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SHOE CUSHIONING PROPERTIES AND GRADE BUT NOT SURFACE INFLUENCE KINETICS IN RECREATIONAL RUNNERS

A Thesis in

Kinesiology

by

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ABSTRACT

Running is a popular physical activity with approximately 40 million Americans participating annually. Unfortunately, there is a high overuse risk with as many as 79% of runners experiencing an injury per year. Recommendations to reduce injury have included four simple, yet contradictory, solutions: 1) run on a softer surface, 2) run in maximal cushioned shoes 3) run in minimal cushioned shoes and 4) run uphill. The purpose of this thesis was to determine the effects of running on two different outdoor surfaces and two different shod conditions over a variety of slopes on components of the ground reaction force. First, we hypothesized that an outdoor grass (soft) surface would reduce loading rates and increase heel-strike index values compared to a compact gravel (hard) surface. Second, we hypothesized that running in minimally cushioned running shoes would reduce both loading rate and heel-strike index compared to maximally cushioned shoes. Third, we predicted that no condition would have a significantly higher active peak. Finally, we hypothesized that loading rate and heel-strike index would be lower during uphill running compared to downhill running regardless of surface stiffness or shoe cushion. Our data suggest that surface stiffness has no effect on running forces and may not be a valid method to reduce injury risk. However, loading rate was less during uphill running in minimally cushioned shoes compared to running downhill in maximally cushioned shoes and thus, may be one strategy to reduce forces to the lower extremity.

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Chapter 1

Introduction

Approximately 40 million people in the U.S. run, possibly due to its accessibility and low barrier to entry (Videbæk et al. 2015). Accordingly, recreational running is an ideal option to combat the large risk of chronic disease that results from sedentary behavior (Sánchez-Oliver et al. 2018; Lachman et al. 2018). Though running is affordable and convenient, injury risk is large, with up to 79% of runners experiencing a running-related injury (RRI) annually (Hreljac et al. 2000). Large ground reaction forces (GRF), related to impact and loading, are correlated with RRI and thus, finding a means of reducing these forces during running could help reduce the rate (Hreljac et al. 2000). Many methods have been proposed to reduce GRF but arguably the easiest variables to modulate are running surface, running grade, and shoe-type as this will not acutely influence training goals as would manipulating speed or running form (Hreljac et al. 2000). While softer surfaces, maximal cushioning shoes, minimal cushioning shoes, and uphill grades are often recommended for reducing injury risk, the literature on these topics presents mixed results.

Common Overuse Injuries and Variables Associated with Overuse Injuries

A recent review found that novice runners experienced 17.8 injuries and recreational runners sustained 7.7 injuries per 1,000 hours of running (Videbæk et al. 2015). Another review found that injuries most commonly occurred at the knee (incidence 7.2% to 50.0%) with injuries to the lower leg (shin, Achilles tendon calf, heel), foot, and upper leg (hamstring, thigh, quadriceps) occurring frequently as well (van Gent et al. 2007). With each step, a ground reaction force (GRF) acts from the ground upon the foot in response to the foot exerting a force on the ground and is an example of Newton’s Third Law (Cavanagh, 1990). Compared to about 1.1 BW of force per step while walking, during running, these forces can reach almost 3.0 times body weight (BW) per step during stance (Keller et al. 1996; Cavanagh and Lafortune 1980). This can result in a large loading force to the lower extremity when multiplied by up to 90 times per minute to each leg (Willy et al. 2016). In addition, runners who heel strike tend to experience two peaks in this GRF, the first peak being the impact peak, and the second peak being the active peak (figure 1-1). Impact peaks are associated with high loading rates, or the rate of rise of the vGRF (Cavanagh and Lafortune 1980). High vertical loading rates and vGRF are frequently associated with common overuse injuries. Specifically, tibial stress fracture (TSF) is associated with high instantaneous and average vertical loading rates (Milner et al. 2006). Another study found that lower impact forces are associated with a lower incidence of running-related overuse injuries (Hreljac et al. 2000). Therefore, finding a means to reduce these variables may provide a solution to high injury rates associated with running.

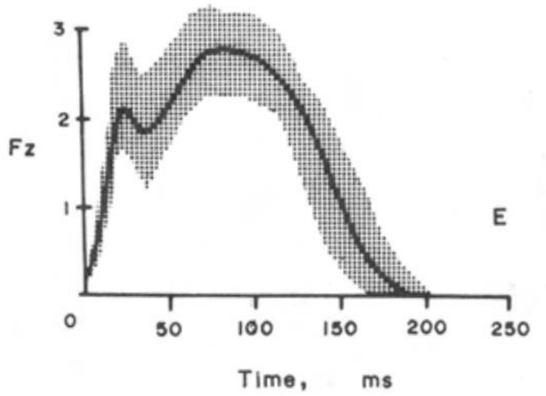

Figure 1-1 Fz-time curves of distance runners running at 4.5 m/s. Adapted from Cavanaugh and Lafortune, 1980.

Running Surface

Numerous methods have been proposed to reduce GRF and therefore RRI risk in runners but the easiest means of reducing injury may be simply running on a different surface. Preliminary data on GRF profiles from different surfaces are mixed and have been collected primarily in a laboratory setting (Ismadi Ismail 2019; S. Dixon 2008; Gantz and Derrick 2018; Fu et al. 2015; Abdul Yamin et al. 2017; Hardin, Van Den Bogert, and Hamill 2004). Ismail et al. had runners strike a bare force plate and a force plate covered with an artificial sports surface and found no significant differences between the two conditions in peak force (Ismadi Ismail 2019). A similar study covered a force plate in three different materials and similarly, found no significant effect of surface on GRF. In contrast, Dixon et al. (2000) saw a 7.6% reduction in loading rate when running on a rubber-modified surface compared to an asphalt surface. Along with the mixed results of indoor studies on running surface, several limitations such as short runways limit the ability to translate these results to clinical recommendations.

Outdoor studies have used pressure insoles to investigate surface effects. Tillman et al. (2003) investigated asphalt, concrete, grass, and a synthetic track on changes in ground contact time, impulse, and shoe reaction force while running over ground. They found no significant differences between these variables for any surface and concluded that no additional injury risk was present while running on harder surfaces. In contrast, Tessutti et al. conducted similar studies and found that running on a grass surface may attenuate in-shoe plantar pressure in recreational runners (Tessutti et al. 2010, 2012). When running at speed of 12 km/hr for 40 m, a natural grass surface resulted in 11.9% lower peak pressure values compared to an asphalt surface. In addition, running on natural grass compared to asphalt, concrete, and rubber resulted in by 16.1%, 16.5%, and 12.3% lower peak plantar pressures, respectively. Results from these two authors may disagree due to differences in methodology. For example, Tillman et al. (2003) instructed runners to self-select a comfortable pace and Tessutti et al. (2010, 2012) imposed a pace.

Previous studies on running surface have been conducted on an indoor runway with a force plate or on an instrumented treadmill with an imposed speed with contradictory results.

Ismail et al. (2019) had participants run over a bare force plate and a force plate covered with a soft, artificial surface and found no significant effects of surface on peak heel and forefoot strike force during walking and running. A similar study found that in minimal cushioning shoes, GRF was 4.3% and 20% higher on grass than rubber and concrete (Abdul Yamin et al. 2017). In contrast, Dixon et al. saw a 7.6% reduction in loading rate when participants ran over a rubber-modified surface compared to an asphalt surface. In addition to conflicting results on the relationship between surface compliance and GRF, laboratory studies may lack external validity because running is typically done over longer distances and running indoors and being instructed to strike a force plate may cause runners to modulate their kinematics. Other limitations of previous studies include using standardized running shoes across participants, failing to determine if differences are present in response to changes in grade, and using artificial surfaces. Furthermore, studies completed outside the laboratory have only been able to measure variables related to plantar pressure (Tessutti et al. 2010, 2012; Tillman et al. 2003). A better understanding of how running GRF forces change in response to running surface will permit a better understanding of running related GRF in the real world and inform recommendations for reducing RRI by clinicians.

Foot strike pattern (FSP)

Another kinematic variable that has been shown to influence kinetics is foot strike pattern (FSP). Runners typically adopt either a rearfoot, midfoot, or forefoot strike when coming in contact with the ground (Cavanagh and Lafortune 1980). Though results are mixed, many studies report that impact peaks, loading rates, patellofemoral joint stress, peak tibial accelerations, and running economy (RE) are improved by a forefoot strike (Ogueta-Alday et al. 2014; dos Santos et al. 2019; Crowell and Davis 2011; Breen et al. 2015; Chu and Caldwell 2004; Diebal et al. 2012; Kulmala et al. 2013; Giandolini et al. 2013; Daoud et al. 2012; Gruber et al. 2013; Miller and

Hamill 2015; Dallam et al. 2005.) In particular, gait retraining to teach habitual rearfoot strikers to progressively adopt more of a forefoot strike has been successful in improving symptoms associated with common running injuries such as anterior tibial compartment syndrome, patellofemoral syndrome and tibial stress fracture (Diebal et al. 2012; dos Santos et al. 2019; Crowell and Davis 2011). In particular a 17% reduction in patellofemoral joint stress has been seen when habitual rearfoot strikers ran with a forefoot strike (dos Santos et al. 2019). While the effects of FSP on running related GRF are clearly potent, the link between FSP and running surface has not been investigated. Importantly, FSP is influenced by a variety of variables such as running speed, experience, and distance, which should be taken into account when designing a study whose results will inevitably be influenced by FSP (Hatala et al. 2013; Hasegawa et al. 2007; Lieberman et al. 2010; Ahn et al. 2014).

Minimal Cushioning Shoe Running

Footwear is another variable which may affect running forces and a recent study prompted the question of shod running on biomechanical variables related to injury (Lieberman et al. 2010). The authors found that Kenyan runners who ran unshod were more likely to run with a forefoot strike and experience lower impact forces and loading rates than traditionally shod US runners. Further support for this idea is provided by Sun et al. (2018) who demonstrated that running with a FFS significantly reduced plantar pressure in both shod and unshod conditions. This study suggested that barefoot running and the associated forefoot strike are the more natural way to run as energy on impact can be stored while intrinsic foot muscle and tissues maintain their integrity. Further, the addition of cushion to shoes reduces the runner’s ability to use proprioception during landing. Thus, shoes which provide a minimal layer of protection between the foot-ground interface may be optimal for encouraging a forefoot-strike pattern and reducing loading on the lower extremity during running (Lieberman et al. 2010).

In response to the barefoot movement, shoe manufactures have attempted to recreate the barefoot condition in a shoe but at this time, there is not a clear consensus of the outcomes of this approach. One study indicated that running in barefoot-mimicking shoes was associated with an increased knee adduction moment compared to traditional training shoes (Sinclair et al. 2019). In contrast to this finding, another study by Sinclair et al. (2014) found that running barefoot-inspired footwear reduced patellofemoral loading rate by 8.5% compared to traditional footwear. Further support for the integration of minimalist shoes into a running program comes from a study which looked at the combinations of shoe type and cadence. The authors found that running in a minimalist shoe combined with increasing cadence reduced patellofemoral joint stress by 29% compared to running in traditional shoes at a preferred cadence (Bonacci and Hall 2017). Though differences in kinetics and kinematics are present while running in minimalist footwear compared to traditional in an unfatigued state, these differences diminish as runners fatigue (Lussiana et al. 2016). However, it is unknown if this is still the case as runners habituate to a minimalist shoe.

Maximal Cushioning Shoe Running

In stark contrast to barefoot inspired shoes, shoes with large midsoles are often marketed as a means attenuating impact during running (Kulmala et al. 2018). To date, the evidence to support this claim is mixed. A study which compared maximal shoes (HOKA ONE® Conquest) to a standard running shoe found no significant differences in impact peak, active peak, loading rate, and stance contact time between shoes. The only significant difference was a slightly greater stance index indicating that runners adapted a slightly more anterior foot-strike in the maximal shoes (Arthur and Aminaka 2018). In contrast, Sinclair et al. (2016) showed that compared to minimalist running shoes, maximal shoes resulted in 115.7% lower instantaneous loading rates when running over a force plate. They also found no significant differences in kinematics between a maximal shoe and a traditional running shoe (Sinclair et al. 2016). Kulmala et al. (2018) found that compared to traditional running shoes, maximal cushioning shoes amplified impact loading rate by 12.3% at 14.5 km/hr. Finally, a study which had participants undergo a 6-week acclimatization period in maximal shoes resulted in 25% greater loading rates and 17.2% higher impact peak values, even after a familiarization period (Hannigan and Pollard 2019). Therefore, it seems that maximal cushioning shoes may amplify, rather than attenuate loads.

Runner's Legs as Springs of Variable Stiffness

Multiple researchers in the biomechanics field have proposed a theory that describes the human leg apparatus as a spring with variable stiffness (e.g., Ferris et al.1998). Ferris et al. (1998) describes this phenomenon as an attempt by the human runner to maintain constant vertical ground reaction forces when encountering a new surface by changing the stiffness of the leg contacting the ground in response to the stiffness of the terrain (Ferris et al. 1998). In a laboratory, runners reduced leg stiffness by 29% when encountering a hard surface and this adjustment maintained center of mass (COM) trajectory (Daniel et al. 1999). These authors concluded that there is no effect of surface on GRF because the leg acts as a spring of variable stiffness. It is unknown, however, if this same effect will be seen while running on different surfaces for a longer duration and in outdoor running environments.

Effect of grade

Surface grade also influences GRF and FSP. In a laboratory study investigating the effect of grade on GRF, normal impact peaks increased by 54% during downhill running at -9˚ and decreased by 22% during uphill running at 9˚ in habitual rearfoot strike runners (Gottschall and Kram 2005). Further, loading rate was increased by 20% and reduced by 23% while running downhill and uphill at 6˚. Foot-strike pattern is also modulated in response to grade as the authors also saw participants adopt a forefoot strike while running uphill at steep grades. Based on previous literature on running surface, it is clear that an outdoor study would aid in assessing the effects of surface grade on GRF.

Running Speed

A final variable that influences GRF results while running is running speed. Loading rates have been shown to increase as walking and running speeds are increased up to 6.0 m/s (Keller et al. 1996). Kulmala et al. (2018) have also showed a 40.5% increase in loading rate while running at a fast speed (14.5 km/hr) compared to a slower speed (10 km/hr).

Technology takes studies outdoors

In-shoe technology with the ability to collect data on multiple consecutive footfalls is necessary in order to advance the field of GRFs in the real world (Cavanagh, 1990). Previously, GRFs have been measured using force platforms with either piezo-electric transducers or strain gauges which are able to sample at very high frequencies (Cavanagh, 1990). These platforms measure GRF and the center of pressure reliably however, collecting reliable data where an individual is able to run normally while striking the force place can be challenging due to the limited surface area (Cavanagh, 1990). In addition, laboratory space limits natural running technique and the collection of multiple steps. Due to these limitations, shoe insoles with the capability of measuring force may be a reasonable alternative.

Prior attempts to create insoles which measure GRF have been difficult due to the wired equipment and data output methodology (Cavanagh, 1990). Outdoor studies have been facilitated by pressure-measuring insoles, however, this technology requires that the runner to wear a backpack to hold wiring (Tessutti et al. 2010) and the GRF recorded are lower due to shoe reaction forces being limited to the surface area of the sensor arrangement.

Recent advances in technology have permitted research on the biomechanics of running over outdoor surfaces to progress. A company which has previously made pressure-recording insoles created force-measuring insoles. The new loadsol sensors consist of three capacitive sensors which are located in the heel, medial, and lateral forefoot regions of the foot. These insoles, made by Novel (Munich, Germany) are capable of recording force measurements that are comparable to force plate readings and thus, running GRF can be reliably studied in a variety of settings (Burns et al. 2018).

Significance

Studies have investigated all of the previously listed outcomes in a laboratory setting using either force plates or instrumented treadmills resulting in limited ability to generalize findings as runners may modify their kinematics to due to the artificial environment. We know that GRF is increased by both negative grades and increased running speed, however the effect of surface and shoe-type has yet to be fully elucidated. To further our understanding of GRF, it is not only important to look at common running surfaces and shoe-type, but also how these variables influence GRF when coupled with variations in grade. Using Novel's new loadsol® insoles, we are able to provide accurate GRF data at the surface of the foot in order to provide valuable insights to surface and shoe effects on GRF (Renner et al. 2019). Discovering the link between these variables would permit more informed advice from coaches and clinicians regarding running surface, running shoes, and running grade to recreational runners trying to improve health and fitness while also avoiding injury.

Chapter 2

Surface grade, not surface stiffness, influences loading rates in recreational runners

2.1 Introduction

Many runners opt to complete their training outside over a wide variety of surfaces such as asphalt, concrete, track, trail, and grass. Traditionally, running kinetic data are collected inside on a treadmill or short runway with a force plate. It is currently unknown how, and to what extent running on different outside surfaces influence variables such as ground reaction force (GRF) that are pertinent to the analysis of running technique and injury risk.

Loading rate (LR), active peak (AP), and heel-strike index (HSI), are variables measured to evaluate how running surface influences kinetics. First, loading rate is the rate of rise of the vertical GRF following contact (Cavanagh, 1990). Dixon et al. (2000) found differences in loading rates for a rubber modified surface compared to an asphalt surface while studying running surface using a force plate. Second, active peak is the magnitude of the large peak in the resultant GRF that occurs during mid-stance (Cavanagh, 1990). It is unknown how this variable changes during outdoor running however, Breine et al. (2017) found a difference in the maximal vertical instantaneous loading rate between two different rearfoot strike patterns when participants ran over a force plate. Third, heel strike index (HSI), is a variable utilized to asses foot strike pattern and quantifies what part of the foot initiates contact with the ground. When runners contact the ground during impact, they either land with the posterior third of their foot, a flat foot, or the anterior third of their foot deemed rearfoot, midfoot, and forefoot strikes, respectively (Lieberman et al. 2010).

Past laboratory studies of the interaction of GRF and surface stiffness are inconclusive. For example, there were no significant effects of surface on peak force when participants ran over a force plate with and without compliant artificial material (Ismadi Ismail 2019). Yamin et al. (2017) found that when running in minimal cushioning shoes, peak vertical GRF was 4.3% and 20.0% higher on grass than rubber and concrete, respectively. In contrast, loading rate was 7.6% lower when running over the rubber modified surface compared to an asphalt surface in another laboratory surface study (Dixon et al. 2000).

Outdoor studies may provide more generalizable results as runners often train on a variety of surfaces. Tillman et al. (2003) investigated the effect of surface (asphalt, concrete, grass, and a synthetic track) on ground contact time, impulse, and shoe reaction force while running outside with pressure insoles. They found no significant effects of surface for any variable and concluded that running on harder surfaces presented no additional injury risk. Tessutti et al. (2010) performed a similar pair of experiments that yielded different results. The first study required participants to run at 12 km/hr for 40 m over a natural grass and an asphalt surface while wearing pressure insoles. The two surfaces were statistically different for peak pressure, contact time, and contact area (values for central rearfoot sensor in % difference from asphalt: 10.8%, 13.8%, 14.3%) and thus, the authors concluded that a softer surface resulted in a decreased load on the rearfoot and forefoot in recreational runners. A second study by the same group found that running on natural grass was effective at reducing peak plantar pressures by 16.1%, 16.5%, and 12.3% compared to asphalt, concrete, and rubber in recreational runners (Tessutti et al. 2012). These conflicting results could be due to different participant populations. Further, both studies had similar protocols (imposed shoes, short runway) however, Tilman et al. (2003) had participants self-select their running pace while Tessutti et al. (2010) imposed at pace (12 km/hr).

Finally, GRF is modulated in response to grade. Gottschall and Kram (2005) found that in comparison to level running, normal impact peaks were 54% greater during -9˚ downhill running. Furthermore, +9˚ uphill running attenuated impact force peaks. These results were partially attributed to runners adopting a more anterior foot-strike for steep, uphill grades and landing with a rearfoot-strike while running downhill, on level ground, and at shallow slopes. Finally, they also showed increased loading rates for downhill running. Rearfoot strike maximal loading rates were 20% greater while running at -6˚ compared to level running and 23% less while running uphill at the same grade.

The purpose of this study was to determine if there is an effect of surface stiffness or surface grade on GRF in recreational runners. We hypothesized that loading rate would be higher on a hard surface and during downhill running. We hypothesized that active peak would not be significantly different for any condition. Finally, we hypothesized that heel-strike index would be greater on a harder surface and during downhill running.

2.2 Methods

Participants

Twelve recreational runners (4 men, 3 women) completed this study however, only seven participant data sets were suitable for analyses (Table 2-1). Five data sets had to be discarded due to technical complications with the insoles (electronics losing connection part way through data collection, etc). The protocol was explained and participants signed an informed consent approved by the Pennsylvania State University Human Research Committee. Participants completed a questionnaire on running and exercise habits before beginning the protocol.

Table 2-1 Participant Descriptive Statistics

	Age	Mass (kg)	Height (m)	Weekly running distance (km/wk)	Years running
Avg	22.7	66.6	1.72	53.5	9.9
SD	2.6	4.5	0.08	25.0	2.7
Range	20-28	58.3-74.9	1.63-1.83	28.2-104.6	7-15

Protocol

Data was collected outdoors during a single session . Height and mass were measured with a portable bathroom scale and measuring tape. Thin three-sensor force-measuring insoles (Novel, Loadsol® Munich, Germany) were placed into the participant's own running shoe and calibrated according to the manufacturer's protocol. A smartphone (Apple iPhone 6) was placed into an arm band to collect data from the insoles via Bluetooth. The protocol required participants to run up and down both a grass (soft) surface and a compact gravel (hard) surface (figure 2-1) a total of four times. The surfaces were adjacent to each other and both included grades of approximately 1˚ of slope (SHALLOW) and 8˚ of slope (STEEP) over a distance of about 200m. Trials were completed at an imposed cadence (160 steps/minute) which was enforced by having participants run in step with a metronome which played out loud from the iPhone on their arm. They were allowed to practice running with the metronome until they felt confident in their ability match the beat. A cadence was imposed rather than a speed due to the logistical difficulties of using timing gates on a longer outdoor surface. A single data collection segment consisted of the participant running either from one end of the hill to the other on one of the surfaces and trial times were recorded with a stopwatch.

One research team member started the collection on the iPhone at the start of the segment and another team member ended the collection on the iPhone at the other end of the running segment. Participants were instructed to run at a comfortable pace (one which they may adopt for a 5+ mile run) and were permitted to rest between segments as long as they wanted. Surface conditions were randomized for each participant.

Figure 2-1 Study surfaces: *hard*, gravel (left) and *soft*, grass (right).

Kinetics

We collected forces normal to the plantar surface of the foot as a surrogate for GRF with Novel’s loadsol® force-measuring insoles (Munich, Germany). Data was collected at 100 Hz. A custom-written Matlab program (Version 2018b, The Mathworks, Natick, MA) was used to process the data as described below. We used a 25 N threshold to define the beginning of stance and analyzed 5 steps per foot per condition.

Dependent Variables

After collection and during processing, the following variables were calculated: (1) loading rate (LR), (2) active peak (AP) and (3) heel strike index (HSI), or the heel contribution to the total loading. Data was filtered using a Butterworth filter at 40 Hz. We defined LR from 3-15% of stance time to keep consistent with Novel's methodology while also capturing approximately 20-80% of the time period from contact to impact peak. We did not define LR based on impact peaks as these were not visible in many of trials. AP values were determined by finding the point at which the ground reaction force returned to 25 N, and stepping backward along the force curve to the point where the change in force was zero. If more than two points were equal, the higher of the values was selected. This method was manually checked using pilot data and produced satisfactory results, Finally, to determine foot-strike patterns, we calculated a heel-strike index (HSI) which was the impulse due to the heel sensor divided by the total impulse for 3% to 8% of LR. Thus, high and low values indicated more posterior and more anterior foot strikes, respectively. The end of stance was determined to be 30 N based on pilot data. The middle 5 steps for both feet were used for analysis for each condition.

Statistical Analysis

We analyzed the effects of surface grade (up/down), surface angle (shallow/steep) and surface type (gravel, grass) on our dependent variables using a three-way analysis of variance (ANOVA) design. Individual interactions were analyzed for differences using a Tukey post-hoc test. Threshold for significance was set at $p<0.05$.

2.3 Results

Running on a steep downhill surface increased loading rate compared to running on a steep uphill surface ($p < 0.001$). Running surface had no effect on LR. Active peak values were not affected by any condition. Finally, heel-strike index was significantly affected by hill and grade ($p = 0.005$). For example, running downhill on the steep portion of the hill resulted in 104.2% and 85.2% greater HSI values than uphill on the soft and hard surfaces. Further, running on a steep, downhill surface resulted in HSI values that were 19.5% greater than a shallow, downhill.

There was a significant main effect of hill, surface, and grade on LR ($p < 0.0001$) and a significant main effect for hill condition (up/down) and grade (steep/shallow, all values $p < 0.0001$). LR was 32.5% less on the steep uphill section of the soft surface compared to the shallow section. Similarly, LR was a 11.7% less on the steep uphill of the hard surface. While running downhill on the soft and hard surfaces, LR was 23.3% and 23.1% greater on the steep compared to the shallow portion.

Table 2-2 Variable means reported in mean ± SD. Loading rate (BW.s-1), active Peak (BW), and heel-strike index values normalized to hard, up, shallow condition

		Normalized To HARD/Flat			**Normalized To Body Weight**		
Hill	Surf	LR	HSI	AP	LR	HSI	AP
UP SHALLOW	HARD	1.00 ± 0.08	1.00 ± 0.13	1.00 ± 0.03	43.39 ± 10.91	0.37 ± 0.10	2.53 ± 0.27
	SOFT	1.09 ± 0.12	1.18 ± 0.43	1.01 ± 0.03	46.26 ± 9.55	0.40 ± 0.09	2.56 ± 0.28
UP STEEP	HARD	0.82 ±0.09	0.79 ± 0.29	0.95 ± 0.04	34.84 ± 7.30	0.27 ± 0.77	2.44 ± 0.28
	SOFT	0.74 ± 0.10	0.73 ± 0.41	1.00 ± 0.06	31.21 ± 5.64	0.24 ± 0.09	2.39 ± 0.30
DOWN SHALLOW	HARD	1.08 ± 0.10	1.10 ± 0.24	1.00 ± 0.04	46.16 ± 11.47	0.39 ± 0.10	2.51 ± 0.24
	SOFT	1.10 ± 0.18	1.19 ± 0.34	0.99 ± 0.04	46.60 ± 11.48	0.42 ± 0.10	2.50 ± 0.25
DOWN STEEP	HARD	1.36 ± 0.19	1.51 ± 0.77	0.98 ± 0.07	57.27 ± 10.28	0.50 ± 0.09	2.48 ± 0.27
	SOFT	1.36 ± 0.27	1.47 ± 0.66	0.96 ± 0.08	57.46 ± 14.65	0.49 ± 0.10	2.42 ± 0.29

There were no main effects of hill, surface, or grade on active peak ($p = 0.08$).

There was a significant main effect of hill, surface, and grade on HSI ($p < 0.01$) and a significant interaction for hill and grade ($p < 0.0001$). When running on a steep uphill grade, participants adopted a forefoot strike pattern. HSI was 47.1% less during uphill running on the steep section of the soft surface and 61.6% less than the shallow portion of the hill. Similarly, HSI was a 27.8% less for the steep section of the hard surface. While running downhill, LR was 23.5% and 38.2% greater than the shallow section for the soft and hard surfaces.

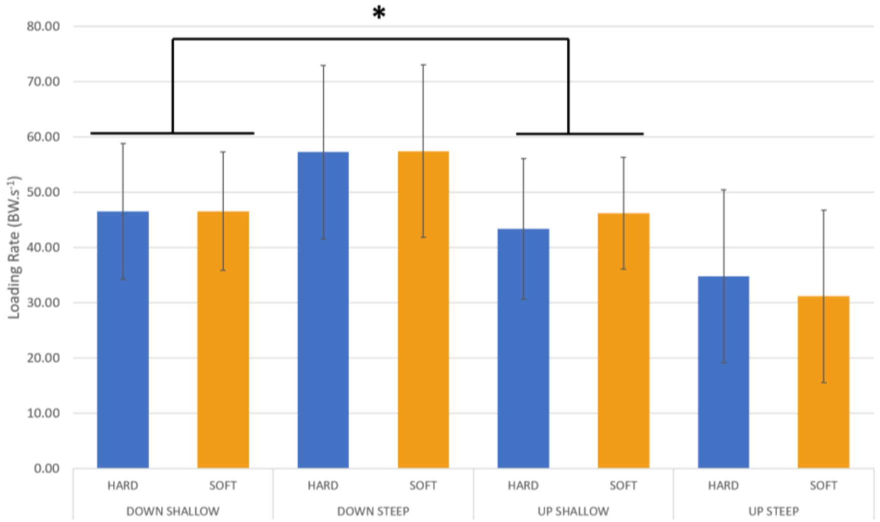

Figure 2-2 Loading Rates. Loading rates normalized to body weight on a soft and hard surface while running uphill. All hill/grade conditions were statistically significant except those marked with a "*".

2.4 Discussion

As predicted by our hypotheses, running uphill and downhill produced significantly greater and lower loading rates respectively compared to running on level ground. These results agree with laboratory studies, despite our study being conducted outside and with different technology. Gottschall and Kram (2005) reported that downhill running at -9˚ increased impact peak by 54% compared to level running. This is similar to our steep hill section which was approximately 8˚ of slope and reduced loading rate by about 21%. In addition, our data also demonstrate that runners adopt a more anterior foot-strike while running uphill (Gottschall and

Kram 2005).Our results are also similar to those of Kowalski et al. (2012) who saw no significant difference of running grade on active peak values.

Our hypothesis that LR would be less when running on a soft surface was not supported. These results are similar to Tillman et al. (2003) who did not find a difference between four different outdoor surfaces. This may due to a compensatory mechanism in order to maintain effective vertical stiffness and thus GRF values. Ferris and Farley (1998) had participants run at a fixed speed over four different surfaces and calculated effective vertical stiffness (k_{vert}) based methods by McMahon & Cheng (1990). Their results showed that runners maintained the same effective vertical stiffness on all surfaces despite encountering a range of surface stiffness properties. This phenomenon is further supported by another experiment in which a force plate was outfitted with four surface conditions with two surfaces of stiffness 21.2 kNm^{-1} (soft) and 533 kNm^{-1} (hard). They randomly ordered trials so that participants ran the length of the track on four conditions: (i) all soft, (ii) all hard, (iii) soft transition to hard, and (iv) hard transition to soft. There was not a significant effect for ground contact time, angle swept by the leg spring, peak vertical ground reaction force, vertical stiffness, or stride frequency. Runners adjusted their leg stiffness to maintain the same effective vertical stiffness between the two surfaces prior to making their first step on the new surface, resulting in similar kinetics and kinematics at the surface transition (Daniel et al. 1999). These studies suggest that there may be no effect of surface on kinetic variables due to kinematic changes by the runner.

Our results are in contrast to those produced by Tessutti et al. (2010, 2012) who used pressure insoles to look at outdoor surface effects on running. Their results showed an attenuation of plantar pressure while running on a natural grass surface in two different studies. Results of our study and pressure insole studies can be attributed to large differences in sample size, shoe condition, running age/experience level of participants, and testing conditions. The current study permitted particpants to wear their own footwear, resulting in a variety of footwear types, while both Tessutti et al. and Tillman et al. (2002) imposed a shoe condition. We are unsure whether or not prescribing a shoe condition would have resulted in significantly different data. Tillman et al. did not provide data on participant running load and experience, however, Tessutti et al. had a slightly higher mean participant age than us (35.7 vs. 22.7), and a slightly lower weekly running volume (35.7 km/wk vs. 53.5 km/wk). In particular, it should be noted that running speed varied between each study. The current study and Tillman et al. permitted participants to self-select speed (we also imposed a cadence) while Tessutti et al. imposed a speed of 12 km/hr. Thus, differences in methods between four similar running surface studies may influence conclusions drawn from each study.

Differences in running speed influence loading rate independent of other variables, making comparisons between studies that use different imposed speeds difficult. A study of the influence of walking and running at varying speeds showed a linear increase in loading rate along with running speed (Keller et al. 1996). Similarly, Kulmala et al. (2018) found that impact loading increased more while running at a fast speed (14.5 km/hr) compared to a slow speed (10 km/hr). Further, it is unknown how imposing a speed in an outdoor running setting affects running kinetics and kinematics.

Examination of individual data across conditions shows that there may be responders and non-responders to surface conditions. For example, in figure 2-3, mean LR data for each subject is shown and for some participants (LR_4, LR_5) mean LR was lower on the DOWN STEEP SOFT condition compared to the DOWN STEEP HARD condition while others (LR_1, LR_3) showed almost no change and the remainder of the participants (LR_2, LR_6, LR_7) had an increased LR on the DOWN STEEP SOFT condition. Those who had an increased LR on the DOWN STEEP SOFT condition seem to generally be more advanced runners (greater weekly running load, and average training pace). Active peak trends (Figure 2-4) also varied between participants however, not as drastically. Results for HSI (Figure 2-5) are also highly variable between participants. For example, when looking at HSI_5, it is clear that there were drastic alterations in foot-strike pattern (FSP) from one condition to another however HSI_1 made much more minimal alterations in their FSP between conditions though the only training difference between these participants is running volume (28.2 km/wk vs 48.3 km/wk).

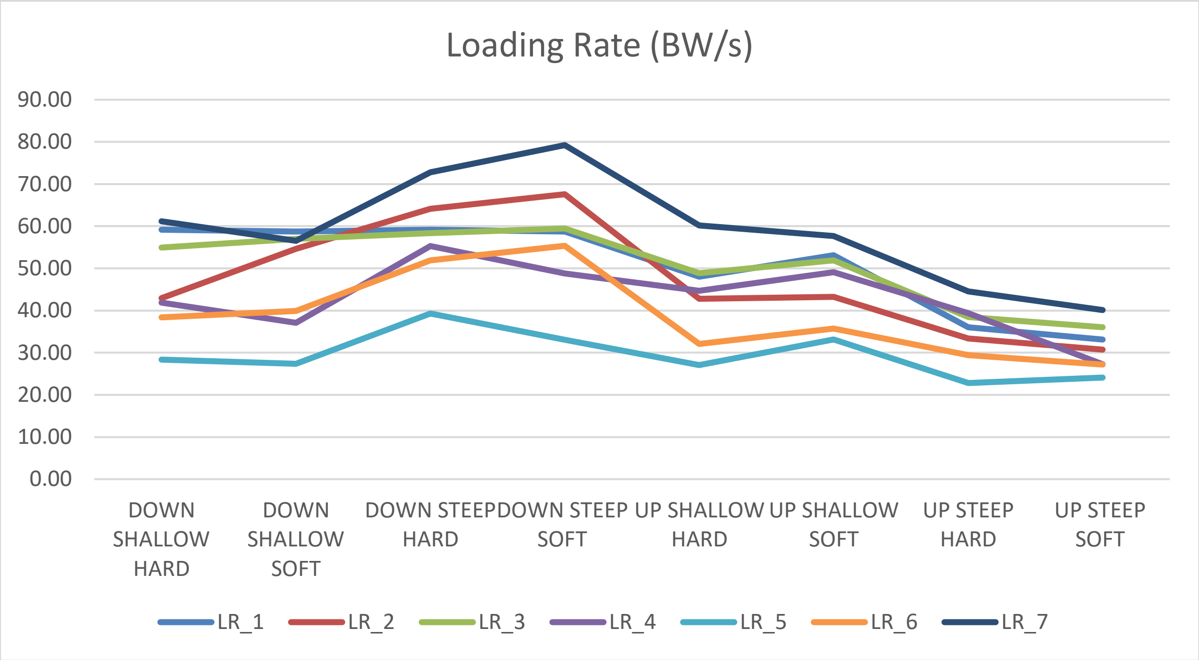

Figure 2-3 Individual participant loading rates. Loading rate (BW/s) for each participant per hill segment. For each participant, loading rate was higher while running uphill compared to running downhill. The effect of surface varied for each participant.

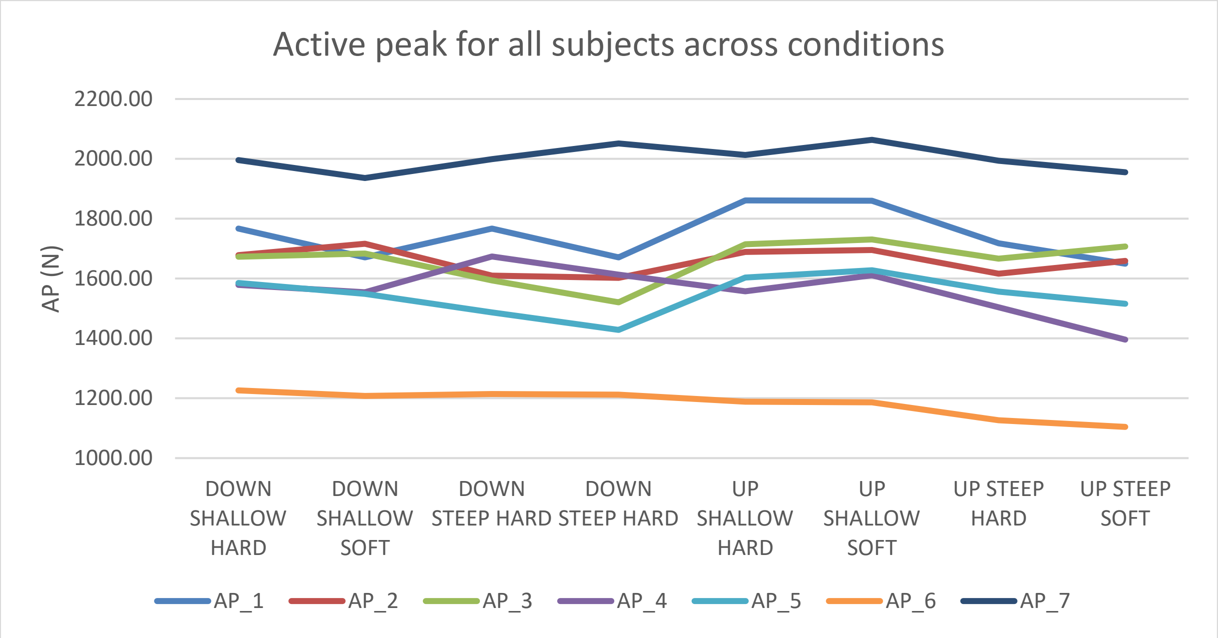

Figure 2-4 Individual participant active peaks. Active peak (AP) normalized to BW for all subjects across all conditions

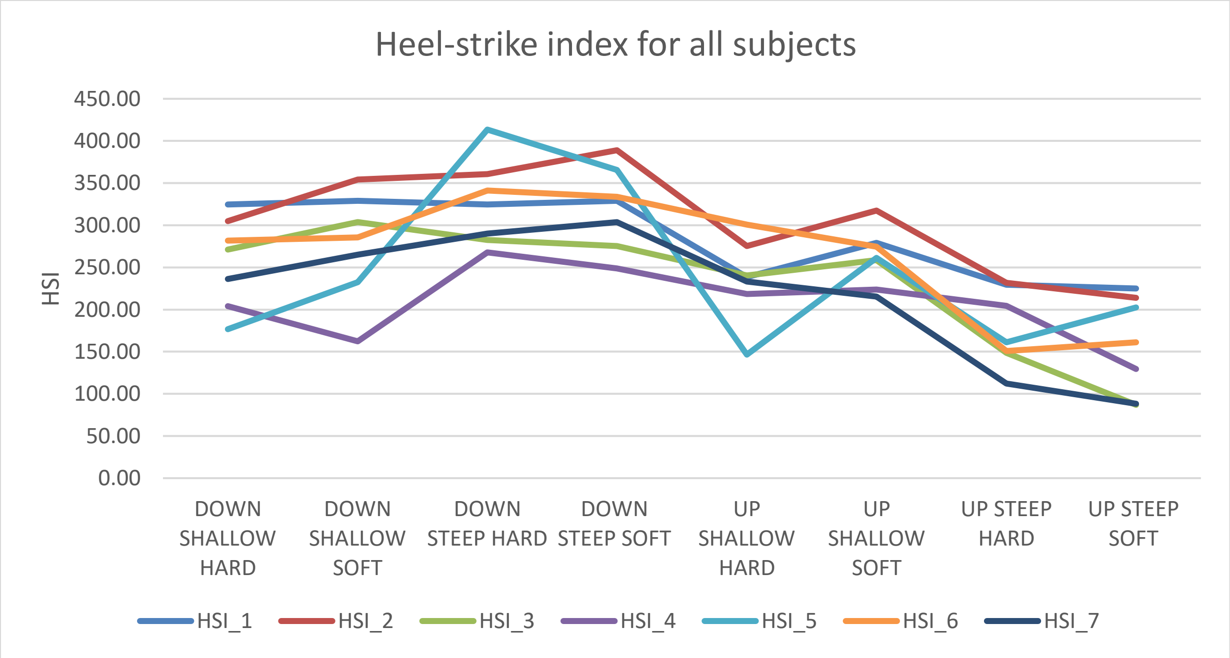

Figure 2-5 Individual participant heel-strike index. Heel-strike index (HSI) normalized to body weight for all participants per hill segment. There were no significant effects for HSI

Limitations and Future Directions

A major limitation of this study is the small sample size which was restricted due to technical difficulties with the insoles as well as difficulty scheduling data collections due to inclement weather and area construction. Over the duration of our study, the weather influenced the surface stiffness which may have caused greater variability. For this study we chose to impose a cadence as opposed to letting participants self-select their own speed as Tilman et al. (2003) or imposing a speed as in previous outdoor insoles studies (Tessutti et al. 2010, 2012). The decision to not use timing gates was for logistical reasons as our testing site was much longer (200 m vs. 40m) than that used by Tessutti et al. (2010, 2012). We dictated cadence in order to standardize a kinematic metric between participants but a limitation to this approach is that that manipulating cadence from preferred cadence has significant effects on loading (Wellenkotter et al. 2014). Furthermore, during testing, we observed that some participants reduced stride length when cadence was imposed. Lastly, running speed is also known to influence running kinetics and kinematics and thus, not being able to control speed was a major limitation to this study (Agresta et al. 2018).

To summarize, future studies investigating surface effects should carefully screen participants prior to experimentation in order to create a homogeneous sample of foot-strike patterns as this variable has been shown to significantly influence kinetics and kinematics (Breine et al. 2017; Lieberman et al. 2010). As previously discussed, running speed also influences these measures, so a well-designed study will include a variety of speeds previously used in surface biomechanics studies (3 m/s, 3.3 m/s, 4.5 m/s) as well as permit participants to self-select speed. Finally, shoe properties have been shown to influence GRF and thus the sample should all be accustomed to wearing traditional running shoes (moderate cushioning, heel-toe drop) so that a standardized footwear can be used (Kulmala et al. 2018; Willy and Davis 2014).

Chapter 3

Shoe cushioning properties and grade alter loading rate and foot-strike patterns in recreational runners

3.1 Introduction

Around 79% of runners experience an injury annually (Hreljac et al. 2000). The initial response of the shoe industry was to create shoes with more cushioning, theorizing that this would reduce the forces on the lower extremity musculoskeletal system (Kulmala et al. 2018). This theory progressed to maximal cushioning shoes seen today with up to 30mm of foam. In contrast, the barefoot or minimal cushion theory claims that running without extra cushion leads to a forefoot strike pattern previously shown to reduce loading rate and impact peak value (Lieberman et al. 2010). Medical professionals have yet to reach a consensus as to which, if either, of these arguments is valid (Blake and Mcclanahan 2018).

Loading rate (LR), active peak (AP), and heel-strike index (HSI) are three variables relating ground reaction force (GRF) to injury risk. First, loading rate is the rate of rise of the vertical GRF following contact (Cavanagh, 1990). Hreljac et al. (2000) reported that LR is correlated to injury by evaluating a group of runners who were injury free throughout their running career and a group of runners who had previously sustained a running-related injury. Second, active peak is the primary vertical GRF peak that occurs during mid-stance. This vertical force has been shown to be increased by 7.8% in runners with patellofemoral pain compared to runners who are injury-free (Messier et al. 1991). Third, heel strike index is a variable used to assess foot strike pattern. When runners contact the ground, they either land with their rearfoot, midfoot, or forefoot. Lieberman et al. (2010) argued that being accustomed to running in cushioned footwear promotes a rearfoot strike which is associated with the presence of an impact peak in the vertical GRF along with significantly higher rates of loading.

Another factor known to influence running GRF is grade. Gottschall and Kram (2005) demonstrated that compared to level running, impact peak was 54% greater during -9˚ downhill running and 22% less during 9˚ uphill running. Further, as participants encountered varying levels of grade, they adapted their foot-strike accordingly with a rearfoot strike at -9˚, -6˚, -3˚, and +3˚ and shifting to midfoot strike at +6˚ and +9˚. Loading rate was also 20% greater during 6˚ downhill running and 23% less during uphill running at the same grade. Therefore, a study investigating GRF should include a variety of grades.

Previous studies have not provided a clear consensus on how maximal (MAX) or minimal (MIN) cushion shoes relate to injury risk (Arthur and Aminaka 2018; Baltich, Maurer, and Nigg 2015; Sun et al. 2018; Sinclair et al. 2016; Kulmala et al. 2018; Hannigan and Pollard 2019; Lussiana et al. 2015). Sinclair et al. (2016) documented that instantaneous loading rates and peak tibial accelerations were 115.7% and 19.4% greater in MIN shoes compared to MAX and 140.0% and 41.8% greater than traditional cushioning shoes when running at a speed of 4.0 m/s. Further, Lussiana et al. (2015) reported that level treadmill running at 10 km/hr in minimal shoes (Merrell Trail Glove) resulted in a greater maximal force and leg stiffness at contact compared to traditional running shoes (Salomon Speedcross 2). Similarly, when compared to TRAD shoes (Nike Pegasus), MIN (Nike Free) shoes produced 8.3% greater vertical impact peaks and 62.0% higher vertical loading rates (Willy and Davis 2014). The results should be carefully interpreted however as their MIN condition shoe still had a fair amount of cushion with a 21mm heel height and a 17 mm toe height, and a 4mm heel-toe drop. In contrast, a similar study of shoes of varying midsole hardness and found that the softest shoe had 3.7% and 9.9% higher vertical impact peaks than the medium and hard midsole shoes while heel-toe running at 3.33 m/s (Baltich et al. 2015). When compared to traditional (TRAD) shoes, MAX shoes (HOKA One One Conquest) have also been shown increase leg stiffness at landing (5.9%) and amplify impact loading (10.4%)

(Kulmala et al. 2018). Hannigan et al. (2019) randomized participants into either a TRAD (New Balance 880v2) or a MAX (HOKA One One Bondi 5) running shoe group and tested them before and after a 6-week acclimatization period. They found that running in MAX shoes resulted in a 25.0% greater LR and 17.2% greater impact peak (IP).

The current study aimed to compare ground reaction force (GRF) variables associated with injury risk between two cushions across varying grades. We hypothesized that there would be a significantly greater LR while running in MIN shoes compared to MAX shoes. Further, we hypothesized that in both shoes, LR would be greater during downhill running (-3˚) and less during uphill (3˚ and 6˚) compared to the level. We anticipated no change in AP magnitude in response to any conditions. Finally, we expected to see a decrease in HSI for running uphill and an increase in HSI while running downhill and no change in HSI in response to shoe condition.

3.2 Methods

Participants

Eighteen recreational runners (10 women, 8 men; age: 26.4 ± 5.9 yr; height: 172 .2 ± 0.08 cm; body mass: 68.4 ± 12.1 kg; weekly running distance: 46.7 ± 25.5 km) provided informed consent which was approved by the Institutional Review Board at the Pennsylvania State University. Participants typically ran in TRAD (heel-toe drop, moderate amount of added cushion) and had no previous experience running in either minimalist or maximalist cushioning shoes. All participants were injury free three months preceding the study.

Protocol

Following consent, participants were outfitted with a Garmin heart rate monitor chest strap transmitter. They stood quietly for 5 minutes for resting heart rate (HR) collection and then completed a 5-minute running warm-up at 0˚ in their typical running shoes at a self-selected speed. Once they completed the warm-up, participants rested while researchers gave them one of the shoe conditions (MIN or MAX) in a randomized order and placed force-measuring insoles into the prescribed shoes (Novel Loadsol®, Munich, Germany). Data were collected at 100 Hz. For this study we used HOKA One Arahi 2 as our MAX shoes (heel height: 33.9-36.6 mm; forefoot height: 26.8-30.1 mm; weight 7.9 – 9.6 oz) and Merrell Vapor Glove 4 (heel height: 6.5 mm; forefoot height: 6.5 mm; weight 6 oz) for our MIN condition. Insoles were calibrated and once the participants returned to resting HR (± 10%), the experimental protocol began. The researcher held a tablet (Apple, iPad) to collect the insole data via Bluetooth.

Participants ran for 3 minutes at each of the following grades on a treadmill: 0°, 3°, 6°, -3° for each shoe condition (MIN and MAX) in a randomized order. Treadmill speed was fixed at 3 m/s with 90 seconds of rest between each grade. After the first shoe condition, participants completed the same protocol with the other shoe after the insoles were calibrated and HR returned to ±10% resting value.

Figure 3-1 Experimental footwear. (A = minimal (MIN); B = maximal (MAX))

Processing

All data were processed in MATLAB (Version 2018b) using a custom script. Analysis was completed on both left and right steps for the middle 50 steps of each condition. All data was normalized to the 0˚, MIN condition. A 25N threshold determined the beginning of stance.

Analysis

For each step, the following variables were calculated: (1) loading rate (LR), (2) active peak (AP) and (3) heel strike index (HSI), or the heel contribution to the total loading. Based upon the Novel recommendations, we defined LR from 3 to 15% of stance. This was based on the manufacturer's methods as well as pilot data in order to capture 20-80% of the rise in force between contact and impact peak. In addition, we could not calculate LR based solely on an impact peak because this was often not present in our data. AP values were determined by finding the point at which the ground reaction force returned to 25N and stepping backward along the force curve to the point where the change in force was zero. If there were multiple sets of consecutive forces, the highest value was chosen. This method was accepted as valid by manual inspection of pilot data. Finally, to determine foot-strike patterns, we calculated HSI which was the impulse due to the heel sensor divided by the total impulse for 3% to 8% of LR. Thus, high and low values indicated more posterior and more anterior foot strikes, respectively. This calculation was based on pilot data as we were unable to use motion capture to capture foot position. The end of stance was set at 30N and was also based on pilot data.

Figure 3-2 Force-measuring insoles and sensor regions

Statistical Analysis

We evaluated the effects of grade (-3˚, 0˚, 3˚, and 6˚) and shoe type (MIN, MAX) with a two-way repeated measure analysis of variance (ANOVA) design. Individual differences were analyzed using a Tukey's post-hoc test. Threshold for significance was defined as $p<0.05$.

3.3 Results

In contrast to our hypothesis, we found a significant difference in loading rate and heel-strike index between shoe types. Our hypothesis that loading rate would increase while running downhill and decrease while running uphill was confirmed. We reject our hypothesis that active peak would not be affected by any condition as there was a slight effect of hill and grade. Finally, we reject our hypothesis that HSI would respond to hill condition but not shoe. HSI varied significantly between shoe conditions but there was no overall effect of grade.

There were significant main effects for grade ($p < 0.001$) and shoe condition ($p < 0.001$) on loading rate without a significant interaction. Tukey's post hoc test revealed significant differences in LR between grades -3˚ and 3˚ ($p = 0.001$), -6˚ and 6˚ ($p < 0.01$), and 0˚ and 6˚ ($p < 0.001$) independent of shoe type. MIN and MAX shoes were significantly different from each other at all grades. LR was 16.1%, 18.7%, 14.1%, and 18.8% greater in MAX shoes at -3˚ ($p < 0.001$), 0˚ ($p < 0.001$), 3˚ ($p = 0.001$), and 6˚ ($p < 0.001$), respectively. To add, loading rate in MAX shoes was 14.4% greater at -3˚ compared to 3˚ ($p < 0.001$), 21.0% greater at -3˚ compared to 6˚ ($p < 0.001$), and 32.7% greater at 0˚ compared to 6˚ ($p = 0.01$). In MIN shoes, there was a 23.8% difference between grades -3˚ and 6˚ ($p < 0.001$).

There was a significant main effect of grade on active peak ($p = 0.01$). Post-hoc analyses revealed that only -3˚ and 6˚ were significantly different without taking into consideration shoe-type ($p < 0.05$). While running in MIN shoes, active peak was 4.0% greater for -3˚ compared to 6˚ ($p < 0.05$).

There were significant main effects of grade ($p < 0.05$) and shoe condition ($p < 0.001$) on heel-strike index. Post-hoc analysis revealed no significant effect of grade without taking shoe condition into consideration. MIN shoes resulted in HSI values that were 19.7% greater at -3˚ compared to 6˚ ($p < 0.05$). MIN and MAX shoes were significantly different from each other for HSI at -3˚, 0˚ ($p < 0.001$), 3˚, and 6˚ by 46.2%, 65.7%, and 80.0%, and 56.3% (all values, $p < 0.001$).

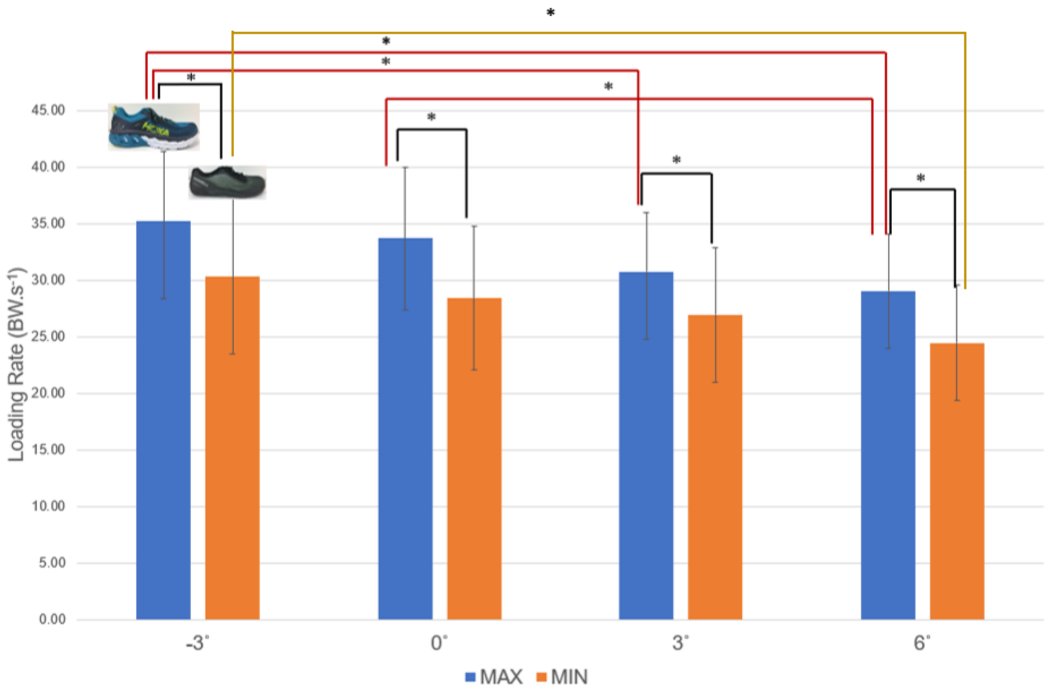

Figure 3-3 Mean loading rates. Loading rates in each shoe across all grades normalized to body weight. Significance ($p < 0.05$) indicated by '*'. Between-shoe comparisons are represented by a black line. Within MAX shoe comparisons are represented with a red line. Within MIN shoe comparisons are represented with a gold line

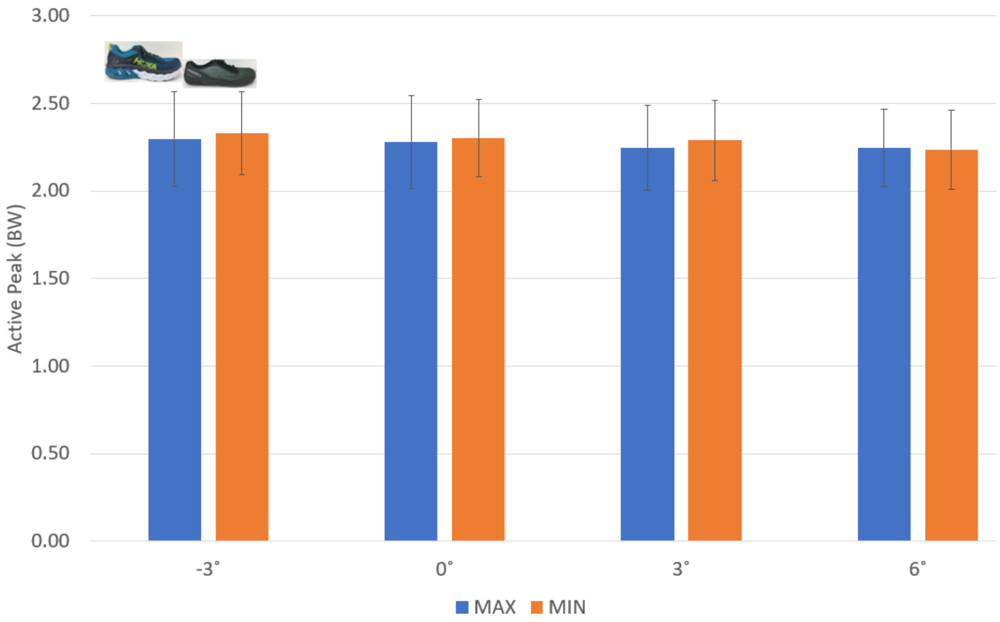

Figure 3-4 Mean active peak values. Active peak rates in each shoe across all grades normalized to body weight (BW). Significance ($p < 0.05$) indicated by '*'. Within MIN shoe comparisons are represented with a gold line

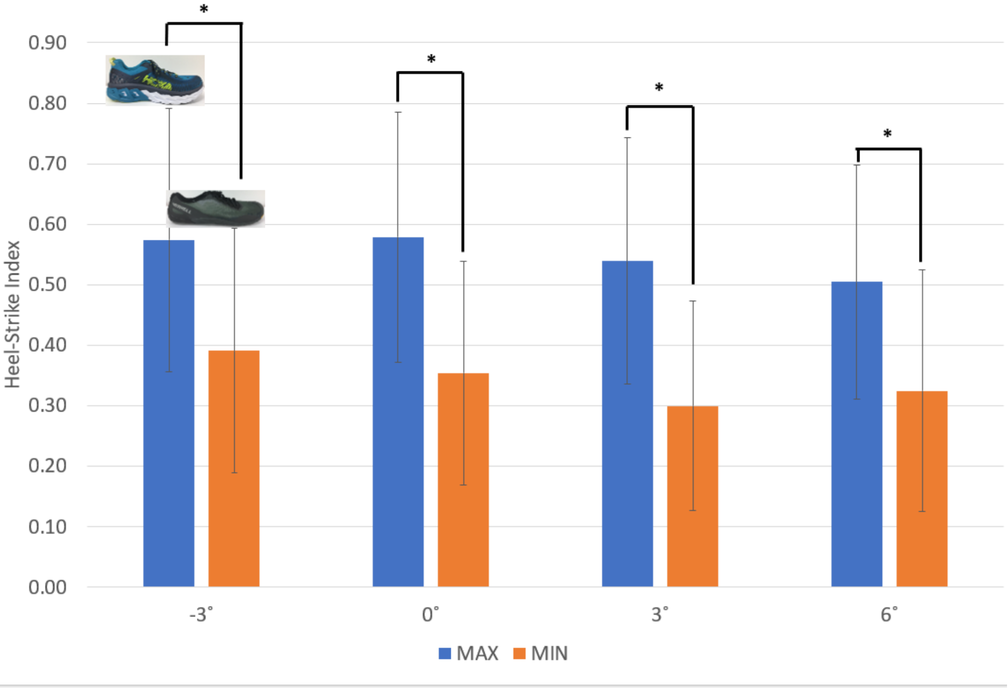

Figure 3-5 Mean heel-strike index values. Mean heel-strike index values (higher numbers indicate more posterior foot-strike pattern) in each shoe across all grades normalized to body weight. Significance ($p < 0.05$) indicated by '*'. Between-shoe differences are represented by a black line.

3.4 Discussion

As predicted, there was a significant effect of grade and shoe on LR however, our prediction that grade would significantly impact HSI was not supported. Interestingly, there was a significant effect of shoe on HSI meaning that participants landed with a more of a posterior foot-strike in MAX shoes and a more anterior foot-strike in MIN shoes.

In agreement with our hypothesis, LR and HSI were significantly larger in MAX compared to MIN shoes at all grades. This is potentially due to the cushioning properties of the shoes causing participants to alter their foot-strike as individuals shifted toward heel-strike in

MAX shoes and forefoot-strike in MIN shoes. These results are in agreement with a recently published study which showed higher impact peak and LR values in maximal cushioning shoes in comparison to traditional running shoes, even after a 6-week acclimatization period (Hannigan and Pollard 2019). Similarly, Kulmala et al. (2018) found that compared to running in a traditional motion control shoe, running in maximal cushioning shoes resulted in 6.4% higher impact peak values, possibly due to a stiffer leg at foot-ground contact. Though significant, changes in loading may have less to do with footwear and more to do with foot-strike pattern changes. Runners adopted more of a heel-strike in the MAX shoe condition and a more forefoot-strike style in MIN shoes. While the shoe may have caused participants to inadvertently modulate their running style, foot strike may be more influential on LR than shoe condition (cushioned shoes vs. barefoot) based on previous studies. Therefore, in terms of injury risk, perhaps runners should pay closer attention to their foot-strike style rather than shoes in order to reduce impact on the lower extremity.

Our hypothesis that grade would not have a significant effect on AP was not supported as grade significantly affected active peak at grades -3˚ and 6˚, both overall and in MIN shoes. Gottschall and Kram (2005) found no significant effects of grade on active peak values during uphill and downhill treadmill running. Further, changes in active peak could be due to large differences in the way participants contacted the ground with their foot across different conditions in this study as foot-strike pattern has been shown to influence this variable (Breine et al. 2017).

Though GRFs are generally unchanged by surface compliance, it seems that shoe compliance does have an effect on GRF (Lussiana et al. 2015; Vercruyssen et al. 2016). Previously, it has been shown that when runners transition from a hard to a soft, or a soft to a hard surface, they maintain the same effective vertical stiffness and GRF values by changing the stiffness of their leg (Ferris et al. 1998). In contrast, Lussiana et al. (2015) found that compared to running in traditional shoes, running in minimal shoes caused no significant changes in leg stiffness and an increase in maximal vertical force. This difference in kinetic response to surface and shoe may also explain why we found a significant difference of grade on HSI on varying surfaces but not in different shoe types. Thus, running shoes may have a greater effect on loading and running kinematics than running surface and this relationship should be examined directly.

In terms of impact, our data show that MAX shoes may increase injury risk and promote a posterior foot-strike pattern during treadmill running. In contrast to our findings, a study which utilized three different footwear conditions (MIN, MAX, and TRAD) reported that minimal shoes had higher instantaneous loading rates and tibial accelerations compared to both maximal and traditional footwear conditions (Sinclair 2014). The difference in results could be due to testing conditions (over ground + force plate compared to treadmill +insole), running speed (4.0 m/s vs 3.0 m/s), or choice of minimalist footwear (Vibram Five Fingers Vs. Merrell Vapor Glove). Arthur and Aminaka (2018) found no significant effect of highly cushioned shoes on impact peak, LR, AP, contact time, or velocity when runners self-selected running speed over a runway with an embedded force platform. They also reported that highly cushioned shoes resulted in a more anterior strike index compared to traditional shoes. These differences could be due to running environment or shoes (traditional shoes vs. minimal shoes).

Finally, when participants ran in MIN footwear, they adopted a more anterior foot-strike and had reduced vertical LR compared to our MAX footwear. Willy and Davis (2014) found somewhat counterintuitive results in their study which compared TRAD footwear to MIN footwear and resulted in a more dorsiflexed foot at ground contact in MIN shoes. This discrepancy may be due to differences in cushioning between their MIN condition as their shoe does have a small amount of foam cushion (Nike Free vs. Merrell Vapor Glove).

The current study was limited to collecting only kinetic data and future studies should also include kinematic measurements in order to better understand the influence of shoe-type on running biomechanics. A homogeneous samples of runners with the same foot-strike patterns would also reduce variability (Breine et al. 2017; Lieberman et al. 2010). To add, we only compared maximal vs. minimal cushioning shoes but comparison to a traditional shoe condition would permit a more comprehensive analysis. Another limitation to this study was that we only tested one imposed speed at all grades which may limit conclusions as running speed is known to influence GRF (Keller et al. 1996; Kulmala et al. 2018). To summarize, future studies should include kinematic data, a tradition cushion shoe, and a variety of speeds.

In conclusion, running in maximal cushioning shoes resulted in higher LR and HSI values compared to running in minimal shoes which may increase the risk of running related injuries. These results may be due to changes in foot-strike pattern in this type of footwear due to different amounts of cushioning. Further, lower LR values were present while running at an incline compared to running downhill which may also reduce injury risk linked to LR.

Chapter 4

Conclusion

This work showed that shoe stiffness and grade, but not surface influenced ground reaction forces in recreational runners. First, our results suggest that running surface has no significant effect on loading rate, active peak, or foot-strike pattern and thus, may not be a valid means of reducing injury risk. Second, loading rate and heel-strike index was greater in maximal shoes compared to minimal potentially leading to higher injury risk in the lower extremity. Finally, loading rate was lower during uphill running than either level or downhill running.

Running participation continues to grow however, rates of injury are still very high (Hreljac et al. 2000). This is not surprising given that runners experience ground reaction forces (GRF) up to 3 times their BW with each step. High loading rate and rearfoot-strike have previously been associated with higher risk for a running-related overuse injury (Hreljac et al. 2000). The current study provides evidence that softer outdoor surfaces may not significantly reduce impact. This is potentially due to runners modulating their leg stiffness in order to maintain constant GRF and vertical stiffness.

Hill condition and grade modified heel-strike index during hill running indicating that individuals adopted a more anterior foot-strike when running on a steep incline and a posterior foot-strike on a steep decline. Together, these results confirm previous findings on hill running despite differences in methodology (ramp, outdoor, treadmill).

Since the 1970’s, running shoes have often been proposed as the solution to running injuries. Many people choose to run in maximal cushioning shoes reasoning that added cushion will reduce loads to the lower extremity while others think that shoes with minimal cushioning that mimic barefoot running will result in a forefoot-strike pattern and reduced GRF. This study supports the latter theory as our maximal cushioning shoes resulted in increased loading rates and heel-strike index values compared to our minimal cushioning footwear. We can speculate that added cushioning limits proprioception and permits runners to land on their heels which leads to a rapid rate of rise in the forces on the lower extremities. The idea that a transition to a forefoot strike pattern in minimal cushioning shoes is confirmed by this study however, this was in comparison to maximal cushioning shoes and more studies should investigate how these forces compare to running in traditional cushioning shoes.

Several limitations arise when conducting biomechanics studies such as this thesis. First, ground reaction forces are affected by a variety of factors. In this study, we included grade as this is known to affect GRF, however we were unable to control for speed and habitual foot-strike pattern. Ground reaction forces have been shown to increase linearly with speed (Agresta et al. 2018) and loading rates and the presence of an impact transient peak increase with a more pronounced rearfoot strike (Lieberman et al. 2010). Therefore, conclusions drawn from our results are limited as we only tested a self-selected speed and imposed cadence and an imposed speed for our studies. Additionally, we did not pre-screen our participants for foot-strike pattern (FSP) and thus a heterogeneous sample of FSPs limits conclusions that may be drawn.

Future studies on surface should be done on shorter outdoor segments so that timing gates can be used in order to collect data at a variety of running speeds and grades. In addition, an attempt should be made to recruit homogenous samples that represent different populations. For example, samples that should be represented include elite runners, recreational runners, competitive recreational runners, and runners accustomed to different distances (i.e. 5k, marathon, ultra-distance). Further, foot-strike patterns should be controlled to allow better recommendations for each type of FSP. Finally, longitudinal studies investigating the long-term effects of each of these variables on incidence of injury should be conducted as current studies are largely cross-sectional. An increased understanding of the influence these variables on ground reaction forces and will permit more informed recommendations to reduce running-related overuse injury risk.

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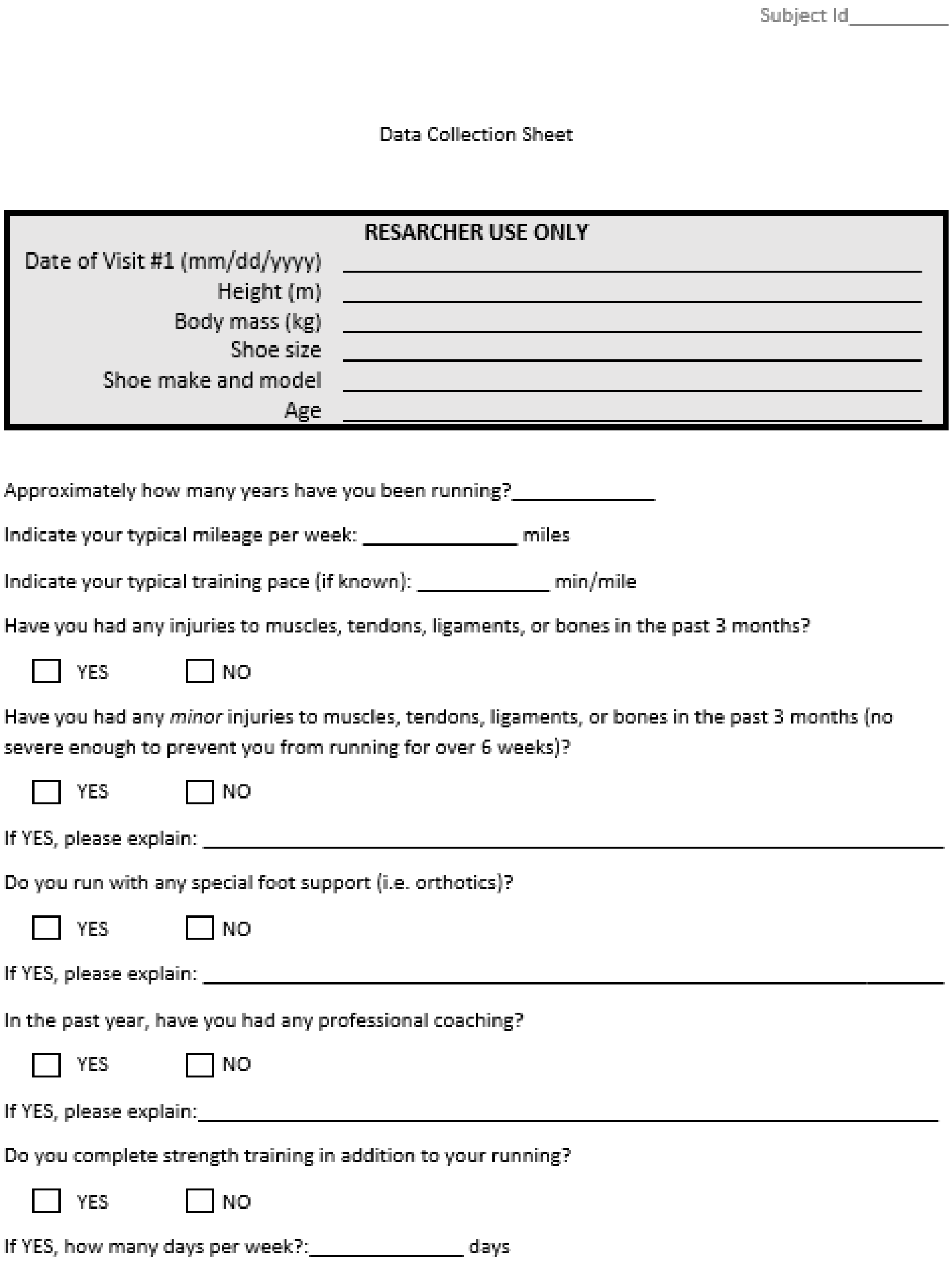
Appendix A

Study 2 Variable Means and Standard Deviations

Grade	Shoe	LR ($BW.s^{-1}$)	AP (BW)	HSI (Normalized to Min/0°)
-3°	MAX	35.18 ± 6.16	2.30 ± 0.27	0.22 ±0.14
	MIN	30.29 ± 6.84	2.33 ± 0.24	0.04 ± 0.08
0°	MAX	33.72 ± 6.22	2.88 ± 0.27	0.22 ± 0.15
	MIN	28.41 ± 6.33	2.10 ± 0.22	0.00 ± 0.00
3°	MAX	30.75 ± 5.18	2.25 ± 0.24	0.18 ± 0.14
	MIN	26.95 ± 5.92	2.29 ± 0.23	-0.05 ± 0.13
6°	MAX	29.07 ± 5.02	2.25 ± 0.22	0.15 ± 0.13
	MIN	24.46 ± 5.07	2.24 ± 0.23	-0.03 ± 0.80

Appendix B

Participant running history questionnaire



Subject Id__________

Data Collection Sheet

RESARCHER USE ONLY

Date of Visit #1 (mm/dd/yyyy) ____________________

Height (m) ____________________

Body mass (kg) ____________________

Shoe size ____________________

Shoe make and model ____________________

Age ____________________

Approximately how many years have you been running?______________

Indicate your typical mileage per week: _______________ miles

Indicate your typical training pace (if known): _____________ min/mile

Have you had any injuries to muscles, tendons, ligaments, or bones in the past 3 months?

☐ YES ☐ NO

Have you had any *minor* injuries to muscles, tendons, ligaments, or bones in the past 3 months (no severe enough to prevent you from running for over 6 weeks)?

☐ YES ☐ NO

If YES, please explain: ____

Do you run with any special foot support (i.e. orthotics)?

☐ YES ☐ NO

If YES, please explain: ____

In the past year, have you had any professional coaching?

☐ YES ☐ NO

If YES, please explain:____

Do you complete strength training in addition to your running?

☐ YES ☐ NO

If YES, how many days per week?:_______________ days

Appendix C

Outdoor Running Surface Diagram

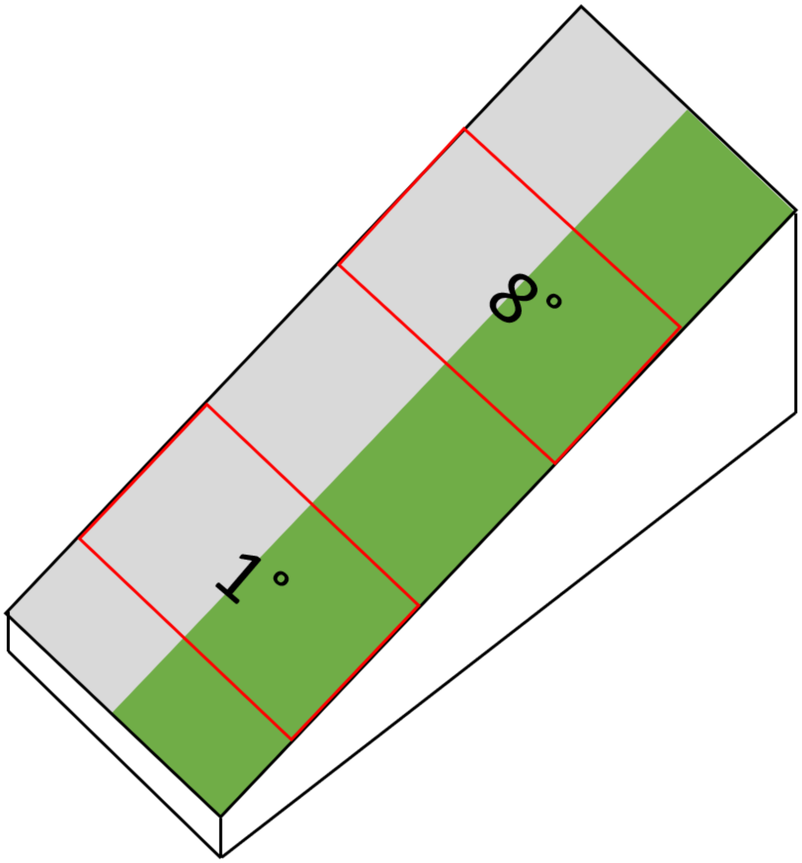


Figure A-1 Outdoor running surfaces. Concrete surface (grey) adjacent to grass surface (green) and matched for grade. Five steps were collected per foot in the 1˚ region of the hill as well as the 8˚ region of the hill for both uphill and downhill running. One trial consisted of running from one end to the other (either up or down) and stopping.