 17% of the stance phase with values of 1.6 b.w. at 3 m/s to 2.3 b.w. at 5 m/s.

Foot strike and antero-posterior GRF

The relationship between foot strike and the antero-posterior GRF is not clear. Some data have shown a distinct double peak of the braking phase of the antero-posterior GRF for mid and forefoot strikers, while the rearfoot strikers showed a clear single peak (Cavanagh & LaFortune, 1980; Nilsson & Thorstensson, 1989). In contrast, results have also been produced in which a double peak was observed for the rear-foot strike group and a single peak for midfoot strikers (Hamill et al., 1983). Furthermore, Munro et al. (1987) noted single, double, and multiple peaks during the braking phase for rearfoot strikers, which led to the conclusion that “the association of foot-strike classification with specific braking patterns is not as straightforward as previously believed” (p. 149).

Foot strike and medio-lateral GRF

There is much variability across studies in medio-lateral GRF data (Munro et al., 1987). This is probably due to the observed variability among individuals in this component. Nilsson and Thorstensson (1987) showed that forefoot strikers first

experience a medial GRF upon foot strike as compared to rearfoot strikers who initially undergo lateral forces, but Cavanagh (1982) presents data that shows great variability which suggests that such a generalization is difficult to make. Cavanagh observed that in rearfoot striking runners, some undergo a net impulse that is laterally directed while for some it is medially directed. The author maintains that due to the variety of foot placement and anatomical alignment across individuals, the variability of the shear component is not surprising (Cavanagh, 1982).

Anatomical effects on GRF

Much research has been done on the medial longitudinal arch height and its relation to GRF. The general findings concerning arch height and its effect on GRF are involved with shock absorption. High-arch feet have less mobility (more rigidity) than normal and low-arch feet and are therefore considered by some to be poorer shock absorbers (Cavanagh, 1980). Forefoot running and over-supination have been associated with high-arched feet, whereas rear-foot running and over-pronation are seen more with low-arched feet (Cavanagh, 1980; Luethi & Stacoff, 1987).

Some studies have shown that arch height does not influence shock absorption, or the vertical GRF (Lees et al., 2005; Nachbauer & Nigg, 1992). Nachbauer and Nigg (1992) studied the effects of arch height on ground reaction forces in running. They found no differences in the vertical or antero-posterior impact forces between runners of different medial longitudinal arch heights. In the medio-lateral component one significant difference was found in the timing of the initial medial peak, which occurred

later (at 17% of the total stance time) in the low-arch group than in the normal (12.6%) and high (1.2%) arch groups.

Concerning this observation of no effect of arch height on shock absorption, the authors acknowledge that other researchers have suggested that high-arched feet have relatively lower shock absorption due to a relatively greater rigidity than in normal and low-arched feet (Cavanagh, 1980; Simkin, Leichter, Giladi, Stein, & Milgrom, 1989). This discrepancy was attributed to the possibility that other authors defined “shock absorption” differently; Nachbauer and Nigg (1992) defined “shock absorption” as the reduction of the vertical impact peak. Another proposed explanation for the controversy was that runners possess neuromuscular control mechanisms that help keep the magnitude of external impact forces constant. Lastly, Nachbauer and Nigg (1992) speculate that the rigidity of the foot at the beginning of the stance phase may not be related to arch height. Support for this argument is in the prevalence of data exhibiting an impact peak in rearfoot strikers, but not in mid or forefoot strikers (Cavanagh & Lafortune, 1980; Nilsson & Thorstensson, 1987).

In summary, these findings suggest that because “net ground reaction forces describe primarily the movement of the center of mass of the runner”, differences due to arch structure “would not be expected during the active phase [or thrust peak] of ground contact” (Nachbauer & Nigg, 1992, p. 1269). Although they maintain that arch height does not affect shock absorption, Nachbauer and Nigg (1992) do state that different arch structures would likely produce significantly different pressure distribution patterns underneath the foot, or in the impact phase.

In agreement with the previous study, Lees et al. (2005) found no association between arch height and the magnitude of vertical impact forces, or any of the dynamic loading rate peaks. They state, “the failure of both force magnitude and load rate characteristics to relate to arch height is clear evidence that arch height may not be a direct causal factor in injury [due to vertical ground reaction force loading]” (p. 1086). However, when high-arched runners run in heel-to-toe, greater average rates of loading are seen presumably because of the increased leg stiffness associated with high arches (Lees et al., 2005).

Another anatomical consideration in GRF is body mass and its distribution. This concern has begun to be addressed by Liu and Nigg (2000) using a spring and damper model. They found the impact forces to be influenced by a larger mass ratio of the upper part of the body. The authors hold these findings as a possible implication that upper body mass may be related to increased risk of injury, but that further research is needed (Liu & Nigg, 2000).

Speed and foot strike

It should also be acknowledged that running speed can influence foot strike (Keller et al., 1996). Because stance time decreases with increasing running speed (Munro et al., 1987), at higher speeds less of the foot comes in contact with the ground. This is supported by Keller et al. (1996) who analyzed foot strike at varying running speeds and reported that at slower speeds most subjects were rearfoot strikers, but at

speeds greater than 3 m/s, the frequency of mid to forefoot strikes increased. At 6 m/s, eighty-six percent of the subjects were mid to forefoot strikers.

Ground Reaction Forces and Fatigue

While various factors contribute to shock attenuation during running, skeletal muscle may be the most important factor because of its ability to adjust the amount of shock absorption, and its capacity to deform under stress (Derrick, Hamill, & Caldwell, 1998). Because muscles play an important role in shock absorption, muscular fatigue could impact the ability to attenuate GRF. This relationship deserves attention considering that GRF can increase 2 to 3 times a person's body weight each time the foot lands, and that a 30-minute run typically involves 5000 foot strikes (Mercer, Bates, Dufek, & Hreljac, 2003). However, limited research exists on the effect of fatigue on the impact forces during running and there appears to be controversies about whether fatigue increases or decreases the GRF on the body.

Mercer et al. (2003) reported less shock absorption during running after an exhaustive run. In this study, a graded exercise treadmill test was used to fatigue the subjects prior to a 3-minute run at 3.8 m/s at zero grade. During the latter run, shock attenuation was observed to have decreased significantly compared to running before the fatigue protocol. In agreement, another study showed an amplification of the heel-strike initiated shock wave with muscular fatigue, which was said to be directly associated with decreased stride length (Verbitsky, Mizrahi, Voloshin, Treiger, & Isakov, 1998).

Some studies support that because local muscle fatigue decreases muscle contraction (which affects joint motion), it reduces the muscles' ability to help attenuate impact forces (Christina, White, & Gilchrist, 2001; Radin, 1986). Christina et al. (2001) found that fatigue of the invertors and dorsiflexors significantly affected loading rates and the magnitude of vertical GRF. They also demonstrated that both decreases of the dorsiflexion angle at heel contact, and increases in rearfoot motion have been observed with fatigue, which can alter the ground reaction forces (Christina et al., 2001; Elliot and Ackland, 1981; Gheluwe and Madsen, 1997). Christina et al. (2001) explained the meaningfulness of these findings as follows:

When a muscle crossing a joint is responsible for acting eccentrically just after heel strike, a localized fatigued state may inhibit the ability of the muscle to contract concentrically to achieve a "desired" joint angle at touchdown. This would result in a more lengthened position of the muscle due to its decreased range of motion between heel contact and foot flat. (p. 272)

Other research results address the ability of muscles to lessen shock waves produced with foot strike (Voloshin, Mizrahi, Verbitsky, & Isakov, 1998). Heel-strike-induced shock waves at the tibial tuberosity and sacrum were recorded throughout a 30-minute run at anaerobic threshold. The results showed that fatigue significantly increases the dynamic loading on the musculoskeletal system, which may be attributed to the reduced ability of the fatigued muscles to efficiently attenuate shock waves.

In contrast, some studies have found no changes in the magnitude of the active peak, and even decreases in the impact peak and loading rate with fatigue (Derrick,

Dereu, & McLean, 2002; Gerlach et al., 2005). Gerlach et al. (2005) conducted a study on kinetic changes in runners with fatigue and its relationship to injury. They found decreases in both impact magnitude and loading rate with fatigue, and no change in the active peak magnitude. These findings were attributed to a decreased cadence and increased stride length in the fatigued condition. In agreement, Derrick, Dereu, and McLean (2002) also observed an increase in shock attenuation with fatigued running. Both studies assert that it is unclear whether the changes in cadence, stride length, and lower extremity joint kinematics occurred as a protective mechanism, or as a manifestation of reduced performance due to fatigue.

The reasons for the discrepancies among studies are uncertain, but may be partly due to different levels of fatigue attained in different studies or the type of run used to induce fatigue (*i.e.*, duration of protocol, uphill or level running) (Mercer et al., 2003). Mercer et al. (2003) state that research on fatigue in running is complex because “the exact nature of fatigue and the exact muscles undergoing fatigue are unknown” (917).

Running Shoe Design and Its Effects on GRF

Many studies have investigated the role of shoes on the ground-reaction forces produced in running (Bates, Osternig, & Sawhill, 1983; Clarke et al., 1983; Komi, Gollhofer, Schmidtbleicher, & Frick, 1987; Nigg, Bahlsen, Luethi, & Stokes, 1987; Robbins & Waked, 1997; Stacoff, Denoth, Kaelin, & Stuessi, 1988). The influence of running shoes on ground reaction forces depends on the type of shoe, and the hardness of the running surface (De Wit et al., 1996). Different components of shoes have been

investigated for their effects on ground reaction forces during running. The main shock absorbers for running shoes are the midsole and the heel wedge, with some contribution from the outsole and the sockliner (Cavanagh, 1980). One study looked at relationships between ground reaction forces and midsole hardness (Komi et al., 1987). The results of this study show that while ground reaction forces increased with the harder shoe sole, they were more dependent on running velocity than sole hardness. Other studies have reported that midsole hardness does not influence the magnitudes of GRF (Clarke, Frederick, & Cooper, 1982; Nigg et al., 1987; Stacoff et al., 1988). Stacoff et al. attribute this finding to possible adaptations of the runner to varied conditions or to differences in midsole construction.

Regardless, shock absorption is one of the primary roles of running shoes. As described by Luethi and Stacoff (1987), the impact phase during running is where most of the shock absorption from a running shoe is needed “to reduce the impact shock in general and to distribute the occurring load on different structures of the locomotor system as evenly as possible” (p. 75). The amount of shock attenuation is dependent on the amount of deformation of the materials under the foot at contact (*i.e.*, ground, shoe sole, calcaneal fat pad) (Luethi & Stacoff, 1987). In most cases, the shoe is relied on for the majority of this shock absorption. Luethi and Stacoff (1987) state that both too soft and too hard of a sole can be detrimental to shock absorption, and that a good, “medium” hardness is recommended for optimal shock absorption (in manufacturing terms, this is about 35-45 Shore A).

Bates et al. (1983) looked at runner-shoe interaction based on ground reaction force data to evaluate shock absorption qualities of running shoes. The subjects ranked different shoes according to certain ground reaction force parameters, demonstrating that they preferred the shoes that absorbed shock the best. Given the vast variability among individual runners, the shoes that performed the best were different for different runners, which is what may be expected.

Cavanagh (1980) presented an evaluation of the structure of racing flats compared with running shoes. Racing flats have much less of a midsole, even bereft in extreme cases, which result in poorer scores on the standard impact tests. Also, the width of the rearfoot is smaller in the average racing flat than in most training shoes, providing less rearfoot control. The flexibility of racing flats is good (due to lack of materials in the forefoot), though some argue that flexibility results in less stability for the foot during the stance phase. Another important consideration is the narrower shoe insole board, as the area of the sole on the medial side of the foot is shaved away to save weight. Again, the heel height in a racing flat is much lower, though there is a variety of forefoot to rearfoot height differences available.

While the literature lacks comparisons between running in training shoes and competition footwear (*i.e.*, racing flats and spikes), there are studies that involve differences in GRF between barefoot and shod running (De Wit et al., 1996; De Wit et al., 2000; Divert et al., 2005). Although running barefoot is not the same as running in racing shoes, the conditions can be somewhat comparable due to the relative lack of protective structural properties in competitive footwear. Because of the scarcity of

literature involving racing flats and spikes, this review will discuss some of the studies that involve GRF under barefoot and shod conditions. It should be acknowledged, however, that the effects of barefoot running on GRF cannot be considered to be the same as the effects of spikes or racing flats. But since racing shoes are deficient in the protective qualities of training shoes, it may be expected that they begin to approach the barefoot condition.

Racing shoes are primarily designed to decrease shoe weight for optimal performance, thus reducing the shock absorption and other protective characteristics of the typical training shoe (Cavanagh, 1980). De Wit et al. (1996) demonstrated that shock absorption is compromised in barefoot running when compared with regular training shoes. They observed the difference not in the magnitudes of the impact peaks, but in the rate of loading at heel strike. The barefoot condition induced a much greater rate of loading at an earlier time – reaching peak impact within the first 10%-15% of the stance phase, compared to 30%-40% in the shod condition (De Wit et al., 1996). In agreement, Komi et al. (1987) also provided supporting evidence for the substantially increased rate of external loading in barefoot running. Furthermore, De Wit et al. (2000) conducted another study in which not only did the loading rate increase under barefoot conditions, but also there were multiple impact peaks on the ground reaction force curve. In light of these studies, racing shoes could possibly have a noticeable increasing effect on the rate of loading in the impact phase.

Chapter 3

Methods

Subjects

Twenty current or former intercollegiate distance runners (10 males, 10 females) ages 18 – 24 years will be recruited as volunteers from NCAA Division I track/cross-country teams. Each subject will be complete a short questionnaire about current injury status prior to participating in the study; only runners who are injury free and have been training regularly for at least three weeks will be included. The height and weight of each subject will be measured at the time of data collection. Each subject will sign a consent form approved by the IRB prior to any participation in the study.

Data Collection

Running protocol

The subjects will be instructed to warm up before running the trials in the same manner as they would before a workout or race. They will run 50 meters before the force plate to allow time to get into a normal running rhythm at the designated pace. Likewise, running will continue after force plate contact for 10-meters. At least 90 seconds of recovery will be allowed between trials and will consist of easy jogging or walking.

The female subjects will run at a 4:40 minute per mile pace (5.74 m/s), and the males at a 4 minute per mile pace (6.7 m/s), which were determined from the speeds needed to qualify for the NCAA Division I Indoor Track National Championship Meet.

Speed will be verified using a photoelectric timing system, with sensors positioned 10 meters apart at neck level on both sides of the force plate.

Three trials within 2% of the desired pace will be obtained for each shoe condition. Only trials in which the left foot lands on the force plate will be valid. The trials will be run on days when the subjects are not training intensively (*i.e.*, “off” or “easy” days), to control for the effects of fatigue. All trials will be run in the afternoon. Data collection will take place within the first two to three weeks of the cross-country season, when the track and field and cross-country teams are practicing.

Force plate

A Kistler force plate (Type 9287BA, serial number 1440145, Amherst, New York, USA) will be used for collecting the ground reaction force data. It is imbedded into a Mondo indoor track with an asphalt foundation, and is covered with the same texture and surface as the rest of the track. The calibration of the force plate took place during manufacturing by the company. The force plate produces measurements of force for each of the horizontal (x and y) and vertical (z) directions, as well as the corresponding moments of force. It also provides a graphical output of the path of the center of pressure of the foot on the force plate.

Before each data collecting session, a few practice trials will be done to verify the appropriate function of all instruments. Antero-posterior and vertical ground reaction forces will be recorded through a laptop computer that will convert the force plate signal from voltage to force. Center of pressure recordings will verify that the whole foot came

in contact with the plate. Recorded forces will be normalized to the body weights of the subjects by dividing force by body weight in Newtons. The impulses will be calculated with the force measurements and center of pressure data.

Shoes

The shoes will be the same for all runners, differing in size only (sizes 6-12 in men's shoe size) and will consist of regular running shoes (Nike® Air Pegasus™ 2005), racing flats (Nike® Zoom Waffle Racer™ 2005), and distance spikes (Nike® Rival D Plus II™ 2005). 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 Rival D Plus II™ 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 Rival D Plus II™ 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.

The subjects will run across the force plate three times in each of the three types of shoes. The order in which the different shoes are worn will be randomized, meaning whichever shoe is randomly selected to be first, all trials will be completed under that condition before running in the next type of shoe.

Statistical Analysis

Differences among the vertical, braking, and propulsive GRF for the three shoe conditions will be measured using MANOVA ($\alpha = 0.05$) and a follow-up t test. The impulses corresponding to these forces will also be analyzed in the same manner. All statistical calculations will be done using SAS (version 9.0) software.

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Appendix A-1

Figure 1

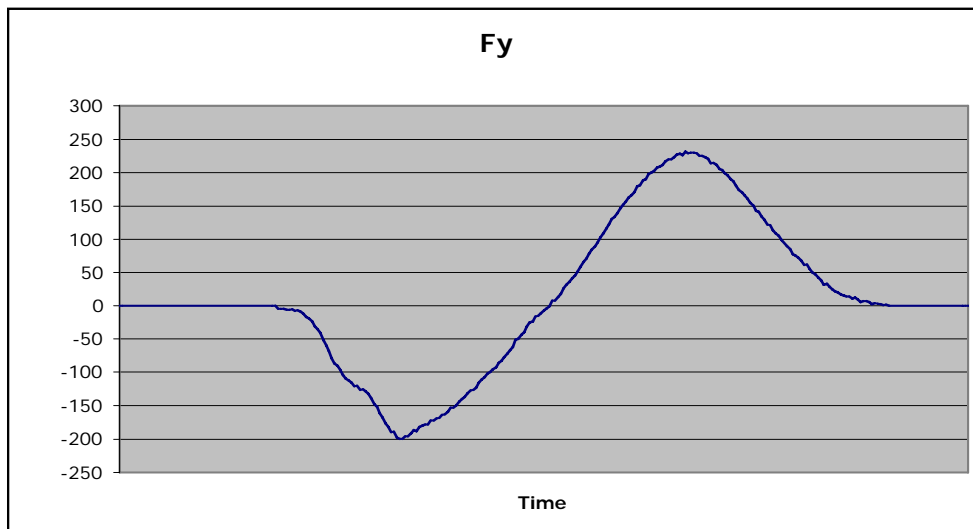


Figure 1. Typical antero-posterior force curve. The negative y-axis values represent the braking phase, while the positive values correspond to the propulsive phase.

Appendix A-2

Figure 2

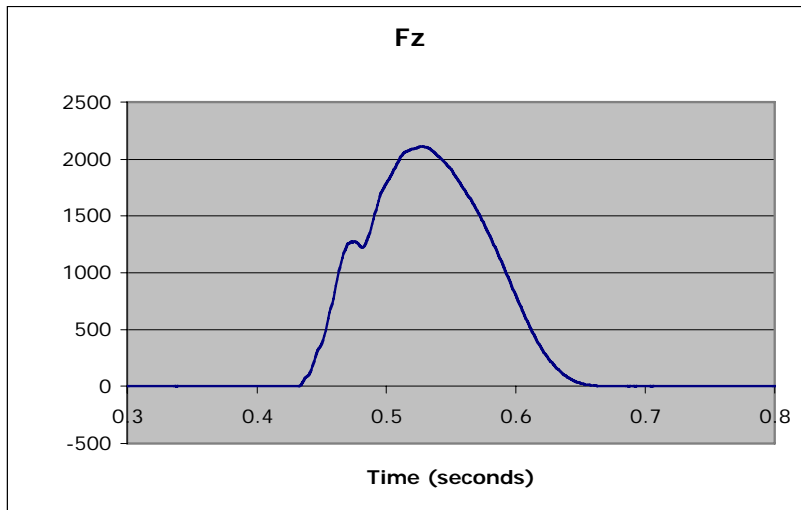


Figure 2. Typical ground reaction force curve. The first peak represents a heel strike.

Appendix A-3
Informed Consent

Consent to be a Research Subject

Introduction

This study is interested in finding if there are differences between running shoes, racing flats, and distance spikes in the amount of force acting on the foot from the ground during running. You were chosen to participate because you are a current or former NCAA Division I intercollegiate distance runner between the ages of 18-24, and are presently participating in a rigorous distance running training program.

The data collection will take place at the indoor track of the Smith Field House, Brigham Young University in Provo, UT 84602.

Procedures

Prior to participating in the study, each subject will be given a short questionnaire regarding his or her current injury/training status to verify his or her eligibility to participate. You will be eligible if you are free from injury and are able to participate in the normal cross-country or track training schedule without restriction. Provided you are eligible, you will be scheduled to come to the indoor track on one of the designated data collection days, which will be on a day that you will not be doing intense training. The data collection will take place in the afternoon. You will arrive dressed in running clothes, and you will again be given the injury/training status questionnaire prior to warming up. After you complete your normal, familiar warm up, you will begin running approximately 60 meter bouts at 4:40 per mile pace if you are female, and 4:00 per mile pace if you are male. You will complete three valid trials in each of three types of shoes – running shoes, racing flats, and distance spikes. In order for a trial to be valid, you will be required to land with your left foot on the force plate that is concealed under the track surface within 2% of the selected running speed. You will be given at least 90 seconds of recovery in between runs in which you will walk or jog easily. These shoes will be made by Nike® and will be provided for you when you arrive at the track.

Risks/Discomforts

During the data collection process subjects will be under the risk of fatigue, tripping, or spraining an ankle, but it is expected that this risk is minimal because the subjects are conditioned and experienced runners.

Benefits

There are no direct benefits to subjects, although you may improve your ability to consistently pace yourself at a high running speed.

Confidentiality

All data from the study will be stored on a laptop and desktop computer – both password-protected – as well as on a jump drive for back-up storage. The investigators in the study will have access to the data. When the study is completed, the data will remain on the computers/jump drive. The raw data will be used to generate means and standard

deviations. It will be compiled in aggregate form, with no personal identifiers of the subjects.

Participation

Participation in this study is voluntary. You have the right to cease participation at anytime without penalty of any kind, including your standing as a BYU athlete.

Conditions of Termination

Only injury free subjects will be included in the study. If at any time between consent and data collection, or during data collection you become injured, your participation in the study will be over.

Questions about the Research

If you have questions about this study you may contact Suzanna Logan at 380-3979, annazus84@gmail.com, or Dr. Iain Hunter at 422-1434, iain_hunter@byu.edu.

Questions about your Rights as a Research Participant

If you have questions you do not feel comfortable asking the researcher, you may contact Renea Beckstrand, IRB Chair, 422-3873, 422 SWKT, renea_beckstrand@byu.edu.

I have read, understood, and received a copy of the above consent and desire of my own free will to participate in this study.

Signature: _____ Date: _____