The effects of an irregular surface on contact geometry, shock attenuation and metabolic cost during running

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The effects of an irregular surface on contact geometry, shock attenuation and metabolic cost during running

by

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ABSTRACT

With the popularity of non-traditional and off-road race events on the rise, the number of runners encountering trail surfaces has undergone a marked increase in recent years. Despite the growing popularity of trail and off-road running, little research has been done to investigate the effects of running on irregular surfaces. PURPOSE: The purpose was to investigate the kinematic and metabolic effects of running on an irregular surface. We hypothesized that the irregular surface would cause runners to reduce frontal plane foot inversion and increase knee flexion at contact, increasing the metabolic cost of running and shock attenuation. We also examined how altering the frontal plane foot angle at contact using real-time feedback would affect these other variables. METHODS: Sixteen participants completed three running bouts lasting 5-7 minutes each on an irregular surface (IS) treadmill created by attaching wooden slats, on a traditional smooth surface (SS) treadmill, and on SS while receiving visual feedback of the frontal plane foot angle at contact (SSF) with a goal of matching IS foot angle on SS. Participants were outfitted with reflective markers on the pelvis and lower limb and accelerometers on the distal anteromedial tibia and frontal bone of the forehead. For a portion of each condition, participants breathed through a mouthpiece for the measurement of the rate of oxygen consumption (VO₂). Statistical analysis was completed using a one-way repeated measures ANOVA with a Sidak post hoc correction to set α=0.0127. RESULTS: Frontal plane foot angle increased by 40% from IS to SS (IS: 8.4±4.09°, SS: 11.8±4.52°, p<0.0001). Knee flexion angle decreased by 33% from IS to SS (IS: 9.23±4.88°, SS: 6.22±5.03°, p<0.0001). Rate of oxygen consumption decreased by 10% from IS to SS (IS: 37.9±5.68 ml·kg⁻¹·min⁻¹, SS: 34.1±5.07 ml·kg⁻¹·min⁻¹, p<0.0001). Frontal plane foot
angle decreased by 14% from SS to SSF (SS: 11.8±4.52°, SSF: 10.1±4.42°, p=0.027) but did not result in significant changes in any variables. There were no significant differences in shock attenuation between any conditions (IS: -9.8±2.26 dB, SS: -9.5±3.12 dB, SSF: -9.9±2.62 dB, p=0.671). CONCLUSION: Running with less inversion at contact on the irregular surface may be an attempt by runners to reduce the perceived potential of an inversion ankle sprain. Muscles of the knee and ankle can absorb impact shock but their effectiveness depends on the angle at contact. As a partial compensation for the decreased foot angle at contact, runners increased knee flexion. This maintained shock attenuation but rate of oxygen consumption was increased. Altering the foot angle at contact using feedback on the SS did result in increased knee angle at contact, but did not change shock attenuation or metabolic cost.
CHAPTER 1. INTRODUCTION

The increase in popularity of running as both a competitive sport and form of recreational exercise has led to the emergence of a variety of “new” race events in addition to traditional road races. According to a Non-Traditional Running Events Special Report released by Running USA, there were nearly 4 million finishers of non-traditional events in 2013, which equates to an increase of 40% from the number of finishers in 2009. In the same report, it is stated that there were over 35 non-traditional or themed events in 2013, including mud, color, foam, electric, zombie and ugly sweater runs (Running USA, 2014). For athletes seeking a greater challenge and more competition, extreme endurance races such as ultramarathons, in which runners cover distances longer than the typical marathon (26.2 miles) over the course of several hours or even days, are becoming increasingly popular (Vernillo et al., 2014). As can be expected, a wide range of surfaces are encountered during these events, including paved or gravel roads, wooded trails, or rocky mountain terrain. Because many of these races take place at least in part on off-road or trail like surfaces, the popularity of trail running has undergone a marked increase in recent years (Hoffman & Wegelin, 2009).

It has long been recognized that the requirements of footwear change when moving from traditional paved road surfaces to more natural dirt trails, in which runners encounter irregular surfaces in the form of tree roots, rocks, soft sand and other naturally occurring obstacles. It was noted by Seung et al. (2012) that several studies have reported hiking on hard, irregular surfaces as a potential cause of foot injury, and footwear designed specifically for irregular surfaces are recommended for use on natural trails (Hettinga, Stefanyshyn, Fairbairn & Worobets, 2005). Despite the increasing popularity of trail running among both recreational and competitive elite runners, there are few projects published in the literature investigating the biomechanical effects
of trail running or running on simulated trail surfaces in the laboratory. A study by Wannop, Worobets, Ruiz and Stefanyshyn (2014) focused on the effect of footwear traction during level, uphill and cross slope walking and concluded that the risk of suffering an injury while hiking may be more strongly related to debris such as loose rock and dirt underfoot rather than the quality of traction provided by footwear. However, because all surfaces used in this study were smooth, further research is required to support this claim. Seung et al. (2010) similarly used a smooth, flat surface to compare biomechanical variables of participants while wearing a traditional shoe and two different trail shoe models and found that the traditional shoes reduced lower muscle activity during level walking compared to the trail shoe, but again, the lack of an irregular surface makes it difficult to quantify the significance of these results.

Multiple studies (Karamanidis, Arampatzis & Bruggemann, 2006; Hettinga, et al., 2005; Ferris, Liang & Farley, 1998; Ferris, Louie & Farley, 1998) have investigated the effects of running on surfaces of different thickness and hardness. Dixon, Collop and Batt (2000) and Creagh, Reilly and Lees (1998) used varied surfaces including asphalt, a rubber modified bituminous surface, and a commercial sport surface; or a surfaced footpath, short grass, and long grass in order to investigate the biomechanical response to changing running surfaces. A select few studies have ventured into the creation of irregular surfaces on treadmills in order to simulate trail running in the laboratory. Kerdock, Biewener, McMahon, Weyand & Herr (1999), fitted a treadmill with surfaces of five different thicknesses to assess the energetics and mechanics of running on different surfaces. Thomas and Derrick (2003) utilized a treadmill modified by the attachment of wooden strips to the treadmill belt in order to create an unpredictable foot landing surface while running. Voloshina, Kuo, Daley, and Ferris (2013) and Voloshina and Ferris (2015) also utilized wooden blocks attached to a treadmill belt for a
walking and running study. These studies were successful in capturing important biomechanical and physiological data while running or walking over varying surfaces, but there is more to be discovered and much to be validated in relation to kinematic and energetic responses to irregular surfaces.

Another facet of running research involves the administration of augmented feedback in attempt to elicit changes in certain running parameters. Many running studies have shown feedback to be successful in altering biomechanics, and it is well supported that individuals can be trained to modify aspects of walking, running, and jumping when given some type of feedback (Crowell, Milner, Hamill, & Davis, 2010). Gait retraining specifically using real time feedback has been used successfully in altering mechanics and loading (Crowell et al., 2010; Crowell & Davis, 2011). However, feedback to alter inversion/eversion angles at the subtalar joint has not been previously studied.

Given the gaps and inconsistencies in the literature, a study supporting the comparison of running on regular and irregular terrain is a well justified area of research. Although some work has been done relating to performance on irregular surfaces, there are many effects that have yet to be sufficiently supported through research. Therefore, it is the purpose of this study to investigate the kinematic and metabolic effects of running on an irregular surface. It was hypothesized that the irregular surface would cause runners to reduce frontal plane foot inversion and increase knee flexion at contact, increasing the metabolic cost of running and shock attenuation. The effect on these other variables of altering the frontal plane foot angle at contact using real-time feedback was also investigated.

This thesis is arranged to first review previous literature (Chapter 2) in relation to the effects of unusual running surfaces on ground reaction forces and loading, leg stiffness, vertical
center of mass, muscle activity, mechanical work, power, step parameters, metabolic cost, accelerations, shock attenuation, and kinematics. A manuscript reporting the results and implications of the present study is presented in Chapter 3, and final conclusions are drawn in Chapter 4.

References


CHAPTER 2. LITERATURE REVIEW

Traditionally, race events are run entirely on paved surfaces in common distances such as 5ks, 10ks and half/full marathons. In recent years, however, there has been an influx of non-traditional race events expanding beyond the pavement and taking to off-road trails and grassy fields. In 2013, there were a reported 4 million finishers of such non-traditional running events representing a 40% increase from 2009 (Running USA, 2014). Additionally, many adventure seeking runners are participating in ultramarathon events covering distances greater than a traditional marathon (26.2 miles) during which participants often must traverse winding mountain paths and other technical trails (Vernillo et al., 2014).

The increase in popularity of competitive and recreational trail running in recent years warrants the development of a deeper knowledge of the biomechanical changes and energetic costs of running on irregular surfaces. Previous research has not altogether neglected running on irregular surfaces, as numerous studies investigating running on surfaces of different stiffness have been completed in the laboratory (Karamanidis, Arampatzis & Bruggemann, 2006; Kerdock, Biewener, McMahon, Weyand, & Herr, 2002; Ferris, Liang & Farley, 1998; Ferris, Louie & Farley, 1998; Kim & Voloshin, 1992; McMahon & Greene, 1979) and a handful of others investigating running on natural or simulated uneven terrain have been completed outdoors or in the laboratory (Creagh, Reilly, & Lees, 1998; Dixon, Collop, & Batt, 2000; Feehery, 1986; Pinnington & Dawson, 2001; Sterzign, Apps, Ding, & Cheung, 2014; Tessutti, Trombini-Souza, Ribeiro, Nunes, & Camargo Neves Sacco, 2010; Thomas & Derrick, 2003; Voloshina & Ferris, 2015; Zamparo, Perini, Orizio, Sacher, & Ferretti, 1992). Such research has provided important information, including evidence that humans use one general running strategy for many different running surfaces (Karamanidis et al., 2006) while maintaining the
ability to adapt to changing environments to improve performance or prevent injury (Derrick, 2004). Similarly, it has been suggested that intermittent sampling of an environment is sufficient to successfully traverse difficult terrain without prior knowledge of disturbances (Patla, Adkin, Martin, Holden, & Prentice, 1996). Even so, there are still many avenues to be explored related to effects and resulting injury potential of running on irregular surfaces. Despite findings supporting effective adaptation techniques during locomotion, certain computer simulations suggest that unexpected changes in surfaces disrupt a runner’s movements (Ferris et al., 1998), increasing potential for injury. The purpose of this literature review is to discuss previous research in relation to running and walking over irregular and uneven terrain, and in so doing highlight deficits that will be addressed in the present study.

**Ground Reaction Forces and Loading**

The literature contains several studies reporting on ground reaction forces (GRF) and loading during walking and running on irregular surfaces. Many studies report no change in peak GRF across surfaces of different stiffness or across acrylic turf, rubber track, or asphalt (Dixon et al., 2000; Ferris et al., 1999; Ferris et al., 1998; Kerdock et al., 2002). Dixon et al. (2000) additionally report no change in peak impact force while running in shoes with different amounts of cushioning. Despite similar peak GRF in this study, running on a rubber-modified asphalt surface resulted in greater impact absorbance than conventional asphalt and less impact absorbance than an acrylic sports surface. This result likely points to adjustments in leg stiffness, a topic of later discussion.

Conversely, some literature supports a change in peak GRF across differing surfaces. Feehery (1986) reported lower peak GRF while running on concrete than on asphalt or grass along with increased time to peak GRF in grass. Reports of running on grass versus asphalt are
inconclusive in that some researchers report higher dynamic loads on grass than asphalt and artificial track (Kim & Voloshin, 1992), and others report greater loads on the rear and forefoot while running on asphalt compared to grass (Tessutti et al., 2010). Rising impact force values have been shown to lead to increased (in this convention, less inversion) rearfoot angles at ground contact (Stergiou, Bates, & James, 2003), a possible mechanism for injury. Voloshina and Ferris (2015) report overall GRF remain relatively similar during running on a smooth or modified uneven terrain treadmill, while impact peaks and GRF variability increased during running on the uneven treadmill. Sterzing et al. (2014) and Thomas and Derrick (2003) also found greater impact variability while running on an uneven compared to smooth surface treadmill and the latter note that increased variability is likely an outcome of uncertainty of when the foot will contact the running surface.

Cross-slope walking on a smooth surface decreased impact peaks compared to walking on level ground (Willwacher, Fischer, Benker, & Dill, 2013). Similar to cross-slope walking, ground level changes in the form of steps up or down in the running path also reportedly affect GRF. In the step prior to a perceived level change, increased GRF have been observed (Ernst, Gotze, Muller, & Blickhan, 2014; Muller & Blickhan, 2010). Increasing knee flexion in the presence of uneven terrain may also bring about changes in GRF. McMahon, Valiant and Frederick (1987) report that GRF was reduced at midstance while running with exaggerated knee flexion, likely a trade-off for increased force in the muscles of the legs.

Rate of impact is another important factor in evaluating injury risk. In a study comparing hiking movements over an uneven terrain comprised of exposed rock in concrete compared to a smooth floor, rate of impact force was increased by 16.7 percent compared to the smooth surface
(Hettinga et al., 2005). The average loading rate of impact force was also reduced while running on a rubber-modified asphalt surface compared with conventional asphalt (Dixon et al., 2000).

Lastly, measurements of plantar pressures suggest the possibility of different effects from surfaces of different stiffness or uneven surfaces; surfaces of different hardness did not significantly change plantar pressures (Tillman, Fiolkowski, Bauer, & Reisinger, 2002), but a treadmill modified with EVA dome inserts mimicking an uneven running surface caused an increase in medial midfoot pressures and decrease in lateral forefoot pressures, with an overall increase in pressure variability (Sterzing et al., 2014).

**Leg Stiffness**

As touched upon previously, adjustment in leg stiffness upon encountering a new surface allows for a similar manner of running on different surfaces. Ferris et al. (1999) report that runners fully adjust leg stiffness by the completion of the first step on a new surface. These changes in leg stiffness compensate for changes in surface stiffness without altering overall support mechanics, as evidenced by only slight changes in knee angle with increasing leg stiffness (Kerdock et al., 2002). It has been observed that rapidly reducing leg stiffness results in a smooth transition when running onto a hard surface following a softer one (Ferris et al., 1998). Similarly, leg stiffness was increased significantly when running on a softer rubber surface compared to a harder rubber surface (Ferris et al., 1999) and by up to 29% with decreasing surface stiffness (Kerdock et al., 2002). Stiffness decreases while running on smooth surfaces with exaggerated knee flexion and increased speed (McMahon et al., 1987). The literature reports less about leg stiffness while running on uneven terrain aside from surfaces of different stiffness, but Voloshina and Ferris (2015) do report that running on an uneven treadmill surface was associated with increased measures of leg stiffness.
Vertical Center of Mass

Center of mass (COM) displacements have been measured under a number of running conditions, creating a relatively clear picture of consequent terrain effects. While running on continuous surfaces of different thickness, COM displacement does not change across surfaces (Karamanidis et al., 2006; Kerdock et al., 2002). Running on irregular terrain, however, results in an increase in COM displacement with increasing difficulty of terrain (Creagh et al., 1998). Decreased speed, an anticipated result of running on irregular terrain, is also associated with an increase in vertical displacement (Creagh et al., 1998; Buckalew, Barlow, Fischer, & Richards, 1985). In a related study using single upward and downward steps as disturbances in a running path, Ernst et al. (2014) found that runners perceiving disturbances ahead raised or lowered their COM during flight phase before reaching the disturbance by approximately 50% of the level change. Complete adaptation, as with leg stiffness, was achieved after the first step on the new level. Increasing the COM before and after an upward step brings the foot closer to the ground and may reduce the chance of tripping. Additionally, the authors of the study suggest that COM lift encourages a more vertical leg position at contact, which decreases leg compression and contact time which may otherwise lead to increases in metabolic cost. Increasing knee flexion while running on smooth surfaces is also a reported mechanism by which COM maintains a smooth trajectory, measured at the hip and head (McMahon et al., 1987).

Muscle Activity, Mechanical Work, and Power

Uneven surfaces have been shown to alter muscle activity. Walking on an exposed rock surface decreased the activity of the tibialis anterior and increased activity in the biceps femoris while having no significant effect on the vastus medialis or gastrocnemius (Hettinga et al., 2005). These findings are contradicted in other studies, in which mean activity in the thigh muscles
including vastus medialis, vastus longus, rectus femoris and semitendinosus were increased while walking on uneven surfaces (Voloshina, Kuo, Daley, & Ferris, 2013). In a nearly identical study on running over an uneven surfaced treadmill, Voloshina and Ferris (2015) report an increase in activity of the vastus medialis, rectus femoris and semitendinosus.

The literature indicates the existence of differences in mechanical work performed at various joints between walking and running on irregular surfaces. During walking, Voloshina et al. (2013) report that work performed at the ankle joint over one stride remained similar from smooth to uneven treadmill surfaces while more positive work was performed at the hip and more negative work at the knee. In a running study over the same smooth and uneven surfaces, Voloshina and Ferris (2015) conversely report no change in work at the hip or knee joint concurrent with a decrease in overall work performed at the ankle joint. Joint power remained unchanged across treadmill surfaces in this study and another utilizing surfaces of different stiffness (Karamanidis et al., 2006), except for at the ankle joint in the first, where overall joint torque and power were unaffected by surface. Joint moments are reportedly unaffected by surface conditions including exposed rock (Hettinga et al., 2005) or different compliances (Karamanidis et al., 2006). Laterally elevated surfaces appear to be the only reported anomaly of constant joint moments, as Willwacher et al. (2013) report an increase in ankle joint moment along with a decrease in adduction moments. These changes could result in overuse injuries or osteoarthritis progression, respectively.

*Step Parameters*

Changes in variables such as step length, step width, step frequency and step variability are among results typically hypothesized in studies of uneven terrain. A decrease in speed with increase in terrain difficulty has been well established; in one study runners failed to maintain
speed while running in short and long grass despite the use of a cyclist acting as a pacer (Creagh et al., 1998). Uneven surfaces increase gait variability during walking (Cook, Kester, & Brunet, 1985; Voloshina et al., 2013) and running (Tessutti et al., 2010; Voloshina & Ferris, 2015). Step frequency is generally not affected by surface irregularity or stiffness (Creagh et al., 1998; Ferris et al., 1999; Ferris et al., 1998; Kerdock et al., 2002), yet Sterzing et al. (2014) report significant increases in step frequency on an uneven treadmill surface and Lussiana, Fabre, Hebert-Losier and Mourot (2013) found increased step frequency on most slope gradients. Contact time is similarly unaffected by surface stiffness or irregularity (Creagh et al., 1998; Ferris et al., 1999; Ferris et al., 1998; Karamanidis et al., 2006; Kerdock et al., 2002). However, there are contrasting results in studies utilizing compliant surfaces in which contact time increases on natural grass and a foam-rubber track (McMahon & Greene, 1979; Tessutti et al., 2010). The increased contact time on these surfaces favors increased mobility at the foot/ankle complex and, consequently, improved absorbance of plantar pressures (Tessutti et al., 2010).

Walking on an uneven treadmill surface additionally increased the stride period, suggesting greater variability in time between ground contact and toe-off, and led to subtle decreases in step length (Voloshina et al., 2013). Step period is seemingly unchanged while running on grass or an uneven surface treadmill (Creagh et al., 1998; Voloshina & Ferris, 2015). Creagh et al. (1998) and Sterzing et al. (2014) also report decreased step length while running on grass and an uneven treadmill surface.

Reduced step length is not upheld while running on surfaces of varying stiffness. Several studies report no change in step length across different stiffness (Kerdock et al., 2002; Thomas & Derrick, 2003; Voloshina & Ferris, 2015), while McMahon and Greene (1979) report an increase in stride length while running on a compliant foam-rubber track. Studies investigating running at
different percentages of preferred stride length on smooth ground have led to conclusions that running at a self-selected, “normal” stride length leads to more coordination between joint movements at the knee and ankle and that running with a stride length greater than the preferred leads to greater impact forces and the possibility of running related injuries as a result (Stergiou, Bates, & Kurz, 2003).

**Metabolic Cost**

There is an overwhelming trend indicating an increase in metabolic cost while walking or running over irregular terrain in the form of modified treadmills and natural surfaces such as snow, grass, and sand (Davies & MacKinnon, 2006; Pandolf, Haisman, & Goldman, 1976; Pinnington & Dawson, 2001; Soule & Goldman, 1972; Voloshina & Ferris, 2015; Voloshina et al., 2013; Zamparo et al., 1992). Kerdock et al. (2002) also report that running on stiffer surfaces increases metabolic cost, with a 12% increase in cost during a 12.5 fold increase from the least stiff to the stiffest of five surfaces. Increased metabolic cost can be extended into sloped surfaces, where uphill running in traditional running footwear has been reported to cause a significant increase in metabolic cost with incremental increase of five slope gradients. Running downhill primarily reduces metabolic cost until a critical point (reportedly near -6% to -8% according to Minetti, Ardigo, and Saibene, (1994) and Minetti, Moia, Roi, and Susta (2002)) at which further decreases in gradient begin to evoke increased metabolic expense (Lussiana et al., 2013). Changes in mechanical work done by muscles during walking and running on uneven terrain may explain nearly half of the increase in metabolic cost from smooth to uneven surfaces (Voloshina et al., 2013; Voloshina & Ferris, 2015). The under-utilization of the stretch-shortening cycle has been cited as the primary cause of increased metabolic cost during uphill running (Cavagna, Heglund, & Taylor, 1977; Minetti, Ardigo, & Saibene, 1994). Significant
differences in metabolic variables while running with differing percentages of preferred stride
frequencies have been reported during treadmill running (Hamill, Derrick, & Holt, 1995),
specifically in the form of increased oxygen cost while deviating from preferred stride frequency
(Holt, Hamill, & Andres, 1991). Since running on uneven surfaces typically elicits deeper knee
flexion, it is also worth noting that purposefully running with increased crouch has been reported
to increase oxygen consumption by as much as 50% from normal running (McMahon et al.,
1987).

Accelerations and Shock Attenuation

Research involving running often utilizes accelerometers placed on the tibia to measure
accelerations of the lower leg. A second accelerometer attached to the head or a bite bar may be
used simultaneously, allowing for calculation of shock attenuation. In studies where running on
grass was compared to running on other surfaces, it is reported that although force time and
acceleration curves are similar in shape across surfaces, grass resulted in higher acceleration
values at the tibia and head (Feehery, 1986; Kim & Voloshin, 1992). Irregular treadmill surfaces
also produced increased peak impact accelerations at the tibia (Thomas & Derrick, 2003).
Likewise, running with increased knee flexion, which is reported during running on uneven
surfaces, also leads to slightly larger peak vertical accelerations at the tibia, but values at the
head were smaller than during normal running (McMahon et al., 1987). When otherwise running
on smooth surfaces, no significant difference in head accelerations or impacts have been reported
with changes in stride frequency (Hamill, Derrick, & Holt, 1995) or at different speeds (Shorten
& Winslow, 1992).

The amount of shock at the head has also been shown to lack significant change while
running at different speeds on a treadmill (Shorten & Winslow, 1992). This is theoretically
applicable to running on an irregular surface with reduced speed, but other factors could alter this outcome on uneven surfaces. Stride frequency is another step parameter influencing shock attenuation and also a possible variable that changes when running on irregular surfaces. Hamill, Derrick and Holt (1995) found that lower stride frequencies resulted in greater shock attenuation than higher frequencies. At low stride frequencies (below 5Hz), the head was found to gain shock amplitude compared to values at the leg.

Running on irregular surfaces has mixed effects on shock attenuation according to available literature. While running on an irregular treadmill surface, greater impacts were normalized at the head because of greater attenuation than running on a smooth treadmill surface (Thomas & Derrick, 2003). In another study, Kim and Voloshin (1992) report that running on asphalt had the highest shock attenuation between running on asphalt, grass and a track surface although grass had the lowest dynamic loading measurements.

There are several proposed mechanisms for shock attenuation in the human body while running. Knee flexion and subtalar pronation have been put forth as natural shock absorbing actions at the expense of increased metabolic cost, as have anatomical components such as the heel pad, ligaments, articular cartilage and bone (Hamill, Derrick, & Holt, 1995; Leung, Mak, & Evans, 1998; Stergiou et al., 1999). Components experiencing higher or more frequent impacts may be more susceptible to overuse injuries and degenerative disease (Hamill, Derrick, & Holt, 1995).

**Kinematics**

The literature reports several kinematic changes while traversing irregular terrain. Joint angle changes are predominately found at the knee and ankle. Aside from more overall variability in joint motion and moments at the knee and hip on uneven surfaces, knee flexion is
typically increased (Voloshina & Ferris, 2015). Voloshina et al. (2013) report an increase in knee and hip flexion at mid swing during walking on an uneven treadmill surface, and a more crouched posture while running on the same treadmill surface. The increased knee flexion leads to shorter active leg lengths and stiffer legs (Voloshina & Ferris, 2015). Similar increases in knee and often hip flexion during ground contact are reported in several other walking and running studies utilizing uneven or unlevel surfaces (Creagh et al., 1998; Derrick, 2004; Lussiana et al., 2013; Sterzing et al., 2014; Thomas & Derrick, 2003). In a study where runners were asked to run with exaggerated knee flexion over smooth ground, the increased knee flexion led to increased contact time and step lengths. In the most extreme condition of knee flexion, step length was increased by an average of 30% compared to normal running (McMahon et al., 1987).

Joint motion at the ankle is also altered, uniformly appearing as reduced rearfoot angles at the subtalar joint (Thomas & Derrick, 2003), and decreased dorsiflexion angles accompanied by increased maximum eversion angles while traversing uneven surfaces (Sterzing et al., 2014) and the softer of two foam surfaces (Karamanidis et al., 2006). Likely as a result of these changes, overall range of motion at the subtalar joint was decreased while running on a modified uneven surface treadmill in a study by Voloshina and Ferris (2015). Comparable alterations in joint angles were reported by Lussiana et al. (2013) in the form of increasing knee flexion and ankle dorsiflexion with increasing gradient of the running surface. According to Hettinga et al., (2005), walking on an exposed rock surface decreased ankle eversion angle and knee external rotation moments, differing from the similar studies previously cited.

Pronation at the subtalar joint releases the mid-tarsal joints of the foot, allowing it to become more flexible and adapt to uneven terrain (Hamill, Bates, & Holt, 1992). This motion at the subtalar joint transmits rotation up the kinetic chain, forming a joint couple that propagates
rotation of the tibia (Stergiou et al., 2003). There is literature indicating that excessive internal rotation of the tibia may lead to patellofemoral pain syndrome (Cheung, Wong, & Ng, 2011), particularly when pronation/supination at the subtalar joint and flexion/extension at the knee joint act asynchronously (Stergiou et al., 2003). This is further evidenced in a study by Stergiou et al. (1999) in which differences in velocity of joint actions at the knee and ankle were significantly correlated with receiving a clinical evaluation of increased susceptibility to injury.

Running on surfaces of different stiffness brought about varied changes in joint angles. Karamanidis et al., (2006) and Kerdock et al. (2002) report that running on foam or five surfaces of different stiffness elicited no change in leg and knee joint angles during ground contact. Dixon et al. (2000) present opposing results in which an acrylic sports surface and rubber-modified asphalt surface produced increased peak ankle dorsiflexion angle and velocity as well as knee flexion compared to a conventional asphalt surface.

These kinematic changes have several implications regarding the kinetic chain, including decreased GRF and leg stiffness via increased knee flexion at ground contact (Clarke, Frederick, & Cooper, 1983; Derrick, 2004; Frederick, 1986), in turn allowing for a smoother gait but increased energy cost (Voloshina et al., 2013). A reduction in leg stiffness could act as compensation for increasing stiffness of the surface/shoe interface (Clarke, Frederick, & Cooper, 1983; Frederick, 1986). It is also worth noting that Tsui & Forrester (2012) report a computer model predicting landing with increased knee flexion during running on damped surfaces could be a successful mechanism to regain the energy lost in the compliant surface.

**Augmented Feedback**

The present study will utilize real time visual feedback in order to manipulate eversion angle at contact. Many running studies have shown feedback to be successful in altering
biomechanics, and it is well supported that individuals can be trained to modify aspects of walking, running, and jumping when given some type of feedback (Crowell et al., 2010). Modes of feedback may include pre-test filming sessions to be viewed before each subsequent training session (Messier & Cirillo, 1989), filming in addition to mirrors (Willy, Scholz, & Davis, 2012), or real time feedback on a TV monitor setting targets at a certain percentage of normal performance values (Eriksson, Halvorsen, & Gullstrand, 2011). Gait retraining specifically using real time feedback has been used successfully in altering mechanics and loading (Crowell et al., 2010; Crowell & Davis, 2011). Full length mirrors were used in a study by Willy et al. (2012) to effectively reduce abnormal hip mechanics during running. Improvements were maintained for 3 months and transferred to stair descent and single leg squatting. Eriksson, Halvorsen and Gullstrand (2011) report that real time feedback displayed on a monitor was successful in reducing step frequency and vertical displacement while running. While many feedback studies employ multiple training sessions over several weeks, Crowell et al. (2010) note that several jumping studies have succeeded in changing parameters in only one training session. In a review of gait retraining in runners using augmented feedback, Agresta and Brown (2015) report the use of visual feedback in the form of mirrors, videotape, and graphical representations. Auditory feedback has included metronomes for the purpose of regulating step frequency and basic verbal feedback from researchers. In another review of studies utilizing feedback to modify gait, real time feedback was reported to be most successful in changing kinematic variables based on the 27 studies included. To date, feedback has been given in attempt to alter ankle angle at toe off, maximum ankle and knee flexion angle in support phase, hip and pelvis kinematics, elbow flexion angle, trunk inclination, vertical center of mass displacement, foot strike pattern, step frequency, step length, step width, peak-positive tibial acceleration, GRF, and general running
Conclusion

The available literature provides a valuable information related to running and walking under uncertain or irregular conditions. Even so, the discrepancies between studies as well as the omission of certain variables represent important topics in need of further investigation. It can be determined that surface stiffness, slope, and level change elicit different biomechanical responses than running or walking on irregular natural surfaces such as grass, or simulated irregular surfaces such as modified treadmills. It is also arguable that walking and running on irregular surfaces are not easily compared. Given the knowledge base in the current literature, there is inconclusive evidence for a definite deduction of the effects of irregular surfaces on GRF, muscle activity and shock attenuation while running. Changes in leg stiffness are well documented while running on surfaces of varying stiffness, but there is less evidence of leg stiffness adaptations while running on uneven surfaces aside from a reported increase on an irregular treadmill surface (Voloshina & Ferris, 2015). The variability of impact peaks and rate of impact have also been shown to increase on irregular surfaces (Hettinga et al., 2005; Thomas & Derrick, 2003), but Voloshina and Ferris (2015) are alone in reporting an increase in impact peaks while running on an irregular treadmill surface. Several studies report an increase in VO$_2$ with irregular terrain (Davies & MacKinnon, 2006; Pandolf et al., 1976; Pinnington & Dawson, 2001; Soule & Goldman, 1972; Voloshina & Ferris, 2015; Voloshina et al., 2013; Zamparo et al., 1992), but there are gaps in explanations for this increase. Other reported changes on irregular surfaces include increased peak acceleration at the tibia (Feehery, 1986; Kim & Voloshin, 1992; Thomas & Derrick, 2003) and decreased knee flexion angle, rearfoot angle, speed, and step
length (Creagh et al., 1998; Sterzing et al., 2014). Given these results, it is expected that the present study will produce increased knee and ankle flexion at ground contact and maximum, and an increase in acceleration at the tibia.

There is also a lack of highly realistic treadmill modifications that successfully capture an irregular foot strike surface as would be encountered on natural surfaces. Voloshina and Ferris (2015) utilized a modified treadmill with irregularities varying in height, but the pattern used would not likely allow for excessive eversion, nor does it present a surface with varying stiffness. For these reasons, the present study will use a treadmill with an arbitrary arrangement of irregularities on a surface with two different stiffness values. It is the belief of the researchers that this design will provide a more realistic trail running experience.

The present study will also alter the frontal plane foot angle at contact on a smooth surface treadmill using visual feedback in order to include pronation variation as an explanatory variable. This, along with measurement of VO$_2$, will likely allow for more refined conclusions about the sources of biomechanical changes on irregular surfaces.

References


Sterzing, T., Apps, C., Ding, R., & Cheung, J.T.M. (2014). Running on an unpredictable irregular surface changes lower limb biomechanics and subjective perception compared
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CHAPTER 3. THE EFFECTS OF AN IRREGULAR SURFACE ON CONTACT GEOMETRY, SHOCK ATTENUATION AND METABOLIC COST DURING RUNNING

Alyssa M. Gantz & Timothy R. Derrick

Abstract

Background. With the popularity of non-traditional and off-road race events on the rise, the number of runners encountering trail surfaces has undergone a marked increase in recent years. Despite the growing popularity of trail and off-road running, little research has been done to investigate the effects of running on irregular surfaces.

Purpose: The purpose was to investigate the kinematic and metabolic effects of running on an irregular surface. We hypothesized that the irregular surface would cause runners to reduce frontal plane foot inversion and increase knee flexion at contact, increasing the metabolic cost of running and shock attenuation. We also examined how altering the frontal plane foot angle at contact using real-time feedback would affect these other variables.

Methods: Sixteen participants completed three running bouts lasting 5-7 minutes each on an irregular surface (IS) treadmill created by attaching wooden slats, on a traditional smooth surface (SS) treadmill, and on SS while receiving visual feedback of the frontal plane foot angle at contact (SSF) with a goal of matching IS foot angle on SS. Participants were outfitted with reflective markers on the pelvis and lower limb and accelerometers on the distal anteromedial tibia and frontal bone of the forehead. For a portion of each condition, participants breathed through a mouthpiece for the measurement of the rate of oxygen consumption (\(\dot{VO}_2\)). Statistical analysis was completed using a one-way repeated measures ANOVA with a Sidak post hoc correction to set \(\alpha=0.0127\).

Results: Frontal plane foot angle increased by 40% from IS to SS (IS: 8.4±4.09°, SS: 11.8±4.52°, p<0.0001). Knee flexion angle decreased by 33% from IS to SS (IS: 9.2±4.88°, SS: 6.2±5.03°,
Rate of oxygen consumption decreased by 10% from IS to SS (IS: 37.9±5.68 ml·kg⁻¹·min⁻¹, SS: 34.1±5.07 ml·kg⁻¹·min⁻¹, p<0.0001). Frontal plane foot angle decreased by 14% from SS to SSF (SS: 11.8±4.52°, SSF: 10.1±4.42°, p=0.027) but did not result in significant changes in any variables. There were no significant differences in shock attenuation between any conditions (IS: -9.8±2.26 dB, SS: -9.5±3.12 dB, SSF: -9.9±2.62 dB, p=0.671).

*Interpretation:* Running with greater eversion on the irregular surface may be an attempt by runners to reduce the perceived potential of an inversion ankle sprain. Muscles of the knee and ankle can absorb impact shock but their effectiveness depends on the angle at contact. As a partial compensation for the decreased foot angle at contact, runners increased knee flexion. This maintained shock attenuation but increased the rate of oxygen consumption. Altering the foot angle at contact using feedback on the SS did cause the knee angle to increase, but did not result in a change in shock attenuation or metabolic cost.
Introduction

According to a Non-Traditional Running Events Special Report released by Running USA (2014), there were nearly 4 million finishers of non-traditional running events in 2013, which equates to an increase of 40% from the number of finishers in 2009. For athletes seeking a greater challenge and more competition, extreme endurance races such as ultramarathons, in which runners cover distances longer than the traditional marathon (26.2 miles) over the course of several hours or even days, are becoming increasingly popular (Vernillo et al., 2014). As can be expected, a wide range of surfaces are encountered during these events, including paved or gravel roads, wooded trails, or rocky mountain terrain. Because many of these races take place at least in part on off-road or trail like surfaces, the popularity of trail running has undergone a marked increase in recent years (Hoffman & Wegelin, 2009). Despite the increasing popularity of trail running among both recreational and competitive runners, there are few projects published in the literature investigating the biomechanical effects of trail running or running on simulated trail surfaces in the laboratory.

Multiple studies (Karamanidis, Arampatzis & Bruggemann, 2006; Hettinga, Stefanyshyn, Fairbairn & Worobets, 2005; Ferris, Liang & Farley, 1999; Ferris, Louie & Farley, 1998) have investigated the effects of running on surfaces of different thickness and stiffness. Dixon, Collop and Batt (2000) and Creagh, Reilly and Lees (1998) used varied surfaces including asphalt, a rubber modified bituminous surface, and a commercial sport surface; or a surfaced footpath, short grass, and long grass in order to investigate the biomechanical response to changing running surfaces. A select few studies have created irregular surfaces on treadmills in order to simulate trail running in the laboratory. Thomas and Derrick (2003) utilized a treadmill modified by the intermittent attachment of wooden strips to the treadmill belt in order to create an
unpredictable foot landing surface while running. Results of this study include significantly
greater knee flexion, a nearly significant 1.3° decrease in rearfoot angle (less inversion), a 13.1%
increase in peak impact at the leg, and a 2.6% increase in shock attenuation while running on the
irregular surface. Voloshina, Kuo, Daley, and Ferris (2013) and Voloshina and Ferris (2015) also
utilized wooden blocks attached to a treadmill belt for walking and running, respectively. In the
latter study, there was a 5% increase in energetic cost, an increase in knee and hip flexion during
mid stance, a 17% increase in impact peak, and decreased sagittal plane range of motion at the
ankle joint. These studies were successful in capturing important biomechanical and
physiological data while running or walking over varying surfaces, but these irregular surface
treadmills did not guarantee that runners would land on an anterior/posterior directed edge that
could alter foot inversion/eversion angles.

Another facet of running research involves the administration of augmented feedback in
attempt to change certain running parameters. Gait retraining specifically using real time
feedback has been successful in altering mechanics and loading (Crowell, Milner, Hamill, &
Davis, 2010; Crowell & Davis, 2011). Visual feedback in the form of mirrors, videotape, and
graphical representations have been used previously to change aspects of running (Agresta &
Brown, 2015). Ankle angle at toe off, maximum ankle and knee flexion angle in support phase,
hip and pelvis kinematics, elbow flexion angle, trunk inclination, vertical center of mass
displacement, foot strike pattern, step frequency, step length, step width, peak-positive tibial
acceleration, GRF, and overall running form have been the parameters of interest in feedback
studies to date (Agresta & Brown, 2012; Crowell et al., 2010; Crowell and Davis, 2011;
Eriksson, Halvorsen, & Gullstrand, 2011; Messier & Cirillo, 1989; Napier, Cochrane, Taunton,
& Hunt, 2015). Missing from this list is feedback to alter frontal plane angles at the foot.
Given the gaps and inconsistencies in the literature, a study permitting the comparison of running on regular and irregular terrain is a well justified area of research. Although some work has been done relating to performance on irregular surfaces, there are many effects that have yet to be sufficiently supported through research. Therefore, it was the purpose of this study to investigate the kinematic and metabolic effects of running on an irregular surface. It was hypothesized that the irregular surface would cause runners to reduce frontal plane foot inversion and increase knee flexion at contact, increasing the metabolic cost of running and shock attenuation. Given the expected change in inversion angle we will also use feedback so that runners will run on a normal treadmill using the same inversion angle at contact as the irregular surface treadmill. This will lend further insight into the effects of altering this angle on shock attenuation and metabolic cost.

Methods

Participants

Sixteen runners (7 male, 9 female) were recruited for this study. Male participants had an age (mean±SD) of 24±4.5 years, height of 1.81±0.07 m, and mass of 67±8.5 kg. Female participants had an age of 22±2.4 years, height of 1.6±0.09 m, and mass of 58.7±6.7 kg. Participants were required to be between 18 and 35 years of age and running at least 10 miles a week. Those who had suffered an injury that affected training in the previous 6 months were excluded from this study. Procedures were approved by the university Institutional Review Board and all participants signed informed consent documents prior to data collection.

Procedures

A traditional treadmill (Trackmaster by Full Vision, Inc., Newton, KS) was used to simulate running on smooth surfaces. A second treadmill (Woodway USA, Waukesha, WI) was
modified to simulate running on irregular surfaces. Treadmill “bumps” were formed using 1.27 cm thick wood that was cut to 5 x 13.5 cm strips and screwed to the surface of the metal slats that composed the treadmill bed (Figure 1). Treadmill speeds were calibrated using a Biddle Tachometer.

Figure 1. Irregular surface treadmill bed.

Data collection took place on one visit to the biomechanics laboratory. Height, mass, and age were recorded. Participants were given a warm up period, allowing as much time as desired to run on the irregular surface treadmill and choose a running speed for trials. Following the warm up, participants ran in three conditions: 1) irregular surface treadmill (IS) with self-selected frontal plane foot angle (FA); 2) smooth surface treadmill (SS) with self-selected FA; and 3) smooth surface treadmill with feedback (SSF) in attempt to match the FA from IS on SS.
Kinematics and accelerations were collected simultaneously, independent from the collection of metabolic data.

*Oxygen consumption*

For a portion of each condition, participants breathed through a mouthpiece while wearing a nose clip for measurement of the rate of oxygen consumption (\(\dot{VO}_2\)). A metabolic cart (Physio Dyne Max 2, Fitness Instrument Technologies) was used to analyze \(\dot{VO}_2\) in each of the running conditions.代谢 cart software output \(\dot{VO}_2\) data every thirty seconds and data collection continued until values stabilized, typically five to seven minutes.

*Kinematics*

Seventeen reflective markers were taped on the right leg and pelvis of each participant: three on the calcaneus, one on the dorsal foot, one on the lateral foot (placed directly on footwear), four on the lower leg, three on the thigh, and five on the pelvis. Two additional markers were temporarily placed on each participant for a static trial: one on the medial malleolus and one on the medial knee. Subjects were asked to stand with toes pointing straight ahead and feet five centimeters apart for collection of the static trial. Segment positions were recorded using an 8 camera motion capture system (Vicon, Oxford, UK).

*Accelerometry*

Two PCB Piezotronics accelerometers (model 353B17) were attached to each participant, one on the distal anteromedial aspect of the right tibia and one over the frontal bone of the forehead. Accelerometers were secured using double sided tape, then tightly wrapped with athletic tape or an elastic band. Accelerations were collected at 1200 Hz.
Real time visual feedback

Condition 3 (SSF) was the only condition during which participants were given visual feedback. This feedback was presented in real time as a graphical display of FA at contact on a computer screen (Figure 2). Previous studies have successfully altered running parameters using visual feedback in this way (Crowell & Davis, 2011; Crowell et al., 2010; Eriksson et al., 2011; Noehren et al., 2011). A custom Matlab program (version 8.6.0 R2015b, Natick, MA, USA) was written to calculate FA at contact in real time and output a graphical display of these angles, as well as a target zone calculated utilizing the measured FA while running on IS in condition one (Figure 2).

![Figure 2. Visual feedback output display. Gray area indicates the target zone of IS frontal plane foot angle (inversion) ±1°. Red line represents actual frontal plane foot angle at contact.](image)

Foot strike was determined using accelerometer data by finding impact peaks then searching backwards until a minimum value was found. Toe-off was determined by moving approximately
one quarter second past foot strike, then finding the local minimum (Mercer, DeVita, Derrick, & Bates, 2003). Figure 3 displays these events and the consequent foot angle at contact.

![Figure 3. Leg accelerometer output with foot strike (a), impact peak (b), and toe-off (c) indicated (top) and frontal plane foot angles with foot contact indicated (bottom) for five seconds.](image)

**Data Analysis**

\[ \text{VO}_2 \] was averaged over approximately 4-7 minutes and normalized by body mass for each subject. Accelerometer data were filtered with a fourth-order bandpass filter with cutoffs of 0.75 Hz and 35 Hz. Kinematic data were filtered with a fourth-order low pass filter with a cutoff of 8 Hz. Foot segment and knee joint angles were calculated by comparing the reflective marker locations of each segment during a static orientation to those during a dynamic trial (Soderkvist and Wedin, 1993). Helical angles were calculated to identify knee and foot angles (Woltring,
1994), with negative angles indicating extension and eversion, respectively. Values for each of these angles were identified at foot contact for statistical analysis. The stance portion of each step was extracted from the accelerometer graphs and transformed into the frequency domain using a fast Fourier transformation. The resulting head and leg power spectral densities (PSD$_{\text{head}}$ and PSD$_{\text{leg}}$) were used to estimate the transfer function from the leg to the head (Hamill, Derrick, & Holt, 1995; Shorten & Winslow, 1992):

$$\text{Transfer function} = 10 \log_{10} \left( \frac{\text{PSD}_{\text{head}}}{\text{PSD}_{\text{leg}}} \right)$$

Positive values indicate a gain in the signal while negative values indicate attenuation. Average attenuation was calculated at the impact frequencies (10 Hz to 20 Hz), as described in Mercer et al. (2003).

**Statistical Analysis**

A one-way repeated measures ANOVA was performed using SPSS (version 23, Chicago, IL, USA) to detect differences between all three conditions (IS, SS, SSF) in oxygen consumption, FA at contact, sagittal plane knee angle at contact, and the average transfer function between 10 and 20 Hz. Statistical significance was set at $\alpha=0.0127$ after a Sidak correction was applied to adjust for the four ANOVA tests. Pairwise comparisons were made to detect differences in the conditions if the overall alpha level was obtained.

**Results**

Participants took an average of 19 steps across all conditions during the thirty seconds of acceleration and kinematic data collection. When runners moved from the irregular surface treadmill to the smooth treadmill they increased frontal plane foot contact angle by 40% (IS: $8.4\pm4.09^\circ$, SS: $11.8\pm4.52^\circ$, $p<0.0001$) and knee flexion contact angle by 33% (IS: $9.2\pm4.88^\circ$, SS: $6.2\pm5.03^\circ$, $p<0.0001$). The rate of oxygen consumption also decreased by 10% (IS: $37.9\pm5.68$...
ml·kg⁻¹·min⁻¹, SS: 34.1±5.07 ml·kg⁻¹·min⁻¹, p<0.0001) (Figure 4). When feedback was added to the smooth treadmill condition the runners attained a frontal plane foot contact angle that was in between the irregular surface and the smooth surface conditions (IS: 8.4±4.09°, SS: 11.8±4.52°, SSF: 10.1±4.42°). Both the SS and the SSF conditions were statistically different from the IS condition (p<0.0001 and p=0.001 respectively) but there were no statistically significant differences between the SS and SSF conditions in any of the variables. Even though visual inspection of the leg power spectral density indicated greater values in the impact range (10-20 Hz) on the IS treadmill, there were no significant differences in shock attenuation between the conditions (IS: -9.8±2.26 dB, SS: -9.5±3.12 dB, SSF: -9.9±2.62 dB, p=0.671) (Figure 7).

![Figure 4. Average VO₂ (SD) for all conditions. *Significance at p<0.0127.](image-url)
Figure 5. Ensemble foot segment (left) and knee joint (right) angles from foot strike to toe-off. Positive values indicate inversion and flexion, respectively.

Figure 6. Power spectral densities at the leg and head (top) and transfer function (bottom).

Discussion

The purpose of this study was to investigate the kinematic and metabolic effects of running on an irregular surface. This study also examined how altering the frontal plane foot angle at contact using real-time feedback would affect other variables. The hypotheses that running on an irregular surface would elicit reduced frontal plane foot inversion and increased knee flexion at contact were supported, as was the hypothesis that the rate of oxygen consumption would increase on the irregular surface. The hypothesis that the irregular surface
would cause increased impact attenuation was not supported. The data suggest that even though FA moved in the direction of the target zone, participants were not able to completely alter eversion angle at contact to match the target value. The changes that were observed had minimal effects on the other variables.

**Kinematics**

Typically, runners strike the ground on the outside of the foot and.evert throughout the first 40% of stance, as observed in Figure 8. The decreased inversion at contact during IS may be a protective mechanism by which runners reduce the perceived probability of landing on the edge of a bump and suffering an inversion ankle sprain. Although it may be safer to land with a reduced frontal plane foot contact angle, it appears that this may have consequences. Eversion is a component of pronation and is considered a shock absorbing mechanism, so limiting the motion of the subtalar joint may increase impacts or cause a compensatory shock attenuating strategy. One such strategy may be to increase knee flexion. In a similar study utilizing a modified treadmill, Voloshina and Ferris (2015) report an increase in knee and hip flexion during mid-stance on an irregular surface, but they did not report statistics for these measures. Sterzing, Apps, Ding, and Cheung (2014) and Thomas and Derrick (2003) reported statistically significant increases in knee flexion while running on a treadmill modified by the attachment of EVA dome pieces or intermittent strips of wood. This increase in knee flexion is likely an attempt to recover some of the shock attenuation that is reduced by the flatter frontal plane foot angle at contact.

**Real Time Visual Feedback**

Overall, subjects did not statistically change their foot angles when given feedback but this may have been due to the relatively small change they were asked to achieve. Runners were requested to use the feedback to change frontal plane foot contact angle by an average of 3.4°,
but were only able to manage a 2.1° change. Of the 16 subjects that received feedback there were only two that failed to move their frontal plane foot contact angle closer to the target value of the IS condition. There was one additional runner that did not change foot angle between the IS and SS conditions. It is suggested that runners be given feedback that could be systematically altered to achieve their individual goal. With the lack of a statistically significant change in foot angle it is not surprising that the other variables did not change when feedback was added to the SS condition.

Rate of Oxygen Consumption

The observed increase in $\dot{V}O_2$ recorded in the present study is supported in the literature. There is a trend indicating an increase in metabolic cost while walking or running over irregular terrain in the form of modified treadmills and natural surfaces such as snow, grass, and sand (Davies & MacKinnon, 2006; Pandolf, Haisman, & Goldman, 1976; Pinnington & Dawson, 2001; Soule & Goldman, 1972; Voloshina & Ferris, 2015; Voloshina et al., 2013; Zamparo, Perini, Orizio, Sacher, & Ferretti, 1992). Changes in mechanical work done by muscles during walking and running on uneven terrain may explain nearly half of the increase in metabolic cost from smooth to uneven surfaces (Voloshina et al., 2013; Voloshina & Ferris, 2015). Since the IS resulted in deeper knee flexion at contact in the present study, it is worth noting that running with increased crouch has been reported to increase oxygen consumption by as much as 50% from normal running (McMahon, Valiant, & Frederick, 1987). The greater knee flexion during IS likely resulted in increased muscle activation during initial stance and was likely a contributing factor to the rise in $\dot{V}O_2$. 

Accelerations and Shock Attenuation

It has been proposed that runners adapt to changing environments by maintaining impacts below a certain threshold, often by increasing knee flexion at contact (Derrick, 2004). Running with increased knee flexion has been shown to produce larger peak vertical accelerations at the tibia while values at the head remain smaller than during normal running (McMahon et al., 1987). Given this knowledge and that greater impact peaks have been reported while running on irregular surface treadmills (Voloshina & Ferris, 2015), it was expected that shock attenuation would increase during IS in the present study in order to maintain accelerations at the head across conditions. Average power at the leg in the 10-20 Hz range was 39% greater during IS (0.17±0.07 g²/Hz) than SS (0.11±0.05 g²/Hz) while power at the head in this range was 24% greater during IS (0.024±0.01 g²/Hz) than SS (0.018±0.01 g²/Hz), which resulted in no statistically significant change in attenuation between the conditions. As previously mentioned, pronation and knee flexion are proposed mechanisms of shock absorption in the body, albeit at the expense of metabolic cost (Hamill et al., 1995; Leung, Mak, & Evans, 1998; Stergiou, Bates, & James, 1999). In the present study, shock attenuation remained the same in IS and SS conditions suggesting that the runners substituted shock attenuation at the knee joint for the restricted shock absorption at the subtalar joint.

Limitations

The irregular surface created in this study is not necessarily a realistic representation of running outdoors on a natural trail. Irregularities in the path can usually be avoided using visual inspection of the route. The restricted time between when an irregularity could be seen on the treadmill surface and when the foot landed prevented such anticipation so the bumps were unavoidable. Lack of experience on the irregular treadmill could have affected variables, but it
has been reported that runners can adapt to a new surface within the first step (Ferris et al., 1999). In addition to the ample warm-up period the runners had 7-8 minutes of running on the IS treadmill during the measurement of metabolic cost. Lastly, the calculation of joint angles at contact depend heavily upon the accuracy of the accelerometer data from which contact points are extracted, and upon the method of extraction itself. Ideally, the reported contact angles would be purely representative of the angle at the exact moment of contact. Because foot angle changes rapidly once a surface is encountered, even slight imprecisions in the identification of contact could cause large changes in calculated angles.

Conclusions

Overall, running on an irregular surface caused alterations in frontal plane foot angles at contact in the form of reduced inversion, suggesting that runners land with a flatter foot on irregular surfaces. It is possible that a flatter foot strike is adopted in attempt to reduce the likelihood of an inversion ankle sprain that could result from landing on an edge with an already inverted foot. A statistically significant 33% increase ($3.1^\circ$) in knee flexion angle at contact was observed between the irregular and smooth surfaces. An increase in knee flexion is a mechanism by which some shock attenuating qualities that are lost without pronation of the foot may be regained. Although these mechanisms allow for a more ordinary running pattern, it could be that they contribute to the increase in metabolic demand observed on the irregular surface by increasing the activation of muscles with increased knee flexion. Despite the slight increase in knee flexion on the irregular surface, there was no change in shock attenuation, indicating that runners were unsuccessful in maintaining accelerations at the head in different running conditions. Lastly, this study has shown that real time visual feedback elicited only a small change in frontal plane foot angle at contact while running.
References


CHAPTER 4. GENERAL CONCLUSIONS

Running mechanics on a smooth and irregular surface were compared in order to determine if contact geometry, shock attenuation, and metabolic cost were altered by the running surface. Participants landed with a flatter foot and slightly more flexed knee on the irregular surface while incurring a greater metabolic cost, but shock attenuation was not affected by surface. Real time feedback was implemented in order to determine the effectiveness of feedback in changing frontal plane foot angle at contact during running. Participants in this study were partially successful in changing this parameter in the desired direction, but did not attain a statistically significant change when feedback was added to the SS condition.

Runners characteristically land on the outside of the foot and pronate during the first 40% of stance phase. Landing with a flatter foot on the irregular surface may be an attempt to reduce the risk of an inversion ankle sprain that may be more likely if a runner were to land on a bump with an inverted foot. However, it appears that this landing scenario comes at a cost in the form of increased impacts and the loss of shock attenuation typically afforded by pronation. It is therefore possible that the slight increase in knee flexion observed on the irregular surface is an attempt to place the knee extensor muscles in a better position to absorb energy and compensate for the loss of shock absorption at the foot/ankle complex. Despite this effort, the lack of change in shock attenuation between the smooth and irregular surfaces indicates that losses in shock absorption were not completely mitigated.

This altered contact geometry results in a greater metabolic cost that could be due in part to increased muscle activation. Participants were given feedback in hopes that the foot angle on the irregular surface would be matched on the smooth surface treadmill, allowing for speculation on foot angle effects.
If feedback for frontal plane foot angle is given with the goal of matching a precise value, it may be necessary to exaggerate the target zone. It is likely that some individuals are able to respond successfully to the feedback while others are not, and that some participants in the present study did not change their foot angle between conditions. If the latter were the case, it could appear that they were successfully responding to feedback when in reality they were running as they normally would without changing any parameters. This is most certainly a topic worthy of further discussion in future studies.
CHAPTER 5. COMPLETE REFERENCE LIST


APPENDIX A. IRB APPROVAL

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
1138 Pearson Hall
Ames, Iowa 50011-2307
515-294-4566
FAX 515-294-4207

Date: 3/1/2016
To: Alyssa Gantz
4708 Steinbeck #207

CC: Dr. Timothy Derrick
249 Forker Bldg

From: Office for Responsible Research
Title: Running on an Irregular Surface
IRB ID: 15-551

Approval Date: 2/26/2016
Date for Continuing Review: 10/29/2017
Submission Type: Modification
Review Type: Expedited

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- Use only the approved study materials in your research, including the recruitment materials and informed consent documents that have the IRB approval stamp.

- Retain signed informed consent documents for 3 years after the close of the study, when documented consent is required.

- Obtain IRB approval prior to implementing any changes to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.

- Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences involving risks to subjects or others; and (2) any other unanticipated problems involving risks to subjects or others.

- Stop all research activity if IRB approval lapses, unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.

- Complete a new continuing review form at least three to four weeks prior to the date for continuing review as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. Approval from other entities may also be needed. For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. IRB approval in no way implies or guarantees that permission from these other entities will be granted.

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 1138 Pearson Hall, to officially close the project.

Please don’t hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.
### APPENDIX B. EXTENDED RESULTS

Table 1. Kinematics and rate of oxygen consumption for all conditions. Mean±SD.

<table>
<thead>
<tr>
<th>Variable</th>
<th>IS</th>
<th>SS</th>
<th>SSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of Oxygen Consumption (ml·kg⁻¹·min⁻¹)</td>
<td>37.9±5.68</td>
<td>34.1±5.07</td>
<td>34.7±5.23</td>
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<tr>
<td></td>
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<td>*</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Inversion angle at contact (°)</td>
<td>8.4±4.09</td>
<td>11.8±4.52</td>
<td>10.1±4.42</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>*</td>
<td>0.001</td>
</tr>
<tr>
<td>Knee flexion angle at contact (°)</td>
<td>9.2±4.88</td>
<td>6.2±5.03</td>
<td>7.3±5.59</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>*</td>
<td>0.004</td>
</tr>
<tr>
<td>Shock Attenuation (dB)</td>
<td>-9.8±2.26</td>
<td>-9.5±3.10</td>
<td>-9.91±2.6</td>
</tr>
</tbody>
</table>

*Significantly different from IS

![Graph](image)

Ensemble foot angles in the frontal (inversion/eversion), transverse (ad/abduction), and sagittal (plantar/dorsiflexion) plane from foot strike to toe-off.
Ensemble sagittal plane motion at the ankle (plantar/dorsiflexion), knee (flexion/extension), and hip (flexion/extension) from foot strike to toe-off. Positive values indicate dorsiflexion and flexion.