Kinetic characteristics of barefoot running

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KINETIC CHARACTERISTICS OF BAREFOOT RUNNING

by

Julia A. Freedman

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ABSTRACT

Kinetic Characteristics of Barefoot Running

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The overall purpose of this study was to better understand impact characteristics during barefoot running. Subjects (n=10; 22.5±3.1 yrs; 170.3±6.8 cm; 66.7±10.5 kg; 5 male; 5 female) completed ten trials (3.8 m/s) in each of three conditions: 1) Shod, 2) barefoot (BF) running without instruction given on footstrike pattern and 3) barefoot with instruction to run heel-toe (BFHT). Ground contact index (GCI), stride length, impact peak (F1), loading rate, and peak leg acceleration (PkLeg) were analyzed. Repeated measures ANOVAs were used to compare each dependant variable across conditions. Neither stride length nor F1 were different across conditions (p>0.05). Loading rate was greater during BF compared to shod (p<0.001) and BFHT compared to BF (p<0.05). PkLeg was greater during BF vs. shod (p<0.05) as well as BFHT vs. shod (p<0.05). GCI was less during BF vs. shod (p<0.0002) and BFHT vs. BF (p<0.05). There appear to be differences in impact characteristics between shod and barefoot running but these differences appear to be functionally significant.
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INTRODUCTION

Overuse injuries are common to runners. James et al. documented that the most common types of overuse injuries in the height of the 1970’s running boom were knee pain, shin splints, Achilles tendinitis, plantar faciitis, stress fractures and Iliotibial tibial tract tendinitis (James et al., 1978). More recently Hreljac (2004) reexamined overuse injuries in runners and observed that runners suffered from stress fractures, shin splints, chondromalacia patellae, plantar faciitis, and Achilles tendinitis (Hreljac, 2004). Taken together, these studies highlight that the type and rate of overuse running injuries has not changed over a 25 year period. It has long been hypothesized that the repetitive impact nature during running is a causative factor of overuse injuries (Hreljac, 2004; James et al., 1978). This hypothesis highlights the importance of the running shoe. Over this same time period, many running shoe companies have emerged and shoe research and design has led to the development of a variety of running shoe styles. The shoe styles of today are built to provide different levels of motion control, stability, cushioning and performance, for example. Despite advances in shoe technology, it is apparent that runners are still susceptible to overuse injuries (Hreljac, 2004; James et al., 1978).

The lack of change in the risk of overuse injuries has led some researchers to question whether shoes should be worn at all (Robbins & Gouw, 1991; Robbins & Hanna, 1987; Robbins et al., 1988). Although there is anecdotal evidence suggesting that
there are benefits of barefoot running, there is a paucity of research investigating impact characteristics during barefoot running (De Wit \textit{et al.}, 2000). A limitation of the De Wit study is that runners were instructed to run with a heel-toe running pattern. Although it is well established that roughly 80% of runners use a heel strike pattern in shod running (Kerr \textit{et al.}, 2003), it is not known if subjects would naturally select a heel-toe pattern during barefoot running. In fact, an investigation on footstrike in barefoot running found that runners contacted the ground with a more plantarflexed position of the foot at contact as compared to shod running (Freedman \textit{et al.}, 2007). Furthermore it is not known how impact characteristics in barefoot running compare when runners are allowed to freely select a footstrike pattern. Therefore the purposes of this study were to 1) compare impact characteristics during barefoot and shod running when footstrike pattern is not constrained and 2) to compare impact characteristics of barefoot running when footstrike is constrained to heel-toe.

**Definitions**

**Ground Contact Index (GCI):** A measure of the position of the foot at the time of ground contact in running.

**Impact Peak (F1):** The peak of the vertical ground reaction force in walking or running that occurs without muscular control. It is dependant on the kinematics of the lower extremity as well as the impact velocity (Hamill & Knutzen, 2003).

**Active Peak:** The peak in the vertical ground reaction force in walking or running that occurs at midstance (Hamill & Knutzen, 2003).

**Loading Rate:** The rate of increase of the vertical ground reaction force from the time of contact the time of F1.
Stride Length: The horizontal distance traveled in one stride. A stride is defined as the time from the contact of one foot until the next contact of the same foot.

Stride Rate: The number of strides in a minute.

Peak Leg Acceleration: The maximum in the profile of the leg accelerometer that coincides with impact.
CHAPTER 2

LITERATURE REVIEW

Functional Anatomy of the Foot and Ankle

The foot is made up of muscles, bones, and ligaments that allow for static weight bearing activity as well as movement and propulsion for walking and running. The foot is often divided into three sections; the rearfoot, the midfoot and the forefoot.

The rearfoot is comprised of both the ankle, or talocrural joint, and the subtalar joint. The ankle joint is formed by the tibia, fibula and the talus. It is a hinge joint and allows for movements of plantarflexion and dorsiflexion. The subtalar joint is made up of the talus and the calcaneous and allows for adduction and abduction of the rearfoot. It is through the calcaneous that body weight is transmitted to the ground through the heel pad.

The midfoot contains the navicular, cuboid and the medial, intermediate, and lateral cuneiform bones. The articulations of these bones provide a flexible connection of the rearfoot to the forefoot. The tarsometatarsal joints occur between the cuboid and the cuneiform bones in the midfoot and provide connection to the forefoot articulating with the metatarsal bones. Only small gliding motions are permitted by the flat surfaces in the tarsometatarsal joints (Gench et al., 1999; Whittle, 2003).

The five metatarsal bones and the toes form the forefoot. The articulation of the metatarsal bones and the phalanges (toes) occurs at the metatarsophalangeal joint. These
joints allow for abduction, adduction, flexion and extension. The interphalangeal joints are hinge joints and allow only flexion and extension (Gench et al., 1999; Whittle, 2003).

**Why Study Barefoot Running?**

It has been hypothesized that the shoe is altering sensory input the body should receive. This altered input may therefore place the runner at risk of injury. Robbins and colleagues have investigated this hypothesis through a series of studies investigating the effect footwear has on impact as well as to the musculoskeletal system of the body (Robbins & Gouw, 1991; Robbins et al., 1989; Robbins & Hanna, 1987; Robbins et al., 1988). Robbins and Gouw (1988) examined barefoot running as a method of injury prevention in that with increased barefoot weight-bearing activity, there would be changes in the structure of the foot. The authors stated that there are reports of lower running related injuries in countries where running shoes are not worn such as in the West Indies or certain countries in Europe and Asia. Researchers did not however, specify where these reports were found nor were they more specific as to which countries this referred. They hypothesized that this decrease in injuries is due to changes in the structure of the foot they expected to see. Researchers chose the length of the medial longitudinal arch, as measured from the medial tubercle of the calcaneus to the most distal point of the first metatarsal head, to be the dependant variable of interest. Researchers created a system to measure the length of the medial longitudinal arch of the weight-bearing foot. They created a force platform that arched with the foot so that when weight bearing, forces were equally distributed along the arch allowing for repeated measurements on various test days. Medial longitudinal arch length was measured using the X-rays taken with subjects standing on the altered force platform. Subjects were
instructed to increase their weight-bearing barefoot activity as much as possible, while maintaining a log of this activity. Medial longitudinal arch length was measured each month for four months. The researchers observed significant changes in arch length in 15 of the 18 subjects. Thirteen of these subjects had a significant shortening of the medial longitudinal arch with increased barefoot activity, while only two subjects saw a lengthening with increased barefoot activity. A control group of subjects was also followed while being asked not to significantly alter their training routines. Within the control group only one subject showed a shortening of the medial longitudinal arch and 10 subjects showed a lengthening through the duration of the study. Authors conjectured that the shortening of the arch length was a result of increased muscular activity in the intrinsic muscles of the foot that are not active during shod running and seem to be positive as the shortening of the medial arch allows the foot to dampen impact protecting the body from injury. Researchers assessed the subject’s training logs and reported increases in total weight-bearing barefoot activity, such as walking and running outdoors while barefoot, in those subjects with the largest adaptations in arch length. Researchers suggest that this change in arch length, especially with outdoor barefoot activity, may be due to plantar sensory feedback. They explained that the musculature that decreases arch length is activated when contact at the medial-posterior joints diminishes. Researchers suspected that this area of the plantar surface may have a decreased pain threshold, and that barefoot activity may increase arch height in order to protect the plantar surface (Robbins & Hanna, 1987).

Robbins, Hanna and Gouw (1988) investigated whether or not there was a relationship between plantar sensory input and impact characteristics. Subjects were
seated with their knee flexed at 90° with a load cell placed under the plantar surface of the weight-bearing foot. Loads were applied at the knee with three surface conditions; 1) with the subject barefoot with the foot in contact with highly compacted gravel, 2) barefoot with the foot in contact with a smooth plastic maintaining an unaltered weight-bearing position, and 3) with the subject’s personal footwear. As loads were applied to the knee, measures termed “avoidance behaviors” by investigators, were recorded. Researchers determined impact avoidance by calculating the difference between the ground reaction force seen on the load cell of the plantar surface and the load of the weight of the leg and load placed on the knee. Any difference observed from the load applied and the force measured was considered to have been avoided using primarily hip strategies. For all surfaces tested researchers found a significant increase in avoidance behaviors when applied load was increased. Avoidance behavior was different only between the gravel and smooth plastic surfaces. Researchers cited the differing levels of avoidance as confirmation that subjects were able to control impact magnitude. Researchers also cited differences in avoidance behaviors that were seen between surfaces, as evidence that sensory input affected the level of impact avoidance (Robbins et al., 1988).

Robbins and Gouw (1991) further investigated impact by researching different amounts of impact that subjects could tolerate with two surface conditions. They hypothesized that humans moderate shock when walking, running and jumping by avoiding discomfort on the plantar surface. They further hypothesized that athletic shoes, in their current form, attenuate these sensations that would otherwise lead to alterations in behavior that would help to avoid injury. Subjects were seated with their knee flexed at a
90° angle with their foot on either a smooth or textured surface. The smooth surface was selected to represent the surface of shoes. A downward directed force was delivered to the thigh near the knee to induce vertical impact. A force was applied to the foot near the Achilles tendon attachment in order to induce horizontal impact. A series of impacts were delivered to each subject with the maximum impact in each direction being delivered only once. A scale was provided with which subjects rated the discomfort associated with each impact. Researchers reported that both horizontal and vertical components of force were important in discomfort as ratings of discomfort increased with both horizontal and vertical components of force increasing independently. They observed that if either the horizontal or vertical forces were low, the subjects felt little to no discomfort. This relationship remained for differences in discomfort between surfaces as well. As long as the vertical impact remained low, differences in discomfort across surfaces were not seen. When the vertical impact increased, however, the textured surface showed significantly more discomfort than the smooth surface. While decreasing discomfort is often looked to as a goal in development of athletic equipment, researchers cited these findings as evidence that shoes block the natural ability to avoid impact. While this provides important evidence for barefoot running, limitations existed within the study that were not mentioned by the researchers. Though the apparatus delivering the impacts was built to simulate running impact, values were not actually obtained while running and differences in sensation may change. The implications of this study also rely on the fact that when running barefoot impact values are decreased as compared to running shod. As indicated by Robbins and Gouw, this may not be the case. While many studies have found similar impact values for barefoot and shod running few found lower
values for barefoot running. They suggest that these findings are due to the fact that subjects had not been trained in barefoot running and therefore had not adapted to the condition, and that trained barefoot runners would have decreased impact values when running barefoot (Robbins & Gouw, 1991).

Sekizawa and colleagues (2001) investigated the validity of the hypothesis that wearing shoes alters sensory perception. The purpose of the study was to determine if wearing shoes influenced the ability of subjects to perceive ankle angle positions. Three different shoe conditions were tested: a thick sole, a thin sole, and a barefoot condition. Prior to testing, subjects wore the test shoes for a total of 16 hours over 2 days so that they could familiarize themselves with the new shoe condition. Testing consisted of subjects placing the ankle in different positions while weight bearing. Ankle position was achieved by utilizing a slant board which was a surface that could be placed at varying angles. Subjects wore headphones and goggles that prevented seeing their feet in order to prevent visual or auditory feedback.

Each condition consisted of having subjects report what angle they felt the ankle was positioned in with angle always being measured between the foot and leg segments (vs. sole of shoe and leg angle). Prior to testing, subjects were familiarized with specific reference values of 0°, 12.5°, and 25° from a foot-flat position. The starting position for the board was set such that the ankle was in zero degrees regardless of the height of the shoe sole. The ankle was then placed at different angles between 0° and 25°. For each trial, subjects placed their dominant leg on the surface and shift their weight to it. They would then estimate the ankle angle and the movement. The dependent variable was angle error (estimated angle minus actual angle) with the independent variable being shoe
condition. Researchers reported that there were significant differences in the angle error between the shoe conditions. The greatest angle error was an underestimate of the actual angle and this was observed during the thick-sole condition (Sekizawa et al., 2001). This lack of ability to perceive the position of the foot provides evidence that shoes may actually mask important sensory information the body receives leading to possible injuries.

As barefoot running often requires contact with varying surfaces it is also important to review research investigating the texture of a surface in contact with the foot. Nurse et al. (2005) investigated the relationship between surface texture and walking behavior by comparing gait with two different textured surfaces. Subjects were instructed to walk at a constant speed (1.5 m/s) on an indoor walkway. The different surface textures consisted of two insoles of the same thickness, one with semi-circular mounds throughout the insole and the other being smooth. During testing, the textured side of the surface was placed on the plantar surface of the foot. Shoes were not worn at all, and the insoles were secured to the feet. Investigators measured kinematic measures of sagittal knee and ankle angles, as well as relative motion between the leg and rearfoot. Kinematic variables of knee and ankle joint angles as well as kinetic variables of joint moments and ground reaction force were also measured. Although there were no significant differences found in the knee joint angle, differences were seen in the ankle joint angle at heel strike. These differences revealed a more plantar flexed position at heel strike in the ankle joint in the textured insole condition. They also found that although there were no significant differences in the ankle joint angle at take off, during midstance there was a significant increase in ankle joint angle with the textured insole.
Investigators also reported that the analysis of kinetic data revealed similar peak vertical impact force values with both insoles, yet while wearing the textured sole there was a significant increase in the time to peak impact. The investigators therefore reported that the body does seem adjust walking behavior to the textured surface (Nurse et al., 2005). This is a considerable finding in that this is actually in opposition to data seen in barefoot running in which time to peak impact is often decreased as compared to shod running (De Wit et al., 2000).

What is Known About Barefoot Running?

While the studies previously mentioned have provided insight into barefoot behavior they lack direct analysis of barefoot running. Few studies have this direct analysis yet those that have, also provide important insight into the differences between barefoot and shod running.

Von Tscharner et al. (2003) investigated electromyography (EMG) signals of the tibialis anterior muscles during barefoot and shod running in order to determine how the activity of the muscle changed between running conditions. The researchers chose the tibialis anterior muscle as it is important in heel-toe running, maintaining a dorsiflexed position of the foot before heel-strike as well as controlling the plantar-flexion of the foot after heel-strike. Researchers hypothesized that there would be a higher level of muscle activity before heel-strike in shod conditions. Forty male subjects were asked to run at 4 m/s along an indoor runway for five trials while barefoot and in two different shoes. The shoe conditions included a standard running shoe and a shoe with pronation control. Data collection included EMG data from the tibialis anterior muscle. Utilizing single subject analysis researchers reported that shod subjects exhibited greater EMG intensities
before heel-strike than after heel-strike while in barefoot conditions EMG intensities were greater after heel-strike than before. They also reported that in the barefoot condition EMG intensities occurred earlier after heel-strike in the barefoot condition than in the shod condition. Researchers concluded that there were physiological differences between barefoot and shod running (Von Tscharner et al., 2003).

Stacoff et al. (2000) investigated differences in skeletal movements of over-ground barefoot running using bone mounted markers. The goal of this study was to determine magnitudes of tibial rotation and movement coupling during barefoot running as this is commonly looked to as a cause of running injuries. Researchers hypothesized that there would be less tibial rotation in barefoot running and therefore running barefoot could protect a runner from injuries. Subjects (n=5) all had reflective markers on pins inserted into the bone on the foot and leg. Subjects ran in each of seven conditions; barefoot, in a normal shoe and with five different variations of the normal shoe. Using kinematic data of the reflective markers, values of tibial eversion and inversion were calculated as were velocities of tibial rotation. Researchers reported that movement coupling between the calcaneous and the tibia were similar in barefoot and shod running as were total magnitudes of eversion. They did, however, report that barefoot running had a lower eversion velocity than shod running. The authors also discussed that these findings differed from other studies in which total eversion differed between barefoot and shod running, yet they believe that the findings differed due to the fact that the previous studies used shoe-mounted markers rather then the bone-mounted markers they utilized (Stacoff et al., 2000).
De Wit and colleagues (2000) investigated kinetic and kinematic parameters of barefoot running at three different speeds. The aim of their study was to develop a comprehensive description of barefoot running. The subjects were trained long distance runners. Subjects ran both barefoot and in shoes over-ground at 3.5 m/s, 4.5 m/s, and 5.5 m/s while ground reaction force and sagittal and frontal plane kinematics were collected. In the analysis of data collected researchers reported that at all of the tested velocities, subjects took significantly smaller steps when barefoot as compared to shod. Further analysis revealed greater differences in angles at the distal segments of the foot during initial foot contact when barefoot. There was also a significantly smaller initial eversion at impact during barefoot running. As the authors hypothesized, barefoot running also showed a significantly larger loading rate than shod running. In spite of these differences, the magnitude of both the impact peak as well as the active peak of vertical force were similar in both conditions (De Wit et al., 2000).

Additional research, while not specifically looking at barefoot running, has included a barefoot condition in studies. Kurz and Stergiou (2003) investigated variability seen with varying footwear in an attempt to show that running shod and running barefoot were different. Two different shoes, a soft and hard midsole, were tested as well as running barefoot. Subjects ran with heel-toe running pattern on a treadmill. In order to determine variability researchers investigated knee and ankle angles and calculated variability using spanning set methods from ensemble curves. Variability was statistically increased in the barefoot condition, with the shod conditions being statistically the same. This increase in variability while barefoot was shown in
both the ankle and knee joints. Researchers therefore concluded that barefoot running was different from shod running (Kurz & Stergiou, 2003).

**Why Look at Impact?**

Impact has been looked to as an important aspect of running behavior, as it is most commonly viewed as the main contributing factor of injuries. James, Bates and Osternig (1978) discussed running injuries from etiological and treatment perspectives. Important factors of training proposed to cause injuries included excessive running mileage, training which is too intense as well as dramatic changes in training routines. Anatomic factors are also associated with running injuries, and commonly pronation of the foot is looked at. Factors related to shoes and footwear of running relate to both the changes in anatomical position of the body as well as cushioning of impact (James *et al.*, 1978).

Hreljac (2003) later investigated running injuries, finding that the rate of injuries remained high despite the time that had passed between this investigation and that performed by James, Bates and Osternig (1978). Hreljac cited training, anatomical and biomechanical factors that cause injury, though the explanation for each of these factors all referred to impact. He described a model of injury threshold, which includes the magnitude of a stress as well as the frequency of application, as factors relating to the threshold where injury will occur. As such, the kinematics of running and the effects the running surface and shoes have injuries are due the effect they have on the translation of impact from the ground through the body (Hreljac, 2004).

Though the explanations of running injuries provided by these investigators were similar, I contend that each of the factors relate back to impact. If mileage is increased
there will also be an increase in the number of impacts placed on the runner. Impacts will also increase when intensity or speed of a workout is increased. To increase speed stride length, stride frequency or both must be increased. Changes to either SL or SF have been shown to alter impact (Derrick et al., 1998; Mercer et al., 2003b; Winslow & Shorten, 1989). Anatomical factors also relate to impact in that they determine how the impact will travel through the body and how this impact can trigger new injuries and exacerbate existing injuries.

**What Alters Impact?**

Cavanagh and Lafortune (1980) aimed to identify how the center of pressure would change at impact in distance running. They hypothesized that altering lower extremity alignment at foot contact in running would alter impact characteristics. This investigation was completed by looking at impact of seventeen runners who were asked to run at 4 m/s. The runners were classified by their footstrike pattern according to center of pressure data. They noted that none of the subjects ran with a forefoot strike pattern leaving all runners in this study as either exhibiting a midfoot or rearfoot strike pattern. Ground reaction force data were compared for the two groups of runners. Researchers reported that the major difference in vertical impact between rearfoot and midfoot strikers was that the force-time profile in midfoot strikers was missing the initial active peak that is seen in rearfoot strikers (Cavanagh & Lafortune, 1980). As this peak is absent in midfoot strikers the time to peak impact is increased, decreasing the loading rate. This shows that heel-toe running may not provide the most protection from impact, and utilizing the design of shoes may place the runner at increased risk of injury.
Kerr et al. (2003) attempted to determine how runners strike the ground in real-life situations. In order to gain information on runners in a non-laboratory setting, researchers videotaped two road races. They classified shod runners as either forefoot, midfoot or rearfoot strikers based on video footage. A total of 753 runners were divided into the footstrike categories. Only two of the 753 runners were considered to be forefoot strikers by researchers. Overall 81% of the runners were classified as rearfoot strikers, making contact with their heel, with the remaining runners classified as midfoot strikers. Researchers cited these results as justification of the design of running shoes, which tend to have most of the cushioning located in the heel region of the shoe (Kerr et al., 2003).

Derrick and colleagues (1998) completed a project to investigate the shockwave that goes through the body at impact when running and how it can be altered. Researchers hypothesized that varying stride lengths would alter impact and therefore, the shockwave from impact. Subjects ran over ground while speed was kept constant at 3.83 m/s. Subjects ran at preferred stride length (PSL) as well as 10 and 20% above and below PSL. Rather than looking at ground reaction forces researchers looked at shock attenuation, which examines the relationship between accelerations at the tibia and the head. They found that as SL increased SA also increased. To further analyze this they looked at the accelerations of both the head and the leg. They found that changes seen in SA were a result of changes in the leg accelerations as changes seen in the head acceleration were significant yet small. They confirmed their hypothesis by finding that as SL increased they also saw increases in vertical impact (Derrick et al., 1998).

Mercer et al. also investigated the relationship between increases in SF and SL and impact by separating the parameters. By altering both SF and SL separately they
hypothesized that they would see which of the parameters affected changes seen in impact that occur with changes in velocity. Keeping velocity constant, subjects ran trials first at PSL, and 15% above and below PSL while maintaining SF at the preferred frequency utilizing a metronome to do so. They then had subjects run at PSL and manipulated SF so that subjects ran at PSF and 15% above and below PSF. Looking at both the head and leg accelerations, they found no changes in the head acceleration in any of the conditions yet found significant changes in the leg accelerations when SL and SF were manipulated. They also found that manipulations in SL created four times greater changes in leg accelerations than manipulations in SF. This allowed researchers to conclude that SL was the major factor influencing changes in impact characteristics (Mercer et al., 2003b).

Why Are We Not Choosing to Run to Protect Ourselves from Injury?

Determining why we choose to run the way we run would provide invaluable information that could lead to injury prevention. Unfortunately there does not seem to be just one factor determining running behavior. Research has determined that there are certain criteria to which we attempt to optimize running behavior (Hamill et al., 1995), yet there are still ranges within these data that suggest other behaviors are contributing as well. Hamill, Derrick and Holt (1995) attempted to answer this vast question by looking at shock attenuation, stride frequency (SF) and oxygen uptake while running. By utilizing stride frequency as the dependant variable, they were able to investigate how manipulating SF would affect oxygen uptake and shock attenuation. Subjects selected preferred running speed and SF through multiple trials. Once this preferred SF was determined trials were completed at 10 and 20% above and below this preferred SF.
Researchers found significant differences in oxygen uptake between all SF trials except for preferred SF and 10% above preferred SF which showed minimum values. This suggested that subjects chose preferred SF in order to minimize oxygen uptake although there did seem to be a range in SF at which energy cost was maintained. So the question remains what other factors contribute to determining this preferred SF. When leg impact was analyzed results showed that there were not significant differences between the preferred SF, 10% above or 10% below. Differences were only seen in the extreme conditions of 20% above and below preferred SF. This information did not lead researchers to believe that optimization was occurring based on impact or shock attenuation criteria (Hamill et al., 1995).

Investigations into the relationship between running economy and associated ground reaction forces were also completed by Heise and Martin (2001). Researchers refer to large variations in aerobic demand while running at submaximal speeds among similar groups of runners as reason to look for explanations more than running economy in determining running behavior. They hypothesized that less economical runners would exhibit higher vertical ground reaction force components as vertical motion takes away from the horizontal movement that is the goal of running. Components of vertical ground reaction force, which included total vertical impulse and absolute medial-lateral impulse (side to side motion that is perpendicular to the direction of movement), were investigated in conjunction with oxygen uptake to determine whether trends could be seen among ground reaction force and running economy. In order to collect data both on running economy and force subjects ran first on the treadmill and then immediately overground running over a force platform. Results showed significant correlations.
between running economy and total vertical impulse. Positive correlations, though not significant, were also seen for absolute medial-lateral impulse and running economy. Although these results supported their hypothesis, there were other characteristics of ground reaction forces investigated that did not fall in line with this (Heise & Martin, 2001). While this data represents only one study and therefore must be considered carefully, it provides possible explanations for variations seen in selected behaviors of runners.

Mercer and colleagues further investigated the notion of optimizing for impact. To complete this project subjects were asked to run with a variety of speeds for twenty trials in two conditions, while maintaining a similar pattern of speeds across both conditions. In the first condition subjects were allowed to run with their preferred stride length and in the second condition they were constrained to run with a stride length of 2.5 meters. As acknowledged by the researchers, this length may be an awkward stride length at both very fast and very slow running speeds. Nevertheless results showed that when subjects were able to vary SL, SL increased as velocity increased. In conjunction with these findings impact also increased with increases in velocity only when SL was allowed to vary. When SL was constrained impact values were maintained in spite of changes in velocity. This suggested to researchers that SL was not being selected to optimize impact. What researchers also saw of interest was that SF did not significantly change in the preferred conditions, also suggesting that running behavior is selected in order to maintain a certain number of strides, not on amount of impact (Mercer et al., 2005).
In summary, injuries suffered by runners have been hypothesized to result from the impact that occurs during each contact with the ground in running (Hreljac, 2004; James et al., 1978). Both increasing velocity and stride length have been shown to increase impact (Mercer et al., 2005; Mercer et al., 2003b; Munro et al., 1987). While 80% of shod runners maintain a heel strike pattern when running (Kerr et al., 2003) a change from this heel strike has been shown to alter impact (Cavanagh & Lafortune, 1980). Barefoot running is hypothesized by some researchers to increase sensory perception compared to shod running, therefore allowing the runner greater protection from injury (Robbins & Gouw, 1991; Robbins et al., 1989; Robbins & Hanna, 1987; Robbins et al., 1988). Changes in muscle activity, angle perception, knee and ankle angles at contact, variability and the position of the foot at contact have all been observed between barefoot and shod running (De Wit et al., 2000; Kurz & Stergiou, 2003; Sekizawa et al., 2001; Von Tscharner et al., 2003). It is however, not yet known how these changes may affect injury rates in runners.
CHAPTER 3

METHODS

Subjects

Ten volunteer subjects were recruited from the university community. All subjects were runners, running at least 10 miles per week, yet had little to no experience running barefoot. Subjects were determined to be inexperienced barefoot runners as long as they had not trained barefoot. Five female and five male subjects with the following characteristics participated: age 22.5 ± 3.1 years; height 170.3 ± 6.8 cm; mass 66.7 ± 10.5 kg. All subjects completed all running conditions.

Instrumentation

Ground reaction force data were collected using a force platform (Kistler Model #9281C). Kinematic data were collected using a 12-camera, 3-dimensional motion capture system (Vicon Corp., V4.6.142). A piezoelectric uniaxial accelerometer (Piezoeletronics) was used to record the acceleration profile of the leg. Lastly, velocity was monitored using two photocell timing lights.

Motion capture and force platform data were collected using Vicon software through a 16-bit A/D board at 120 Hz and 1000 Hz, respectively. Accelerometer and timing light data were collected through Bioware acquisition software at 1080 Hz. A laboratory constructed squarewave signal allowed for data synchronization of both data acquisition systems.
Procedures

After granting written consent as approved by the, subjects were weighed and their height measured in order to gather demographic information. The accelerometer was attached to the distal aspect of the right tibia on the medial side, using a flexible band that would allow for the accelerometer to be tightly secured to the leg. Subjects were also instrumented with 7-25mm reflective markers (Figure 1) on the right foot and ankle (medial and lateral malleoli, heel, and the head and base of the first and fifth metatarsals). The researcher explained and demonstrated the task the subject would be asked to do. All conditions consisted of the subject running on a 10 meter indoor runway with a force platform installed in the center. Subjects completed ten acceptable trials in each condition. An acceptable trial consisted of the subject fulfilling the requirements of the specific condition, striking the force platform with their right foot without altering stride in any way, as well as maintaining a speed within ±5% of 3.83 m/s.

![Figure 1. Photographs of Shod and Barefoot Marker Placement](image)

Each subject completed three running conditions. All conditions were performed at 3.83 m/s. Speed was determined using timing lights set up to record running speed through a ten meter test area. Two conditions consisted of runners completing trials...
without directions on how they should contact the ground with their feet while running.
In the first of these conditions subjects ran while running in laboratory shoes and in the
second subjects ran barefoot. In the final condition subjects ran barefoot while being
instructed to run with a heel-strike pattern.

Data Reduction

All data were reduced using two Matlab programs (appendix II) written for this
study. Leg acceleration profiles for each trial were graphed with the timing light profiles.
The leg acceleration peak occurring just before the signal for the first timing light
appeared was selected as well as the leg acceleration peak that occurred between the two
timing light signals, and coincided with contact on the force platform. Stride frequency
(SF) was calculated using stride time, which was the time between the selected leg
acceleration peaks (SF = 1/stride time). Velocity was calculated using distance between
the timing lights and the time it took to travel between the timing lights (velocity =
distance/time). Stride length (SL) was calculated based on the velocity and SF values
(Velocity = SF * SL). The leg acceleration peak occurring between the two timing light
signals was selected as the peak to be analyzed. The magnitude of this peak was
extracted from the data.

In order to determine footstrike pattern both kinematic and kinetic data were
utilized. The vertical and horizontal positions of each marker were extracted for the time
of contact (vertical ground reaction force greater than 40N). The vertical position of each
marker determined from the static trial was subtracted from the vertical position at
contact. This allowed for the normalization of the markers so that when the subject was
standing still the vertical position of each marker was zero. The horizontal and adjusted
vertical positions of the markers were used to graphically represent the data. First order polynomials were fit to scatterplots of the horizontal versus adjusted vertical marker position data sets. The slope of this line of best fit was used to represent the position of the foot and was termed Ground Contact Index (GCI). This process was completed for both the medial and lateral markers separately. The medial and lateral GCI values were averaged to represent the overall position of the foot with one GCI value.

The vertical ground reaction force curve was graphed so that F1 and loading rate could be determined. F1 was selected as the first peak that occurred between the time of contact and the active peak. The active peak was identified as the peak occurring midstance. The magnitude of F1 and time of occurrence, the time from the point of contact to the time of F1, were extracted from the data. The loading rate was calculated by dividing the value of F1 by the time to the F1 peak. Both the F1 peak and loading rate were normalized to the subjects’ body weight.

Statistical Analysis

Five dependant variables were analyzed: F1, stride length, loading rate, leg impact acceleration, and GCI. Repeated measures ANOVAs were used to compare each dependent variable between running conditions (shod, barefoot, and barefoot heel-toe). When repeated measures revealed significant differences, pairwise comparisons were made to determine where the differences occurred.
CHAPTER 4

RESULTS

F1 did not change between running conditions (Table 1, p=0.051). The loading rate, however, was different across running conditions (Table 1, p<0.0001). Specifically, loading rate was four times greater during barefoot vs. shod running (p<0.0001). Furthermore, loading rate was greater during barefoot heel-toe vs. barefoot running (p<0.05).

<table>
<thead>
<tr>
<th>Running Condition</th>
<th>Impact Peak (F1) (BW)</th>
<th>Loading Rate (BW/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHOD</td>
<td>2.00 ± 0.32</td>
<td>61.8 ± 12.3</td>
</tr>
<tr>
<td>BAREFOOT (BF)</td>
<td>2.25 ± 0.35</td>
<td>248.4 ± 90.1 *</td>
</tr>
<tr>
<td>BF HEEL-TOE</td>
<td>2.11 ± 0.36</td>
<td>315.7 ± 67.9 *^</td>
</tr>
</tbody>
</table>

* Significantly Different (p<0.001) from Shod
^ Significantly Different (p<0.05) from BF

Peak leg acceleration (Figure 2) was different between running conditions (p<0.0001). Peak leg accelerations were less during shod vs. barefoot running (p<0.05) as well vs. barefoot heel-toe running (p<0.05). There was no difference in the peak leg acceleration.
accelerations during barefoot and barefoot heel-toe running (p>0.05). Stride length (Table 2) was not different between running conditions (p=0.09).

![Peak Leg Acceleration](image)

*Significantly different (p<0.05) from shod running

Figure 2. Peak Acceleration Values of Each Running Condition

<table>
<thead>
<tr>
<th>Table 2 Stride Length Mean ± Standard Deviation Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running Condition</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>SHOD</td>
</tr>
<tr>
<td>BAREFOOT (BF)</td>
</tr>
<tr>
<td>BF HEEL-TOE</td>
</tr>
</tbody>
</table>

Footstrike patterns changed between all conditions as evident from significant (p<0.0001) changes seen in GCI (Figure 3). The greatest GCI value was seen in the shod (0.49 ± 0.12 GCI units) running condition. Significantly smaller GCI value was seen
between shod and barefoot heel-toe (0.35 ± 0.07 GCI units) running (p<0.05), as well as between barefoot heel-toe and barefoot (0.14 ± 0.18 GCI units) running conditions (p<0.05).

Figure 3. Representation of Mean GCI for Each Running Condition
The purpose of this study was to determine whether impact characteristics change between barefoot and shod running when footstrike pattern is not constrained as well as in barefoot running when footstrike changed. Increases in loading rate and peak leg acceleration were seen from shod to barefoot running. Loading rate also increased from barefoot running with no instruction to barefoot heel-toe running. These changes in impact characteristics were anticipated since it was that GCI would differ between barefoot, barefoot heel-toe and shod running. The lower GCI observed during barefoot running was an indication that the foot was more plantarflexed at contact compared to running in shoes or with instructions to run heel-toe while barefoot.

The magnitudes of $F_1$ in the shod condition in this study were similar to other published data (Miller, 1990; Milner et al., 2006; Munro et al., 1987). Miller (1990) reported that $F_1$ ranges between 2 and 3 BW for running velocities between 3 and 5 m/s (Miller, 1990). Similar values for $F_1$ can be seen both in the current study as well as those completed by other investigators (Table 3). Across several studies the magnitude of $F_1$ ranged from 1.7 to 2.0 BW (Miller, 1990; Milner et al., 2006; Munro et al., 1987), the running velocities from the same investigations ranged from 3.7 to 4.0 m/s. Increases in velocity have been shown to increase $F_1$ (Munro et al., 1987). Therefore, the range of $F_1$ values seen is likely due to the range seen in running velocity. Loading rate was also
calculated in each of these investigations. Loading rate values ranged in these investigations from 61.8 to 90.5 BW/s (Miller, 1990; Milner et al., 2006; Munro et al., 1987). While changing velocities may have also caused this variation, it could also be due to differences in methods of calculating loading rate. Munro et al. (1987) used the vertical ground reaction force curve from the time it exceeded 50 N until it reached 50N greater than 1BW (Munro et al., 1987). Milner et al. (2006) calculated loading rate using the portion of the vertical ground reaction force curve that fell from 20 to 80% of the time between contact and F1 (Milner et al., 2006). While all methods of calculating loading rate are looking at rate of increase of the vertical ground reaction force, the slight alterations in calculations are likely to result in different loading rate values.

Table 3  Velocity, F1 and Loading Rate Mean and Standard Deviation Values from Investigations of Shod Running

<table>
<thead>
<tr>
<th>Study</th>
<th>Velocity (m/s)</th>
<th>F1 (BW)</th>
<th>Loading Rate (BW/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Current Study (Shod)</td>
<td>3.83</td>
<td>2.00</td>
<td>0.33</td>
</tr>
<tr>
<td>(Munro et al., 1987)</td>
<td>3.75</td>
<td>1.86</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>4.00</td>
<td>1.95</td>
<td>0.21</td>
</tr>
<tr>
<td>(Milner et al., 2006)</td>
<td>3.7</td>
<td>1.7</td>
<td>0.32</td>
</tr>
</tbody>
</table>

The magnitude of stride lengths and leg impact accelerations observed in the present study are comparable to published data (Derrick et al., 2002; Mercer et al., 2003a; Mercer et al., 2003b; Mizrahi et al., 2000; Valiant, 1990) (Table 4). Within these
studies stride length ranged from 2.43 to 2.78 meters (Derrick et al., 2002; Mercer et al., 2003a; Mercer et al., 2003b). Peak leg acceleration also varied within these studies ranging from 5.0 to 7.9 (Derrick et al., 2002; Mercer et al., 2003a; Mizrahi et al., 2000; Valiant, 1990). The ranges found in both of these parameters again can be explained by variations in running velocity as both stride length and leg acceleration have been shown to increase with increases in velocity (Mercer et al., 2005).

<table>
<thead>
<tr>
<th>Study</th>
<th>Velocity (m/s)</th>
<th>Stride length (m)</th>
<th>Peak Leg Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Study (Shod)</td>
<td>3.83</td>
<td>2.78</td>
<td>0.22</td>
</tr>
<tr>
<td>(Mercer et al., 2003a)</td>
<td>3.8</td>
<td>2.71</td>
<td>0.15</td>
</tr>
<tr>
<td>(Derrick et al., 2002)</td>
<td>3.4 (0.4)</td>
<td>2.43</td>
<td>0.04</td>
</tr>
<tr>
<td>(Mizrahi et al., 2000)</td>
<td>3.5 (0.2)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>(Valiant, 1990)</td>
<td>3.83</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>(Mercer et al., 2003b)</td>
<td>3.8</td>
<td>2.75</td>
<td>0.12</td>
</tr>
</tbody>
</table>

While there is abundant research available on impact characteristics of shod running, barefoot running research is less prevalent. De Wit et al. (2000) completed a study investigating both kinetic and kinematic parameters of running (De Wit et al., 2000) allowing for similarities between the findings of this and the current study to be
seen (Table 5). While GCI was not a measure previously used in the literature, De Wit et al. (2000) also reported a flatter foot position at contact as measured in conjunction with various other kinematic parameters. In the De Wit et al. (2000) study various velocities were investigated to determine differences that occurred with changing velocities. The current study had subjects run at only one velocity. Although the velocities differed between studies, the velocity used in the present study (3.83 m/s) was within the range of the velocities used by De Wit, et al. (2000) (3.5 m/s - 4.5 m/s).

Table 5 FI, Loading Rate and Stride Length Mean ± Standard Deviation Values from Current and Previous Barefoot Running Study

<table>
<thead>
<tr>
<th>Variable</th>
<th>Current Study 3.83 m/s</th>
<th>De Wit et al. 2000 3.5 m/s</th>
<th>De Wit et al. 2000 4.5 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI (BW)</td>
<td>2.00 ± 0.33</td>
<td>2.25 ± 0.35</td>
<td>2.11 ± 0.36</td>
</tr>
<tr>
<td>Shod</td>
<td>0.33</td>
<td>0.35</td>
<td>0.30</td>
</tr>
<tr>
<td>Barefoot</td>
<td>2.00 ± 0.33</td>
<td>2.25 ± 0.35</td>
<td>2.11 ± 0.36</td>
</tr>
<tr>
<td>Heel-Toe</td>
<td>1.9 ± 0.30</td>
<td>1.8 ± 0.30</td>
<td>0.40</td>
</tr>
<tr>
<td>Stride Length (m)</td>
<td>2.78 ± 0.22</td>
<td>2.76 ± 0.22</td>
<td>2.69 ± 0.11</td>
</tr>
<tr>
<td>Shod</td>
<td>2.76 ± 0.22</td>
<td>2.66 ± 0.22</td>
<td>2.56 ± 0.22</td>
</tr>
<tr>
<td>Barefoot</td>
<td>2.76 ± 0.22</td>
<td>2.66 ± 0.22</td>
<td>2.56 ± 0.22</td>
</tr>
<tr>
<td>Loading Rate (BW/s)</td>
<td>61.8 ± 12.3</td>
<td>248.4 ± 90.1</td>
<td>315.7 ± 67.9</td>
</tr>
<tr>
<td>Shod</td>
<td>91.0 ± 35.0</td>
<td>409 ± 139</td>
<td>123 ± 48</td>
</tr>
<tr>
<td>Barefoot</td>
<td>575 ± 203</td>
<td>575 ± 203</td>
<td>575 ± 203</td>
</tr>
</tbody>
</table>

Magnitudes of FI for shod running were similar between the current study and the slower speed of the study by De Wit et al. (2000), yet still fell between values of FI for the two speeds. It has been established that FI will increase with increasing velocity (Munro et al., 1987), so the slight increase in FI in shod running in this study from FI at

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3.5 m/s is expected. The same trend can be seen in the magnitude of F1 during barefoot running when comparing the results of the present study to those of De Wit, et al. (2000). The magnitude of F1 during both barefoot running conditions fell in between the magnitude of F1 in the faster and slower speed condition of the previous study. Results of both studies also indicated that there were not significant differences in F1 between barefoot and shod running (De Wit et al., 2000).

Like the current study, De Wit also observed that loading rate increased in barefoot running as compared to shod running. However, the magnitude of the loading rates reported by De Wit were nearly two times greater than those observed in the current study. The difference between the magnitude of loading rate observed in each of these studies is most likely related to the method of calculating loading rate. In the current study loading rate was calculated by determining the ratio of the magnitude of F1 to the amount of time from contact to the occurrence of F1. The previous study, however, determined the loading rate as the peak value seen in the ratio of vertical force to change in time from the time of contact to the occurrence of F1. Therefore, the lower magnitude of loading rate seen in the current study for barefoot and shod running as compared to those observed by De Wit are reasonable findings (De Wit et al., 2000).

In the De Wit (2000) study step length was reported and analyzed rather than stride length. In order to compare their results to the results of the current study the step length values were doubled to represent stride length (Table 5). While the results of stride length for running conditions were also similar between studies, the previous investigation reported greater and significant differences in stride length between barefoot and shod running that were not seen in the current study (De Wit et al., 2000).
There was a trend (p=0.051) that F1 was changing between running conditions in the current study as F1 was greater during barefoot running with no instructions compared to F1 during shod (p=0.087) and compared to barefoot heel-toe running (p=0.091). The magnitudes of F1 in shod and barefoot heel-toe running were similar. These similarities were initially believed to be the result of the more dorsiflexed position of the foot at contact observed in these conditions, as compared to barefoot running. However, it was hypothesized that F1 in barefoot heel-toe running would be greater than F1 in barefoot running with no instruction. It was thought that the increased dorsiflexion seen in barefoot heel-toe running would lead to an increase in F1 as compared to the flatter foot position of barefoot running. It was, however, observed that the highest mean value of F1 (2.25 BW) occurred in the barefoot condition with no instruction. While this was unexpected, it is conjectured that the 0.25 BW decrease in F1 from barefoot to shod running is a result of the cushioning properties of the shoe. The 0.14 BW decrease in F1 of barefoot heel-toe running from the F1 of barefoot running without instruction, however, may be explained by the reaction of the subjects when they were asked to run heel-toe. Many of the subjects were hesitant to run on the tile surface of the lab contacting the ground with their bare heel. Although it was not measured in this investigation, perhaps runners altered the kinematics of the lower extremity above the ankle to allow for a “softer” running style. This can be further justified as the magnitudes of F1 in barefoot heel-toe running (2.11BW) and shod running (2.00 BW) were similar. It appears that in the barefoot heel-toe running condition subjects adopted a running style that allowed for F1 to be decreased as much as the cushioning system of the shoes decreased F1 in shod running.
In spite of the lack of significant changes in F1 between conditions, there was still an increase in the loading rate from shod to barefoot to barefoot heel-toe running. The calculation of loading rate was based upon the magnitude of F1 and the time to F1. Therefore, an increase in loading rate in conjunction no change in F1, suggests a decrease in time to F1 from shod to barefoot and barefoot to barefoot heel-toe running. The likely cause of shod running resulting in the lowest loading rate is once again the cushioning properties of the shoe. The running shoe is designed to absorb impact. Therefore, as the foot contacts the ground in shoes, the sole of the shoe compresses delaying F1 until the shoe sole has reached maximum compression. As runners were barefoot in both barefoot and barefoot heel-toe running conditions there was not a difference in the surface (i.e. a shoe sole) to explain the increase in loading rate observed from barefoot to barefoot heel-toe running. However, this increase was likely caused by the change in the position of the foot at contact. Runners had a more plantarflexed position at contact in barefoot running with no instruction as compared to the dorsiflexed position observed in the barefoot heel-toe running condition. The plantarflexed position places more of the foot in contact with the ground and it is conjectured that this creates a longer loading time, decreasing the loading rate.

The third and final parameter of impact that was investigated in this study was peak leg acceleration. Peak leg acceleration was 2.5 times greater in both barefoot conditions as compared to shod running. The changes in peak leg acceleration are likely related the shock absorbing function of the shoes. In contrast, peak leg acceleration were not different between barefoot running conditions as had been hypothesized. It was hypothesized that barefoot heel-toe running would result in higher values of peak leg acceleration.
acceleration. Perhaps this finding of no difference also relates to the subjects desire to run "softer", decreasing the leg peak in barefoot heel-toe running, as this condition was described as uncomfortable for the subjects.

As it has been established that stride length influences magnitude of peak leg acceleration (Mercer et al., 2003b), it was important to determine if stride length changed between running conditions in the current study. If the running conditions had affected the stride length the comparisons of impact characteristics would have to be carefully evaluated. Although stride length did not differ between any of the conditions, there was a trend (p=0.09) that stride length decreased from shod to barefoot running especially when subjects run barefoot with a heel-toe running pattern. The changes in stride length were small, with only a 0.09 meter difference between the conditions with the longest and shortest strides, and not significant. It is therefore unclear if allowing subjects to select preferred stride length altered the impact characteristics. Future research is needed to determine the influence of stride length on these parameters. By determining impact during barefoot and shod running at the same stride length, yet not preferred length, greater comparisons of how the running conditions may alter impact can be made.

There were constraints on the methods of this study that may have affected the outcome. The order of conditions was not counterbalanced in this study. Although this imposes a risk of an affect due to the order of conditions, it was felt that this risk was lesser than the risk of counterbalancing the conditions. It was important to the design of the experiment that runners selected a preferred running style during barefoot running without being biased by first being instructed to run with a heel-toe pattern. It was suspected that if subjects had already been instructed to change the way they were
running (i.e., with instructions to run heel-toe), they would no longer be able to run without thinking about their running style, and their preferred running style would not be maintained.

Although data were collected for ten subjects, only data from nine subjects were used for the analysis of FI and loading rate. This is due to the fact that in one subject there was a complete absence of FI in the vertical ground reaction force curve (Figure 4). Since the calculation of loading rate utilized in this study was dependant on FI it was not possible to calculate the loading rate for this subject.

![Figure 4. Representative Vertical Ground Reaction Force Curves for Two Subjects](image)

As one subject could not be included in the analysis of loading rate, it can be seen that the method of calculating loading rate in this study may be a limitation. Had more subjects exhibited this pattern it would be important to use a different method of calculating loading rate. The absence of FI means that there is a lower loading rate as the subject is running to completely avoid this impact peak. As it has been seen in the literature, this is often seen in runners with a midfoot strike (Cavanagh & Lafortune, 1980) and may be seen in more runners than were found in this study.
The kinematic data collected in this study allowed for calculations of the position of the foot at contact, yet did not provide information on any other joints of the lower extremity. It is impossible to know whether or not subjects were altering other aspects of the geometry of the lower extremity that may have also altered impact. If the subjects had in fact attempted to run softer in the barefoot heel toe condition this would be evident through changing the angle at contact of the knee and hip joints. While other studies have reported differences in these angles at contact between barefoot and shod running, they have still restricted their subjects to heel-toe running when barefoot (De Wit et al., 2000). It is unclear whether these changes are simply a result of subjects trying to lessen the impact in heel-toe barefoot running, or if this is the preferred style in barefoot running.

The increases that are seen in impact in barefoot running with similar stride lengths to shod running show that, over a given distance, a barefoot runner will incur a greater amount of impact than a shod runner. Thus, runners do not appear to be selecting running behavior in order to modulate impact. Perhaps the flatter foot placement seen in barefoot running is altering the way this impact is attenuated in the body. It is therefore important that future research on barefoot running not constrict the runner to a heel-toe running pattern. With the more plantarflexed position at contact that is seen in barefoot running, there is a greater area that the impact is acting on. Plantar pressure information as well as looking at the joint moments would be an important next step in barefoot running research to allow researchers to see how these impacts may be acting on the body differently from shod running.
Many questions on barefoot running remain unanswered. If impact parameters are increasing in barefoot running, as seen in this study in loading rate and peak leg acceleration, why would runners want to run barefoot? Impact has long been looked to as the cause of injuries so why would runners not choose to minimize impact when running? Yet hundreds of marathoners choose to take off their shoes and run barefoot each year. Many anecdotal accounts from barefoot runners can be found. They report suffering from many common running injuries until they began running barefoot. They look to barefoot running as a cure. So what is missing in the literature that could explain this phenomenon? Are there other runners who have not been heard who tried to run barefoot but found instead that it worsened their injuries? There is a great need for further research on barefoot running in order to understand what is really happening.
APPENDIX I

BIOMEDICAL SCIENCES INSTITUTIONAL REVIEW BOARD INFORMED

CONSENT AND SUBJECT DATA COLLECTION SHEET
INFORMED CONSENT
Department of Kinesiology

TITLE OF STUDY: Footstrike Patterns in Barefoot Running
INVESTIGATOR(S): John A. Mercer Ph.D

Julia A. Freedman

Purpose of the Study
You are invited to participate in a research study. The purpose of this study is to identify footstrike patterns in barefoot running.

Participants
You are being asked to participate in the study because you are a healthy adult between the ages of 18 and 40 with no injuries that will affect your ability to run.

Procedures
If you volunteer to participate in this study, you will be asked to do the following: Arrive at the lab wearing comfortable clothes that will allow you to run, including shorts. Up to 14 reflective markers will be attached via duct tape to your right foot, ankle and lower leg. You will also be asked to wear a plastic headband that will hold a lightweight accelerometer on your forehead as well as a rubber band around your right leg above your ankle to hold another lightweight accelerometer.

Once all instruments are attached you will be asked to stand still on the force plate for the completion of a static trial. At this point you will be asked to run 10 meters along the indoor runway at a self-selected pace so that your right foot completely contacts the forceplate that is in the middle of the runway. This run will be repeated for 30-70 trials while maintaining a similar speed. After running trials are completed the reflective markers will be removed.

Benefits of Participation
There may not be direct benefits to you as a participant in this study. However, we hope to learn what natural running patterns are when running barefoot. This will contribute to further research providing more insight into preventing injuries among runners.

Risks of Participation
There are risks involved in all research studies. This study may include only minimal risks. As with any exercise running can lead to muscle soreness. While not a risk of injury, the secure attachment of the accelerometers may lead to slight discomfort, although researchers will take all measures possible to reduce this discomfort. As this running task will be completed barefoot, there is also a minimal risk of cuts or scrapes on your feet. This risk will be greatly minimized by the careful inspection of the running surface prior to data collection.
Cost /Compensation
There will not be financial cost to you to participate in this study. The study will take approximately 90 minutes of your time occurring on one day. You will not be compensated for your time. The University of Nevada, Las Vegas may not provide compensation or free medical care for an unanticipated injury sustained as a result of participating in this research study.

Contact Information
If you have any questions or concerns about the study, you may contact Julia Freedman at 895-3419. or Dr. John Mercer, principal investigator, at 895-4672. For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted you may contact the UNLV Office for the Protection of Research Subjects at 702-895-2794.

Voluntary Participation
Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with the university. You are encouraged to ask questions about this study at the beginning or any time during the research study.

Confidentiality
All information gathered in this study will be kept completely confidential. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for at least 3 years after completion of the study. After the storage time the identifiable information gathered will be destroyed by shredding all materials.

Participant Consent:
I have read the above information and agree to participate in this study. I am at least 18 years of age. A copy of this form has been given to me.

Signature of Participant ____________________________ Date ________________

Participant Name (Please Print) ________________________________

Participant Note: Please do not sign this document if the Approval Stamp is missing or is expired.
Kinetic Characteristics of Barefoot Running
(Footstrike Patterns in Barefoot Running)

Subject # ___________  Gender: M / F  Height (cm) ___________
Birthday/Age ___________________________  Weight (kg) ___________
Location of Files: ________________________  Distance between timing lights
3meters

<table>
<thead>
<tr>
<th>Condition 1 (Shod)</th>
<th>Condition 2 (barefoot)</th>
<th>Condition 3 (BF HT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>Time (s)</td>
<td>Good Trial (Y/N)</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>2</td>
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<td>20</td>
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</table>
APPENDIX II

MATLAB DATA REDUCTION PROGRAMS
Footstrike Program to calculate GCI and Vertical GRF parameters

%footstrike
%written to calculate GCI and vertical GRF parameters for thesis project
%

clc
clear;
clear all;
fclose('all');
temporary_directory = pwd;
fprintf(1,'n
Processing
n');

% Change the following parameters
% prior to running program

subjects = 1; % number of subjects to process
conditions = 1; % number of conditions per subject
trials = 2; % trials per condition
startwithsubj = 27; % subject number to start with
startwithcond = 3; % condition number to start with (there were 6 conditions)
startwithtrial = 1; % trial number to start with

directory = 'c:\biomech\Thesis\S27'; % directory where data is located
outputfile = 's27extratrials.txt';

% some conditions did not have continuous trial numbers
actualtrialnumberC1 = [17 18 19 20 22 23 24];
actualtrialnumberC2 = [3 5 7 8 9 10 11 12 13 14];
actualtrialnumberC3 = [9 18 5 10 17 18 21 22];

precision = 4; % output precision
searchwindow = 5; % number of points for searching max

savedata = 'yes';
savefiles = 'yes';

% motion capture data
viconheadersmc = 11;
fsmc = 120;
viconcolmc = 22;
%analog data
fsa = 1080;
viconcola = 13;
viconheadersa = 9;

%ground contact cutoff
f\text{zcuttoff} = 40;

\begin{verbatim}
filenumber = 0;
for s = startwithsubj:(startwithsubj+subjects-l)
    for c = startwithcond:(startwithcond+conditions-1)
        for temp t = startwithtrial:(startwithtrial+trials-1)
            if c == 1
                t = actualtrialnumberC1(temp_t);
            else
                if c == 2
                    t = actualtrialnumberC2(temp_t);
                else c == 3
                    t = actualtrialnumberC3(temp_t);
                end
            end
            %keep loop counter
            filenumber = filenumber+1;
            %open a file
            [viconmcdata, inputfile] = foot_open(s, c, t, 'me', directory, '.txt', '.mot',
                viconcolmc, inf, viconheadersmc, 0);
            [viconadata, inputfile] = foot_open(s, c, t, 'a', directory, '.txt', '.grf, viconcola, inf,
                viconheadersa, 0);
            %open static file and adjust data so that static vertical position is zero.
            if temp t == startwithtrial
                [staticdata, inputfile] = foot_open(s, c, t, 's', directory, '.txt', '.mot', viconcolmc,
                    inf, viconheadersmc, 1);
            end
            %identify motion capture variables from vicon
            heely = viconmcdata(:,9);
            heelz = viconmcdata(:,10) - mean(staticdata(:,10));
            mmaly = viconmcdata(:,3);
        end
    end
end
\end{verbatim}
mmalz = viconmcdata(:,4) - mean(staticdata(:,4));
Imaly = viconmcdata(:,6);
Imalz = viconmcdata(:,7) - mean(staticdata(:,7));
mth5y = viconmcdata(:,12);
mth5z = viconmcdata(:,13) - mean(staticdata(:,13));
mtb5y = viconmcdata(:,15);
mth5z = viconmcdata(:,16) - mean(staticdata(:,16));
mtl1y = viconmcdata(:,18);
mth1z = viconmcdata(:,19) - mean(staticdata(:,19));
mtb1y = viconmcdata(:,21);
mth1z = viconmcdata(:,22) - mean(staticdata(:,22));
mcframe = viconmcdata(:,1);

%identify Fz
Fz = viconadata(:,10);
aframe = viconadata(:,1);
[HC, TO] = findHCTO(Fz, Fzcuttoff);

%identify HC for mc data
% mcHC = floor(HC/fsa*fsmc)- mcframe(1)+1;
mctime = mcframe/fsmc;
tempmcHC = fmd(mctime > FIC/fsa);
mHC = tempmcHC(1);

%plot
subplot(2,1,1)
plot(aframe/fsa,Fz)
hold on
plot(aframe(HC)/fsa, Fz(HC), 'ro')
plot(aframe(TO)/fsa, Fz(TO), 'bo')
ylabel('Fz')
xlabel('time (s)')
title('Ground Reaction Force')

subplot(2,1,2)
plot(mcframe/fsmc, heelz)
hold on
plot(mcframe(mcHC)/fsmc, heelz(mcHC), 'ro')
ylabel('position')
pause

%pull out data at contact for medial and lateral sides
medialfootz = [heelz(mcHC) mmalz(mcHC) mtb1z(mcHC) mth1z(mcHC)];
lateralfootz= [heelz(mcHC) Imalz(mcHC) mtb5z(mcHC) mth5z(mcHC)];
medialfooty = [heely(mcHC) mmaly(mcHC) mtb1y(mcHC) mth1y(mcHC)];
lateralfooty= [heely(mchC) lmaly(mchC) mtb5y(mchC) mth5y(mchC)];

close(gcf)
%plot all parameters
subplot(2,1,1)
plot(mctime, heelz)
hold on
plot(mctime, mmalz)
plot(mctime, mtb1z)
plot(mctime, mth5y)
plot(mctime(mchC), mmalz(mchC), 'bo')

subplot(2,1,2)
plot(mctime, heely)
hold on
plot(mctime, mmaly)
plot(mctime, mtb1y)
plot(mctime, mthly)
plot(mctime(mchC), mmaly(mchC), 'ro')

pause

close (gcf)
%plot all parameters
subplot(2,1,1)
plot(mctime, heelz)
hold on
plot(mctime, lmaly)
plot(mctime, mtb5z)
plot(mctime, mth5y)
plot(mctime(mchC), lmaly(mchC), 'bo')

subplot(2,1,2)
plot(mctime, heely)
hold on
plot(mctime, lmaly)
plot(mctime, mtb5y)
plot(mctime, mth5y)
plot(mctime(mchC), lmaly(mchC), 'ro')

pause

%fit data with a linear line
[med_p, med_s] = polyfit(medialfooty, medialfootz, 1);
medial = polyval(med_p, medialfooty);
[lat_p, lat_s] = polyfit(lateralfooty, lateralfootz, 1);
lateral = polyval(lat_p, lateralfooty);

%plot x,y
close(gcf)
%plot([1 2 3 4], medialfootz, 'rx')
plot(medialfooty, medialfootz, 'rx')
hold on
plot(medialfooty, medial, 'r')

%plot([1 2 3 4], lateralfootz, 'bo')
plot(lateralfooty, lateralfootz, 'bo')
plot(lateralfooty, lateral, 'b')

xlabel('horizontal position')
ylabel('vertical position')
pause

hold off

%find stance
stance = find(Fz > Fzcutoff);
stancetime = aframe(stance)/fsa - stance(l)/fsa;
Fzstance = Fz(stance);

%plot stance data
plot(stancetime,Fzstance,'k')
hold on

%find F1
[F1, F1pos] = findpeak(Fzstance, searchwindow, fsa);

plot(stancetime(F1pos), Fzstance(F1pos), 'ro')
pause(1)

F1time = F1pos/fsa;
loadingrate = F1/F1time;

%save data
total(filenumber,:) = [s c t med_p(l) lat_p(l) heelz(mcHC) heelz(mcHC) mmaly(mcHC) mmalz(mcHC) lmalz(mcHC) lmalz(mcHC) ...
mth5y(mcHC) mth5z(mcHC) mtb5y(mcHC) mtb5z(mcHC) mth1y(mcHC) mthlz(mcHC) mtb1y(mcHC) mtb1z(mcHC) F1 loadingrate];

end %next trial
end %next condition
end %next subject
%output data using a function 'my_save'
    if strcmp(savedata, 'yes')
        my_save(directory, outputfile, total, precision);
    end

%change back to original directory
    eval([`cd 'temporary_directory'])

%clean house
    close(gcf);
    fclose('all');

%identify done processing
    fprintf(1, 'done

');

%%%%%%%%%%%%%%%%%%%%%%%%---clean up-----------------------------------------
%                     clear;
%function: foot_open
%this function will run the commonly used commands to open a file.
%
%called as:
%   data = foot_open(s, c, t, datatype, directory, datain, dataout, columns, rows, headers)
%
%where
% directory = location of file
% filename = name of file with extension
% columns = number of columns
% rows = number of rows
% headers = number of headers to get rid of

function [tempdata, inputfileroot] = foot_open(s, c, t, datatype, my_dir, datain, dataout, columns, rows, headers, static);

    %create s?c?t? filename
    subj = int2str(s);
    cond = int2str(c);

    if static ~= 1
        tri = int2str(t);
        f_name = ['s' subj 'c' cond 't' tri datatype];
    else
        f_name = ['s' subj 'c' cond datatype];
    end

    fprintf(1,f_name); fprintf(1,'
');
    inputfileroot = f_name;

    %create filenames
    inputfile = [f_name datain];
    grfout = [f_name dataout];

    %my_dir = data directory
    %inputfile = filename with extension
    %columns = number of columns
%headers = number of headers to discard

%set up commands for eval function
%change to working directory
eval(['cd ' my_dir ';']);

%open the file
%create substrings
c = 'fid=fopen("';
d = ","rt");';

%create filename
file_name = [c, inputfile, d];

%open peak input file
eval(file_name);

%check to see if the open was successful
if fid == -1
    clc
    message = ['The filename ' inputfile ' does not exist in directory ' my_dir];
    error(message);
    fprintf(1,\n');
end

%get rid of headers
for h = 1:headers
    fgets(fid);
end

%read in data
A = fscanf(fid, '%f', [columns rows]);
tempdata = A';

%close files
fclose('all');
Program written to use timing light and accelerometer information to calculate leg peak and SL

%thesis data processing
%program written to process accelerometer data for leg peak and stride length

clc;
clear;
close gcf;
fprintf(1,'\n\nProcessing\n\n');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Change the following parameters prior to running program
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

subjects = 1; %number of subjects to process
conditions = 1; %number of conditions per subject
trials = 10; %trials per condition
startwithsubj = 25; %subject number to start with
startwithcond = 3; %condition number to start with (there were 6 conditions)
startwithtrial = 1; %trial number to start with

%conditions did not have consecutive trial numbers
actualtrialnumberC1 = [7 15 16 17 18 19 20 22 23 24];
actualtrialnumberC2 = [3 4 5 6 7 10 11 12 13 14];
actualtrialnumberC3 = [1 5 6 7 8 9 10 12 13 18];
directory = 'c:\Biomech\Bioware\s25\'; %directory where data is located
outputfile = 'S25C3out.txt';
precision = 4; %output precision
searchwindow = 15; %number of points for searching max

savedata = 'yes';
savefiles = 'yes';

%analog data
fs = 1000; %sampling frequency for the data
accelcol = 6; %number of columns in data
accelheaders = 14; %number of rows to discard from data
tl_distance = 3; %distance between timing lights

52
filenumber = 0;  %start counter

for s = startwithsubj:(startwithsubj+subjects-1)
    for c = startwithcond:(startwithcond+conditions-1)
        for temp_t = startwithtrial:(startwithtrial+trials-1)

            if c == 1
                t = actualtrialnumberC1(temp_t);
            else
                if c == 2
                    t = actualtrialnumberC2(temp_t);
                else c == 3
                    t = actualtrialnumberC3(temp_t);
                end
            end

            %keep loop counter
            filenumber = filenumber+1;

        %open a file
        [acceldata, inputfile] = thesis_open(s, c, t, directory, '.txt', '.mot', accelcol, inf, accelheaders);

        %identify variables from data
        time = acceldata(:,1);
        leg = acceldata(:,3);
        head = acceldata(:,4);
        tlstart = abs(acceldata(:,5));
        tlstop = abs(acceldata(:,6));

        %calculate velocity using find function to find time of voltage from each timinglight
        %data set
        %plot timing light start data
        subplot(2,1,1)
        plot(time,tlstart,'k')
        ylabel('timing light')
        xlabel('time')
        hold on

        %find timing light start time
        temp_start = find(tlstart > 1);
        tlstarttime = temp_start(1);
%plot point where start timing light signal occurs with a black circle
subplot(2,1,1)
plot (time(tlstarttime),tlstart(tlstarttime),'ko');

%plot timing light stop data
subplot(2,1,1)
plot(time,tlstop,'g')
ylabel('timing light')
xlabel('time')

%find timing light stop time
temp_stop = find(tlstop > 1);
tlstoptime = temp_stop(1);
%plot point where stop timing light signal occurs with a green circle
subplot(2,1,1)
plot (time(tlstoptime),tlstop(tlstoptime),'go');

%stop graphing on same figure
hold off

%calculate velocity
%amount of time between timing light signals
tl_time = (tlstoptime/fs)-(tlstarttime/fs);
%the distance the lights are set apart divided by the time it took to cross both
velocity = tldistance/tl_time;

%plot leg accelerometer data
subplot(2,1,2)
plot(time,leg)
ylabel('leg accleration')
xlabel('time')
hold on

%find first leg peak and graph on plot
fprintf(1,"\n\nClick on leg peak that comes before peak between timing light signals\n\n")
[firstpeak, firstpeaktime] = findpeak(leg, searchwindow, fs);
subplot(2,1,2)
plot(time(firstpeaktime), leg(firstpeaktime),'ro')

%find second leg peak and graph on plot
fprintf(1,"\n\nClick on next consecutive leg peak (one between timing light signals)\n\n")
[secondpeak, secondpeaktime] = findpeak(leg, searchwindow, fs);
subplot(2,1,2)
plot(time(secondpeaktime), leg(secondpeaktime),'ro')
%ask user to visually inspect graph
fprintf(1,"n\nCheck plotted max values\n click enter to continue\n\n');
pause(1);
hold off

%find time between peaks
stride_time = secondpeaktime/fs - firstpeaktime/fs;

%calculate the stride frequency
stride_freq = 1/stride_time;

%calculate the stride length
stridelength = velocity/stride_freq;

%save data
total(filename, :) = [s c t tl_time velocity stride_time stride_freq stridelength firstpeak secondpeak];
%clear screen for next trial
clear

end %next trial
end %next condition
end %next subject

%output data using a function 'my_save'
if strcmp(savedata, 'yes')
    my_save(directory, outputfile, total, precision);
end
Program written to open files for leg acceleration and SI.

%function: thesis_open
%this function will run the commonly used commands to open a file.
%called as:
data = foot_open(s, c, t, directory, datain, dataout, columns, rows, headers)

%where
directory = location of file
filename = name of file with extension
columns = number of columns
rows = number of rows
headers = number of headers to get rid of

function [tempdata, inputfileroott] = thesis_open(s, c, t, my_dir, datain, dataout, columns, rows, headers);

%create s?c?t? filename
subj = int2str(s);
cond = int2str(c);
tria = int2str(t);

f_name = ['s' subj 'c' cond 't' tria];

fprintf(1,f_name); fprintf(1,'n');
inputfileroott = f_name;

%create filenames
inputfile = [f_name datain];
grfout = [f_name dataout];

%my_dir = data directory
%inputfile = filename with extension
%columns = number of columns
%headers = number of headers to discard

%set up commands for eval function
%change to working directory
eval(['cd ' my_dir ';']);

%open the file
%create substrings
c = 'fid=fopen("';
d = '"","rt"');

%create filename
file_name = [c, inputfile, d];

%open peak input file
eval(file_name);

%check to see if the open was successful
if fid == -1
    clc
    message = ['The filename ' inputfile ' does not exist in directory ' my_dir];
    error(message);
    fprintf(1,'n
');
end

%get rid of headers
for h = 1:headers
    fgets(fid);
end

%read in data
A = fscanf(fid, '%f', [columns rows]);
tempdata = A';

%close files
fclose('all');
<table>
<thead>
<tr>
<th>Subject</th>
<th>19</th>
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</thead>
<tbody>
<tr>
<td>Birthday</td>
<td>12/20/1984</td>
</tr>
<tr>
<td>Age</td>
<td>22</td>
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<tr>
<td>Gender</td>
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</tr>
<tr>
<td>Height (cm)</td>
<td>178</td>
</tr>
<tr>
<td>Mass (kg)</td>
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<table>
<thead>
<tr>
<th></th>
<th>Shod Mean</th>
<th>Shod SD</th>
<th>Barefoot Mean</th>
<th>Barefoot SD</th>
<th>Barefoot Heel-Toe Mean</th>
<th>Barefoot Heel-Toe SD</th>
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<tr>
<td>GCI</td>
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<td>0.05</td>
<td>0.13</td>
<td>0.11</td>
<td>0.35</td>
<td>0.04</td>
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<tr>
<td>F1 (BW)</td>
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<td>0.19</td>
<td>1.78</td>
<td>0.21</td>
<td>1.73</td>
<td>0.13</td>
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<tr>
<td>Loading Rate (BW/s)</td>
<td>48.24</td>
<td>6.48</td>
<td>139.28</td>
<td>40.07</td>
<td>216.99</td>
<td>27.58</td>
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<tr>
<td>Leg Peak (g)</td>
<td>6.39</td>
<td>1.37</td>
<td>14.29</td>
<td>2.09</td>
<td>12.10</td>
<td>1.65</td>
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<tr>
<td>Stride Length (m)</td>
<td>2.75</td>
<td>0.06</td>
<td>2.80</td>
<td>0.05</td>
<td>2.67</td>
<td>0.05</td>
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<td>Mass (kg)</td>
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<th>SD</th>
<th>Barefoot Mean</th>
<th>SD</th>
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Tests of Within-Subjects Effects

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Pairwise Comparisons

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<th>(J) ftbw</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig. &lt;sup&gt;a&lt;/sup&gt;</th>
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<td>BFHT</td>
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Based on estimated marginal means

<sup>a</sup> Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).
## GCI

**Tests of Within-Subjects Effects**

Measure: MEASURE 1

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**Pairwise Comparisons**

Measure: MEASURE 1

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<th>(J) gci</th>
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<th>Std. Error</th>
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Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).
### PEAK LEG ACCELERATION

**Tests of Within-Subjects Effects**

Measure: MEASURE 1

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**Pairwise Comparisons**

Measure: MEASURE 1

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Based on estimated marginal means

- Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).
### LOADING RATE

Tests of Within-Subjects Effects

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<tbody>
<tr>
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<td>311372.566</td>
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<td>155666.283</td>
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### Pairwise Comparisons

<table>
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<tr>
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<th>(J) loadingr</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig. ^a</th>
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</thead>
<tbody>
<tr>
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<td>29.653</td>
<td>.0002</td>
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<tr>
<td>BF BFHT</td>
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<td>20.840</td>
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Based on estimated marginal means

^a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).
### STRIDE LENGTH

**Tests of Within-Subjects Effects**

<table>
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<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
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<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
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<td>.021</td>
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</table>

**Pairwise Comparisons**

<table>
<thead>
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</thead>
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<td>BF</td>
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</tr>
</tbody>
</table>

Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).
REFERENCES


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