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Stepping over obstacles of different heights and varied shoe traction alter the kinetic strategies of the leading limb

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Abstract

This study aims to investigate the effects of shoe traction and obstacle height on friction during walking to better understand the mechanisms required to avoid slippage following obstacle clearance. Ten male subjects walked at a self-selected pace during eight different conditions: four obstacle heights (0%, 10%, 20%, and 40% of limb length) while wearing two different pairs of shoes (low and high traction). Frictional forces were calculated from the ground reaction forces following obstacle clearance, which were sampled with a Kistler platform at 960 Hz. All frictional peaks increased with increases in obstacle height. Low traction shoes yielded smaller peaks than high traction shoes. The transition from braking to propulsion occurred sooner due to altered control strategies with increased obstacle height. Collectively, these results provided insights into kinetic strategies of leading limb when confronted with low traction and high obstacle environments.

Statement of relevance

This study provides valuable information into the adaptations used to reduce the potential of slips/falls when confronted with environments characterized by low shoe-floor friction and obstacles. It also provides the necessary foundation to explore the combined effects of shoe traction and obstacle clearance in elderly people, more sensitive to slippage.

Keywords: Shoe Traction, Gait Kinetics, Obstacle Clearance, Slip and Fall.

1. Introduction

Injuries due to slips and falls are not purely random events, but rather predictable entities with known risk factors that may be extrinsic (environmental factors), intrinsic (human factors) or mixed (system factors). The primary risk factor for slipping is, by definition, low friction between the footwear and the surface (Chang *et al.* 2001a, Chang *et al.* 2001b, Grönqvist *et al.* 2001b). Secondary risk factors ('predisposing factors') for slipping accidents are related to multiple, interacting human and environmental factors. Human factors include gait biomechanics, expectation, the health of the sensory systems (i.e. vision, proprioception, somatosensation, and vestibular) and the health of the neuromuscular system (Moyer *et al.* 2006). Among the most important environmental factors are uneven or clustered pavements and slippery surfaces that could potentially cause instability, due to the fact that many goals have to be reached: negotiation of obstacles, avoidance of tripping, achievement of a safe landing, and avoidance of slipping (Petrarca *et al.* 2006). The adaptive strategy to maintain gait stability is to minimize the effect of disturbance on the locomotor behavior by taking into consideration the convergence of proprioceptive and exteroceptive inputs provided by the environment (Patla *et al.* 1996). Indeed, we know from experience that people accustomed to walking on slippery roads can walk without reducing gait speed, yet avoid slipping. In particular, recent studies have investigated how subjects with sufficient practice manage to control their gait movements on slippery surfaces (Marigold and Patla 2002, Gao and Abeysekera 2003, Asaka *et al.* 2004).

One fundamental principal in determining the slip propensity of a given situation is the relationship between the friction required to perform a particular task (*required* *friction*) compared with the friction available at the walkway/shoe interface (*available friction*) (Hanson *et al.* 1999). The risk of slipping occurs whenever the required friction exceeds the available friction (slip-resistant properties of the shoe/floor interface) (Tencer *et al.* 2004). Thus, biomechanical analysis of gait is potentially a valuable tool in setting thresholds of minimal friction needed to achieve slip-safe environments (Marpet 1996). Ground reaction forces at the shoe-floor interface are probably the most critical biomechanical parameters in slips. A number of researchers have examined ground reaction forces (GRF) during normal gait on a level surface (Perkins 1978, Strandberg and Lanshammar 1981, Perkins and Wilson 1983, Strandberg 1983, Winter 1991, Redfern and Dipasquale 1997, James 1980, Bring 1982, Cham and Redfern 2001, Cham and Redfern 2002, Gao *et al.* 2003, Lockhart *et al.* 2003, Gao *et al.* 2004, Lockhart *et al.* 2005, Burnfield and Powers 2006).

The ratio of the anteroposterior (shear) to vertical (normal) foot forces generated during gait, known as the required coefficient of friction (RCOF) during normal locomotion on dry surfaces or ‘friction used/achievable’ during slips, has been one biomechanical variable most closely associated with the measured frictional proprieties of the shoe-floor interface (usually the coefficient of friction or COF). The significance of the force ratio (Fy/Fz) is that it indicates where in the step cycle a slip would most probably occur (Figure 1). According to Perkins (1978), the most dangerous slipping during walking is most likely to occur in the braking period due to a low initial vertical ground reaction force at heel strike, which produces a small amount of friction. If friction is not sufficient during the braking period, an anterior slip of the foot would likely occur (Perkins, 1978). This slip could be particularly dangerous due to the rapid transfer of weight to the landing foot. Recent findings related to the human adaptations to "potentially" slippery surfaces (anticipation trials) resulted in significant differences in gait biomechanics when compared with characteristics of baseline trials, during which subjects walked onto a known dry surface (high shoe traction) (Heiden *et al.* 2006, Moyer *et al.* 2006, Siegmund *et al.* 2006). The overall effect of these adaptations was a reduction in the peak required coefficient of friction values (Redfern and DiPasquale 1997), thus humans have the ability to reduce slip potential on possibility contaminated shoe-floor interfaces (Cham and Redfern 2002).

However, the slipperiness of the shoe/floor interface may not be a sufficient explanation for falls and other slip-related injuries. The secondary risk factors (as described above) and their possible cumulative effects seem to further complicate both slipperiness measurements and the prevention of accidents and injuries due to slipping. There have already been numerous studies that have measured friction-based criteria and thresholds for walking without slipping for a variety of activities (e.g. walking on a level or an inclined surface, running, stopping and jumping, as well as stair ascent and descent,) (Grönqvist *et al.* 2001a, Redfern *et al.* 2001, Burnfield *et al.* 2005). However, limited attention was devoted to the combined effect of obstacles and low friction shoe-floor interface on the landing strategy adopted to avoid slipping after obstacle clearance (Patla and Rietdyk 1993, Bentley and Haslam 1998, Leclercq 1999). Until now, obstacles were used to stimulate the path over a cluttered environment in the perspective of elucidating the kinetic and kinematic characteristics of adaptations to obstacles and understanding processes of gait control (Patla *et al.* 1991, Patla and Rietdyk 1993, Chen *et al.* 1994, Sparrow *et al.* 1996, Chou and Draganich 1997, Begg *et al.* 1998, McFadyen and Prince 2002, Jaffe *et al.* 2004, Chen and Lu 2006, Petrarca *et al.* 2006). The research questions have primarily focused on aspects dealing with tripping due to obstacles so that observations were mainly made on the trail limb as the lead limb went over the obstacles. Later, much of the research work on obstacles has focused on the trajectories and timing characteristics for both the lead and the trail foot. However, the kinetics of the lead foot has not been investigated in a similar fashion (Patla 1991, Patla *et al.* 1991; Begg *et al.* 1998; Petrarca *et al.* 2006). It is important to note that lead foot kinetics reflect both control of landing and also its influence on ongoing control of trail limb crossing. While there has already been some interest in the process by which lead foot kinetics are modified to negotiate different height obstacles, current criteria and thresholds for safe friction in an obstacle environment are still incomplete. Two main categories of adaptive strategies are used when an individual subject encounters both an obstacle and a more slippery zone: "strategies of avoidance" that consist of modifying walking patterns in order to step over the obstacle, and "strategies of accommodation" that consist of the modification of walking patterns in order to adapt to the low friction footwear-floor interface (Patla 1991).

Therefore, the purposes of the present study was to investigate the combined effects of shoe traction and obstacle height on friction during walking to better understand the control strategies adopted to avoid slippage following obstacle clearance in normal young adults. We hypothesized that friction, measured as the ratio (Fy/Fz) between the horizontal (Fy) and vertical (Fz) ground reaction force components, will decrease with increased obstacle height and decreased shoe traction. In this study, obstacle height was adjusted to percentages (0%, 10%, 20%, and 40%) of limb length to ensure that individuals of different stature would make the same qualitative adaptation in going over obstacles. The dependent measures were variables derived from the lead foot-ground reaction forces, including peaks from the force ratio trace, time of the braking phase (TB), time of the propulsive phase (TP), and time of stance (TS).

2. Methods

2.1. Subjects

Ten healthy young male subjects from the general student community of the University of Nebraska at Omaha volunteered as subjects (age: 25.8 ± 4.29 years; body mass: 82.8 ± 8.25 kg; height: 179.6 ± 6.34 cm; leg length — as measured from the right anterosuperior iliac spine to the right lateral malleolus: 95.6 ± 4.49 cm; shoe size: 10). All subjects were without appreciable leg length discrepancy and had no injuries or abnormalities that would affect their gait. Prior to testing, each subject provided an informed consent approved by the University of Nebraska Medical Center Institutional Review Board.

2.2. Instrumentation

A Kistler force platform (Kistler Model 9281-B11, Amherst, NY) was used to record the foot-ground reaction forces (GRF) data at a sampling rate of 960 Hz. The force platform was mounted flush with the floor in the middle of the walkway. A Kistler signal conditioner/amplifier (Kistler Model 9807) was interfaced to a 16-channel Peak Performance Technologies Analog/Digital Interface Unit (Peak Model 2051, Englewood, CO) containing the analog to digital sampling modules interfaced to an personal computer. The GRF data were stored on a hard disk during the testing sessions. The vertical (F_Z) and the anterior-posterior (F_Y) GRF components were then extracted and used for further analysis.

2.3 Footwear

Two identical pairs of men's shoes (Pro-wing Joggers, size 10) with homogenous midsoles and rubber outsoles were used in this experiment (Fig. 2). The same shoes and shoe size were used for all subjects to minimize any such effects of the results of the study. To decrease the coefficient of friction of one pair of the shoes, without significantly modifying their weight, flexibility and general performance, 88 metallic one-half inch diameter disc thumbtacks, were inserted into the outsole of both the left and right shoe. The thumbtacks were carefully placed in order to ensure no part of the actual shoe was able to contact the ground during walking locomotion. They were also roughed and cleansed to expose the metal originally covered with enamel. The thumbtacks increased the weight of the shoes by 25 grams (475 g without the tacks versus 500 g with the tacks). The pair with the high traction had dynamic coefficient of friction (DCOF) of 0.7 and static coefficient of friction (SCOF) of 0.8. The pair with the low traction had DCOF of 0.3 and SCOF of 0.35. The two selected tractions were based upon previous literature (Denoth 1989, Perkins 1978) and test pilot work suggesting the high traction pair was a very safe shoe, while the low a borderline safe shoe. Both high and low traction shoes were roughed with 20 passes of the 100 grit sand paper, and then the surfaces were cleansed with rubbing alcohol to remove from the outsoles any solvents or residues of the shoe manufacturing process.

2.4 Mechanical measurement of friction coefficient

Measurements of frictional characteristics were conducted using a foot prosthetic with an artificial metal shank placed inside each shoe. This procedure was used because our data were collected prior to the release of the international standard on the determination of footwear slip resistance (ISO 13287:2006; Personal protective equipment - Footwear - Test method for slip resistance). The procedure used in this study was also based on personal communication with Dr. Edward C. "Ned" Frederick. Dr

Frederick is the Former Director of Research and Development at Nike Inc, the founder of the Nike Sports Research Laboratory and the president of Exeter Research, Inc. Based on our procedure, an eyebolt was screwed into the posterior aspect of the prosthetic heel, thru the heel cup of the shoe. Afterwards, the foot prosthetic was loaded with 100 lbs through the artificial shank corresponding to the subject's body-weight as closely as possible. Previous investigators demonstrated that such a procedure allows for a more accurate calculation of the shoe COF with respect to the subject's body-weight (Frederick 1998, Wojcieszak 1998). The weighed shoe was placed on one end of the force platform with the shoe heel toward the center of the force platform. GRF were collected while the shoe was pulled across the platform, in the horizontal plane, with a chain attached to the eyebolt. Horizontal pulling velocity (7 ± 1 mm.s^{-1}) was cautiously monitored using a photoelectronic timing system in order to compare consistent data on frictional properties of the two shoe conditions (high and low traction). DCOF and SCOF were measured by dividing the anterior-posterior GRF (Fy) with the vertical GRF (Fz).

2.5 Experimental protocol

Walking trials were conducted on a 10 meter pathway with a 0.6 meter wide lane. Walking speed was monitored at the location of the force platform over a 3 m interval using a photocell timing system. Subjects were given time to accommodate to the experimental set-up prior to testing. During familiarization, the investigator asked the subjects if there is any inconvenience regarding the shoe comfort (e.g. shoes that fit tight in some areas and loose in others) that may alter their natural gait. If no problems were reported, the subjects proceeded in establishing a comfortable self-selected walking pace which was recorded. This pace (± 5%) was used as a baseline speed for subsequent testing. Following this procedure a foot placement marker was located approximately 7 m before the timed interval to allow for a normal right foot contact (FC) on the force platform. Visual inspection of the force curves allowed for an inter-trial rest interval of one minute.

All subjects were asked to walk at their previously established baseline pace under four different obstacle conditions. The first condition was walking on a level surface while the other three conditions were walking over obstacles of three different heights. The average height of the obstacles was approximately: 8-10 cm (low, 10% leg length), 18-20 cm (medium, 20% leg length) and 36-40 cm (high, 40% leg length). These obstacle heights were established based upon the dimensions of obstacles commonly encountered in the everyday environment and the related literature (Chen *et al.* 1991, Chen *et al.* 1994, Chou and Draganich 1997, Patla *et al.* 1991, Patla and Rietdyk 1993, Patla *et al.* 1996). The 10% obstacle height characterize the door thresholds, the 20% obstacle height represent the typical curbstones separating cars in parking lots and stair risers, and 40% obstacle height correspond to those of a bathtub rim, where frequent falls occur especially among the elderly. The obstacles were placed directly before the force platform so that the subject had to clear the obstacle with the right leg and land on the force platform. The obstacles were made of light weight wood so that if a subject stepped on or hit the obstacle by mistake while walking, the obstacle was destroyed. This minimized the risk of tripping and falling. All subjects were required to complete the baseline and obstacle conditions with the two pairs of shoes (high and low traction outsole) as described previously.

Each experimental condition (shoe traction – obstacle) consisted on ten trials for a total of eighty trials per subject. The order of the presentation of conditions was predetermined as follows: (1) low traction – 0%; (2) low traction – 10%; (3) low traction – 20%; (4) low traction – 40%; (5) high traction – 0%; (6) high traction – 10%; (7) high traction – 20%; (8) high traction – 40%. This predetermined order was used because it was enforced by the Institutional Review Board of our University. This gradual presentation of the conditions minimized any possible falls/accidents due to slips and/or trips. Furthermore, subjects were given several practice trials prior to each condition to familiarize themselves with the task and the environmental constraints.

2.6 Data analysis

The dependent measures were variables derived from the lead-foot GRF. Three time values were identified from the horizontal GRF (Fy) plot: the time of the braking period (TB), the time of the propulsive period (TP) and the time of the stance phase (TS) by adding the braking and propulsion times (i.e. TB and TP). These three time values were identified for each trial by the same investigator using laboratory software. Four distinct points (P) were extracted from the force ratio (Fy/Fz) trace: P1 which is the first maximum negative peak on the force ratio trace, indicative of a high possibility of a forward slip; P2 which is the first maximum positive peak indicative of a slight possibility of a backward slip; P3 which is the second maximum negative peak indicative of a high possibility of forward slip (P3 is representative of peaks 3 and 4 on Figure 1); P4 which is the second maximum positive peak indicative of a high possibility of relatively safe backward slip (P4 is representative of peaks 5 and 6 on Figure 1).

The means and standard deviations of all parameters were calculated across trials for each subject-condition. A 2X4 (shoe traction versus obstacle height) repeated measures ANOVA was performed on the subject means for each parameter (TB, TP, TS, and P1 to P4). In tests that resulted in significant F ratios ($P < 0.05$), a *post hoc* Tukey multiple comparison test was performed to identify the location of significant differences. All statistical comparisons were conducted at $\alpha = 0.05$.

3. Results

The peak P1 was discarded from the analysis due to inconsistencies in its occurrence. The other three peaks (P2, P3 and P4) were consistent in their occurrences and easily discernable. The force ratio trace is an estimate of friction in-vivo, and thus it was expected that all peaks would have higher values for the high traction shoes. As expected, all peaks showed significant increases from the low to the high traction shoe (Tables 1 and 2). In addition, all peaks significantly increased with increases in obstacle height. P2 and P3 significantly increased from the no obstacle to the obstacle conditions for both shoes. For P4 the obstacle height had no effect regarding the low traction shoes. However, for the high traction shoes, P4 showed similar results as in the other two peaks. The increase in the peak values between the obstacle conditions was much more prominent in the high traction shoes. Peaks P2 and P3 increased 3 to 5 units between 0% and 40% obstacle conditions for the low traction shoes (peak P4 remained unchanged across obstacle conditions), while all peaks increased 7 to 17 units for the high traction shoes. This diverse effect that the obstacle height had on the two different pairs of shoes (low and high traction) was revealed in terms of significant interactions in all three peaks.

TS was significantly altered due to both traction and obstacle height (Tables 1 and 2). TS was significantly larger for the high traction shoe, and it showed a direct linear relationship with obstacle height for both shoes. Similar to the force ratio peaks, the increase of TS across obstacle conditions was more prominent in the high traction conditions, resulting in a significant interaction. TB showed no significant differences between the shoe conditions, whereas TP values were significantly larger for the high traction shoes. The effect of the obstacle height was opposite for TB and TP. TB significantly decreased with increases in obstacle height, while TP significantly increased. This result was much more noticeable with the 40% obstacle condition.

4. Discussion

The parameters investigated in our study were determined from the lead foot-ground reaction forces, including peaks from the force ratio (Fy/Fz) trace (P1, P2, P3 and P4) and three time values from the horizontal GRF (Fy) plot (TS, TB and TP). P1 was discarded from the analysis due to its inconsistencies. P1 was difficult to discern and was irregular in its occurrence. Perkins (1978) also stated that P1 was very inconsistent in its appearance. The values of all the other peaks were similar as in Perkins (1978). Furthermore, the hypothesis of the present study stated that the force ratio will decrease with increased obstacle height and decreased shoe traction. The first part of the hypothesis was rejected, while the second part was supported by our results.

The assumption according to which the force ratio will decrease as obstacle height increases was presumed incorrectly. It was assumed that Fz would increase with increases in obstacle height, which would yield lower force ratio values (Fy/Fz). This blindly assumed that Fy would remain constant. However, the force ratio increased with increased obstacle height, and Fy increased proportionally more than Fz. The fact that the force ratio increased with increases in obstacle height can possibly be explained by the position of the body's centre of mass (CoM) with respect to the foot. Indeed, the higher the obstacle, the larger the time to clear the obstacle (Begg *et al.* 1998, Chen *et al.* 1991). This additional time allocated to overcoming the obstacle, positioned the CoM more anteriorly over the leading leg at foot contact. As a result, this leads to a shorter braking time with the increased obstacle height, so that the shift from braking to propulsion occurred sooner (ST also increased with obstacle height).

The assumption that the force ratio will decrease as shoe traction decreases was supported by our results. All peaks showed significant decreases from the high to the low traction shoe, as expected. However, all peak values for both shoe conditions were smaller when compared with in-vitro calculations of the COF. This may be explained by the usage of a lighter weight (45.5 kg) in the in-vitro procedure as compared with the subjects' average weight (mean: 82.8 kg). Moreover, Frederick (1993) stated that in-vitro tests produce higher COF values than in-vivo, probably due to accommodation strategies performed by humans during the stance phase.

Peak P2, which coincides with the resistance opposing a posterior slip, was significantly increased from level walking (no obstacle) to the obstacle conditions for both shoes. This difference between level walking and the obstacle conditions may be due to the trajectory of the foot during late swing. During unobstructed locomotion, the foot swing is horizontal and relatively close to the walking surface until the end of the swing phase, when the foot touches down (Patla and Rietdyk 1993). On the contrary, during obstructed locomotion, the foot is raised to overcome the obstacle so that it moves through a more vertical and posterior direction at touchdown. This yields a larger force for opposing posterior motion, which may be the cause of increased peak P2 values in the obstructed conditions. The posterior motion of the foot would also explain the lack of the peak P1 in many trials, since P1 represents the resistance to an anterior slip. Group mean results for peak P2 during level walking (i.e., high traction shoes, 0% obstacle; Table 1) closely reflected peak P2 mean values achieved by subjects in Perkins (1978): 0.268 and 0.24, respectively. Because of the lack of studies investigating the interaction effects that exist between obstacles and low friction shoe-floor interface on the landing strategy**,** peak

P2 values in the three other obstacle conditions cannot be compared directly to previous literature.

Peak P3 coincides with the resistive force opposing anterior slipping of the foot on the force platform. Similarly to peak P2, peak P3 was less abrupt in low traction conditions. This effect was easily observed in 0% and 10% obstacle conditions. During experiments, qualitative assessment consistently revealed more occurrences of noticeable anterior slippage at foot contact (or shortly after foot contact) during low obstacle clearance (i.e. 0% and 10% obstacle conditions). This may explain why peak P3 was smaller in the low obstacle conditions. In these conditions, the foot is glancing off the walking surface as a pebble glances off the surface of a pond when it is thrown at a low, horizontal trajectory. In contrast, when the foot contacts the walking surface with a high, vertical trajectory, as occurs in the obstacle conditions, the foot is being pushed in a downward direction (as opposed to being pushed in an anterior direction). Group mean results for peak P3 during level walking (Table 1) were close to peak P3 mean values in Perkins (1978): 0.221 and 0.22, respectively.

Peak P4, which coincides with the resistive force opposing posterior slipping of the foot on the force platform during the propulsive period, was significantly different between shoes. Peak P4 values were significantly remained constant across obstacle crossing conditions for the low traction shoes, but steady increased for the high traction shoes. The significantly lower values force ratio values in low traction conditions may be due to an inadequate push-off. Group mean results for peak P4 during level walking (Table 1) were comparable to peak P3 mean values in Perkins (1978): 0.329 and 0.30, respectively.

TS was significantly different between shoe conditions for all obstacles heights. The low traction conditions yielded a shorter stance time in comparison with the high traction conditions. This trend was also observed for both TB and TP. More generally, TS increased with increases in obstacle heights, and the highest obstacle had the most noticeable effect on this parameter. This result is in agreement with Begg *et al.* (1998). Dividing stance phase into its two periods, braking and propulsion, allowed for a better understanding of the differences within this phase. Overall, TB was inversely related to the obstacle height, while TP was linearly related to this factor. As previously mentioned, such a result may be explained by the position of the body's CoM with respect to the foot. The additional time allocated to overcoming the obstacle, located the CoM more anteriorly over the leading left at foot contact. As a result, the shift from braking to propulsion may take place sooner than during the absence of the obstacle or in the low obstacle conditions.

Our results should be viewed in lieu of the following limitations. The lack of randomization is a possible limitation of the present study. The use of non-randomization may actually introduce a learning effect. Indeed, when all trials for each subject are predetermined, the subjects might gain experience and gradually become more capable in negotiating the obstacles and therefore change their gait strategies. This learning effect might have led to the rejection of one of the primary hypotheses, i.e. the force ratio (Fy/Fz) would decrease as obstacle height increase. However, we performed pilot work which indicated that the order of the testing conditions did not show any learning effect. In addition, subjects were given one or more practice trials prior to each condition to familiarize themselves with the task and the environmental constraints. Lastly, our results in terms of gait adaptations are in agreement with those found in the literature (e.g. Begg *et al.* 1998, Cham & Redfern 2001, 2002a, 2002b, Chen *et al.* 1991, Frederick 1993, Perkins 1978).

Another possible limitation of this study may be the method used to measure friction during walking. The interaction between the rubber and the metal, as opposed to metal-metal interaction, could have cause differences between low and high traction conditions. It is well known in the field of tribology that synthetics and rubbers do not follow the linearity of the mechanical laws. Consequently, calculation of friction by dividing Fz and Fy may not be the most appropriate method.

Conclusions

The purpose of this research was to investigate the combined effects of shoe traction and obstacle height on friction during walking. All peaks of the force ratio (Fy/Fz) increased with increases in obstacle height. As expected, the low traction shoes yielded smaller peaks than the high traction shoes. Increases in obstacle height lead to shorter time of braking to propulsion with increased obstacle height. These changes appear to reduce the risk to the subject when confronted with an environment characterized by low traction and high obstacles. This investigation provides the necessary foundations to explore the combined effects of shoe traction and obstacle clearance in other populations (i.e. elderly) that are more sensitive to slippage.

Acknowledgments

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Figure Captions

Figure 1. Gait phases in normal level walking with typical horizontal (Fy) and vertical force (Fz) ground reaction components and their ratio, Fy/Fz, for one step (right foot). Note that peak 1 is caused by the forward force of impact of the heel onto the force plate. Peak 2 is the result of a backward force exerted on the heel after contact during the early landing phase. Peaks 3 and 4, often recorded as one broad spike, are caused by the main forward force, which retards the motion of the foot. Finally, peaks 5 and 6 are recorded during the push-off phase, with the toes in contact with the force plate, pushing in the backward direction (from Perkins 1978). Critical from the slipping point of view are the heel contact (peaks 3 and 4) and the toe-off (peaks 5 and 6) phases (Grönqvist *et al.* 1989).

Figure 2. Soled of the high traction shoe (left) and the low traction shoe (right). The shoes (size 10) are regular running shoes (Pro-wing Joggers, 0456-2011-09-04). One pair of the shoes was altered to decrease its coefficient of friction by inserting 88 metallic one-half inch diameter disc thumbtacks into the outsole.

Figures

Figure 1.

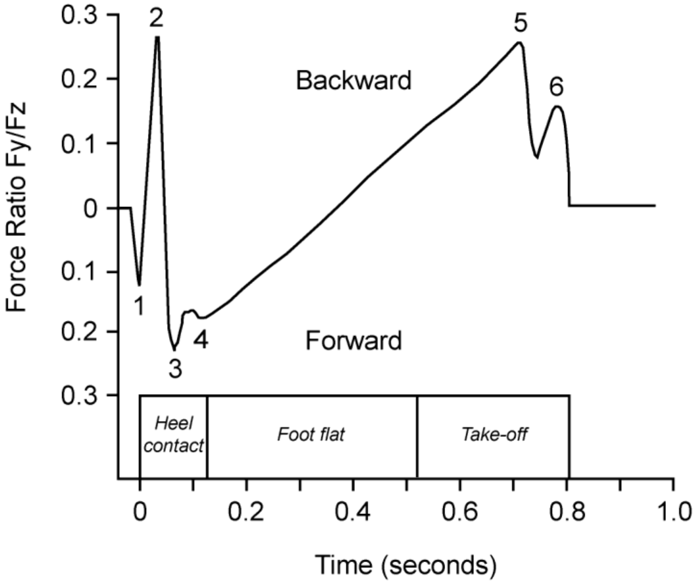

Figure 2.

Table Captions

Table 1. Group means (M) and standard deviations (SD) for parameters (multiplied by 100) derived from the lead-foot ground reaction forces. The four distinct points (P) were extracted from the force ratio trace: P1: first maximum negative peak; P2: first maximum positive peak; P3: second maximum negative peak (P3 is representative of peaks 3 and 4 on Figure 1); P4: second maximum positive peak (P4 is representative of peaks 5 and 6 on Figure 1). However, the peak P1 was discarded from the analysis due to inconsistencies in its occurrence. Three time values were identified from the horizontal GRF: TB: time of the braking period; TP: time of the propulsive period, and TS: time of the stance phase. The value for P3 is multiplied by -1, while the values for TS, TB, and TS are in seconds multiplied by 100.

* : significantly different between shoes within the same obstacle height ($p < 0.01$).

$^{10,20,40\%}$: significantly different between obstacle heights within the same shoe ($p < 0.01$).

Table 2. Results of a 2X4 ANOVA with repeated measures on both factors: shoe traction (s) and obstacles (o). In tests that resulted in significant F ratios ($p < 0.05$), a *post hoc* Tukey multiple comparison test was performed to identify the significant differences. Fs: between shoes; Fo: between obstacles; Fs×o: interaction.

Tables

Table 1.

Parameters		Low traction				High traction			
		0%	10%	20%	40%	0%	10%	20%	40%
P2	M	16.224$^{*10,20,40\%}$	18.813*	20.246*	19.757*	26.751$^{10,20,40\%}$	38.256$^{20,40\%}$	42.359	43.480
	SD	2.192	2.844	2.658	3.069	3.780	4.783	5.309	4.762
P3	M	17.311$^{20,40\%}$	19.316*	20.664*	21.857*	22.128$^{10,20,40\%}$	25.895$^{20,40\%}$	30.049$^{40\%}$	35.650
	SD	1.653	2.245	2.115	2.201	2.862	5.183	6.947	8.119
P4	M	18.305*	18.106*	17.988*	18.006*	32.908$^{10,20,40\%}$	36.667$^{20,40\%}$	39.966	39.081
	SD	3.264	3.252	3.506	3.515	3.415	3.885	2.892	4.126
TS	M	66.426$^{*40\%}$	67.883$^{*40\%}$	67.507$^{*40\%}$	71.051*	69.207$^{20,40\%}$	70.599$^{40\%}$	72.236$^{40\%}$	76.669
	SD	3.394	3.356	4.697	4.018	3.187	2.844	2.912	3.576
TB	M	36.736$^{40\%}$	36.682$^{40\%}$	34.451$^{40\%}$	29.616	36.752	37.195$^{40\%}$	35.503	33.088
	SD	2.273	2.426	4.852	6.168	2.508	3.268	3.603	5.458
TP	M	29.69$^{*40\%}$	31.201$^{40\%}$	33.056$^{*40\%}$	41.435	32.454$^{20,40\%}$	33.404$^{40\%}$	36.733$^{40\%}$	43.580
	SD	2.513	4.144	4.642	4.965	1.911	3.909	4.896	4.283

Table 2.

Parameters	Fs	p <	Fo	p <	Fs×o	p <
P2	141.376	0.01	59.864	0.01	30.121	0.01
P3	33.431	0.01	29.705	0.01	12.123	0.01
P4	345.174	0.01	13.191	0.01	16.572	0.01
TS	81.545	0.01	16.305	0.01	7.804	0.01
TB	4.928	-	6.880	0.01	1.881	-
TP	17.774	0.01	28.877	0.01	0.718	-