BIOMECHANICAL DIFFERENCES BETWEEN HEEL-TOE AND FOREFOOT RUNNING

A Thesis in
Kinesiology

by
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ABSTRACT

**Biomechanical Differences Between Heel-Toe Running and Forefoot Running**

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Forefoot running has been suggested to decrease chronic injury when compared to heel-toe, or rearfoot running. Large, repetitive ground reaction forces (GRF’s) during the impact phase of running, when passive mechanisms absorb energy, may result in injury. Forefoot running traditionally results in greater angles of plantar flexion and knee flexion during impact, possibly providing shock absorption during running. The purpose of this study was to examine changes in sagittal plane ankle joint angles and differences in GRF’s between rearfoot and forefoot running. It is hypothesized that forefoot running would result in an elimination of impact peak GRF, higher active peak GRF’s, increased peak plantarflexion and total ankle joint excursion when compared to rearfoot running. Sixteen healthy participants (8 males, 8 females), between ages 18-45, classified as rearfoot runners were recruited for this study. Participants were tested while running across a force plate using a rearfoot strike. GRF’s were calculated and joint angles were recorded using motion analysis. Following a simple verbal instruction, participants were retested using a newly acquired forefoot running technique. Statistical analysis was conducted using paired t-tests with p< 0.05. Significant increases in peak plantar flexion (+6.1°) and total joint excursion (+2.5°) and a decrease in peak dorsiflexion (-3.6°) were observed in forefoot running when compared with rearfoot running. Impact peak GRF was not eliminated in all participants but was significantly lessened (-0.70 x BW) with forefoot strikes. Active peak GRF’s were significantly greater (+0.18 x BW) with forefoot strikes. The decrease and elimination of impact peak GRF and increases in plantar flexion may result in less stress being placed on bone and ligaments during impact, possibly leading to a decrease in chronic injuries associated with long distance running.
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Chapter 1

Introduction

Distance running has become one of the most commonly used modes of exercise, with participants ranging from competitive and recreational athletes competing for sport, to military recruits engaging in distance running for fitness training. As more individuals engage in distance running, there is a substantial increase in injury incidence. A systematic review recently conducted has found that between 19.4-92.4% of athletes will experience some form of injury as a result of running.60

While the incidence and sites of injury are well documented, little is still known about the mechanisms of these injuries. There are a number of intrinsic factors that are thought to be linked to injury incidence including body mass index, gender, age, structural abnormalities and previous history of injury. Extrinsic factors thought to be linked with running injuries include footwear, running surface, level of fitness, intensity and duration of training.16, 32, 55, 60

It has been suggested that how a runner contacts the ground with the foot is an important predictor of injuries. Between 75-90% of runners are rearfoot strikers, making contact with the ground with their heel, while the rest are midfoot and forefoot strikers.27, 35 Forefoot runners make initial impact with the toe and metatarsal heads and have vertical alignment of the shoulder, hip and ankle of the support leg with the body’s center of mass.19 This alignment shifts range of motion and joint moments from the knee and hip, making the ankle the primary joint of work.57, 64
A recent retrospective study found that rearfoot runners were 2.4-2.6 times more likely to experience an injury than forefoot runners.\textsuperscript{16} Forefoot runners are characterized by lacking an impact peak ground reaction force that is typically seen with rearfoot runners.\textsuperscript{64} Impact peak has been associated with an increase in injury incidence.\textsuperscript{23} It has been proposed that running with a forefoot strike will eliminate injuries associated with this impact peak.\textsuperscript{16, 64}

**Objectives**

The objectives of this study are to: 1) compare differences in ankle joint range of motion in the sagittal plane during stance phase, including angle at impact, peak plantar flexion, peak dorsiflexion and total joint excursion between rearfoot and forefoot running and 2) compare impact and active peak vertical ground reaction forces between rearfoot and forefoot running.

**Hypotheses**

*Hypothesis 1:*

Forefoot strikers will demonstrate a significant increase in plantar flexion at impact and a greater peak plantar flexion angle.

*Hypothesis 2:*

Forefoot striking will result in an increase in total ankle joint excursion when compared to rearfoot striking.

*Hypothesis 3:*

Impact peak ground reaction forces will be eliminated with a forefoot strike, but forefoot striking will exhibit larger active peak ground reaction forces when compared to rearfoot striking.
Chapter 2

Review of Literature

Biomechanics of Running

Gait Cycle

The gait cycle is commonly broken into two phases: the stance phase and the swing phase. The stance phase is described as the point of initial foot contact. It is divided into four subphases: loading response, midstance, terminal stance and pre-swing. The swing phase begins during toe-off and ends with the next initial contact.47

Running gait cycle is differentiated from walking by the presence of propulsion, in which the runner has become airborne. During running, there are two periods in which the runner becomes airborne, leading to an increase in swing phase time and a decrease in stance phase time. As velocity increases, stance phase generally decreases.47

Foot Contact

Depending on the running style, there are 3 distinct types of foot contact. Runners can be characterized as having a rearfoot, midfoot or forefoot strike. Rearfoot strike is exhibited in heel-toe running, where the runner contacts the ground with the lateral portion of the heel. Center of pressure then shifts medially and anteriorly, until push off where the center of pressure shifts back to the lateral portion of the foot.27 Roughly 75-80% of experienced endurance runners and 90% of recreational runners contact the ground with a rearfoot strike,35 making it the most common type of foot contact.38

Midfoot strike can be classified as initial contact being made with the entire sole of the foot, rather than just the rear third. Hasegawa, Yamauchi, & Kraemer (2007) found that 24% of elite runners during a half marathon contacted the ground with the midfoot, making it the second
most common type of heel strike. They also found that 36% of runners finishing in the top 50 of the marathon were midfoot strikers. Compared to 3.6% of midfoot strikers observed when examining recreational runners, it would appear that faster runners have a tendency to strike with the midfoot.\textsuperscript{27, 35}

Forefoot running is characterized with initial impact being made with the distal third of the foot. Forefoot running requires vertical alignment of the shoulder hip and ankle of the support leg with the body’s center of mass over the ball of the foot during impact with the ground. The hamstring muscles are utilized to pull the support foot vertically while the runner falls forward onto the ipsolateral leg, instead of driving it forward.\textsuperscript{19} Arendse et al. (2004) also discovered a greater angle of knee flexion during foot strike, resulting in a decrease in eccentric work performed at the knee. Several studies indicate that forefoot runners have a shorter stride length and an increase in stride frequency.\textsuperscript{3, 19}

It would also appear that as speed increases, foot strike shifts to initial contact being made at the forefoot. While a majority of endurance runners are rearfoot strikers, elite sprinters initial contact is made with the forefoot, sometimes without the rearfoot contacting the ground at all.\textsuperscript{47}

**Barefoot Running**

It has been suggested that humans became rearfoot runners as a result of the development of footwear. Shoes are developed with elastic material in the heel to absorb transient forces from impact.\textsuperscript{38} When footwear is removed, runners tend to adopt more of a midfoot or forefoot strike, possibly in an effort to keep loading within an individual’s optimal range.\textsuperscript{11} Despite this shift to a mid and forefoot contact, the change is not immediate. No acute changes were found in foot contact when footwear was removed.\textsuperscript{54} When footwear is removed from runners and they
continue to utilize a rearfoot strike, there is a significant increase in loading parameters in the barefoot condition, suggesting that the shift to forefoot running typically seen when footwear is removed, is likely a response to better attenuate force.\textsuperscript{53}

Running surface may play a role in the adoption of a non-rearfoot strike in barefoot running. Only 20\% of runners exhibited a midfoot or forefoot strike on a soft surface when footwear was removed, while 65\% of participants ran with a midfoot or forefoot strike on a hard surface.\textsuperscript{36}

**Pose Running**

The Pose running method is a style of forefoot running. It was designed based on previous research that determined running economy was improved with less vertical oscillation, reduced support time with greater power, earlier co-activation of the hamstrings and gastrocnemius during the support phase and reduced plantar flexion during foot removal.\textsuperscript{13}

Several studies have been done examining effects of the Pose Running method on performance. Running economy is associated with an individual’s chosen stride frequency and length. Altering these variables usually result in negative effects on sub-maximal oxygen cost. Dallam et al. (2005) examined running economy following a 12 week Pose running training protocol. Individuals running in the Pose method elicited a significant increase in oxygen cost when compared to the control. A study done by Fletcher et al. (2008) comparing Pose running to heel-toe running produced no significant increase in sub-maximal oxygen cost between the Pose group and the control group.

**Ground reaction forces**

Ground reaction force is the force the ground exerts on a body that comes in contact with it. During running, vertical ground reaction forces are typically between 2-4 times the
individual’s bodyweight. Biomechanical variables such as running speed, running surface, and type of footwear all have an impact on ground reaction forces. It has been shown that backward running produces a peak ground reaction force 25-33% of that produced from forward running.\textsuperscript{46}

During heel-toe running, vertical ground reaction forces have a passive peak and an active peak. The passive peak, commonly referred to as initial impact peak, is the peak ground reaction force from initial foot contact.\textsuperscript{64}

Figure 2-1. Rearfoot Running Vertical Ground Reaction Forces

![Graph of Ground Reaction Forces During Rearfoot Running](image)

The way in which the foot strikes the ground may have different effects on ground reaction forces, however there are conflicting reports. Oakley & Pratt (1998) found that forefoot running resulted in a decrease in magnitude and rate of shock at the tibia during foot contact,
while Laughton, Davis & Hamill (2003) found that tibial accelerations increased with forefoot running. An absence of an initial impact peak\(^5\) and greater active peak ground reaction forces were found with forefoot running,\(^3\) although a study performed by Arendse et al. (2004) showed that rearfoot running caused greater magnitudes and loading rates of vertical force at peak magnitude compared to forefoot running and Laughton et al. (2003), found an impact peak was still present some individuals engaging in a forefoot strike.

**Force Attenuation**

Although impact peak ground reaction forces are smaller than active,\(^4\) the impact peak occurs quicker than the lower extremity muscles can be activated. When muscle activation is delayed, it is unable to absorb impact forces, resulting in passive structures such as bones, ligaments and fat pads, being responsible for force attenuation.\(^3\) Repetitive force absorption by passive structures is thought to be the cause of a variety of chronic injuries seen in runners.

Wright, Neptune, Bogert & Nigg (1998) found shoe hardness had no effect on external impact ground reaction forces, but internal force was attenuated through passive mechanisms. Changes in midsole hardness do not affect impact ground reaction forces. Instead, runners alter mechanics by shifting initial impact laterally with increasing midsole hardness.\(^4\)

Compliant joints allow for greater force attenuation, while stiffer joints transmit force throughout the body.\(^2\) Lower limb joint stiffness can be altered during hopping activity of varying frequencies.\(^1\) Joint stiffness is also altered by varying stride frequencies during running, with stiffness increasing as stride frequency increases.\(^1\)

During rearfoot running, the knee has been identified as the primary joint for force attenuation during impact, with greater angles of knee flexion resulting in larger absorption of
force. In forefoot running, the ankle acts as the primary joint for attenuation, with the knee and hip being much stiffer than during heel-toe running.

It is believed that muscle activity increases just prior to impact in order to better attenuate impact forces. This “muscle tuning” is thought to occur within 100 ms of impact and serves to offset muscle latency. Alteration of muscle activity prior to impact will result in changes in joint stiffness. During running, the Achilles tendon stores elastic energy via the stretch-shortening cycle. Pre-activation of the gastrocnemius occurs before the stance phase, allowing negative work to be absorbed by tendon during the first 50% of the stance phase, and then utilized during push-off.

Different frequencies in tibial acceleration affect the mechanisms in which force is attenuated. At higher frequencies, passive mechanisms are responsible for attenuating force, while at lower frequencies, active mechanisms attenuate force. Greater tibial acceleration in the higher frequency range can be seen in rearfoot running when compared to forefoot. This may be a result of the increase in ankle compliance that is associated with forefoot running.

**Muscle Activity**

During running, muscle activation during the stance phase begins with a burst of activation from the leg extensor muscles (glutei, quadriceps, gastrocnemius and soleus) and co-contraction of the hamstrings and tibialis anterior. While onset of individual muscles is not simultaneous, activation will start prior to foot contact in order to have a stiff leg during landing.

Muscle activity of the lower extremity during gait is altered depending on the loading rate of impact forces at foot contact. Muscle activity varied among individuals when changing shoe midsole hardness, possibly as a mechanism to negate vibrations caused by impact.
During heel-toe running, the tibialis anterior is responsible for positioning the foot in dorsiflexion prior to impact and serves to reduce the plantar flexion moment upon contact. During shod running, EMG intensity for tibialis anterior was higher than barefoot running.\textsuperscript{61} Shih, Lang & Shiaing (2003) found that gastrocnemius activity increased in both the preactivation and stance phase when runners switched from heel strike to forefoot contact. This increase in activity can be attributed to a greater angle of plantarflexion at initial contact.
Etiology of Injuries

Although acute injuries occur during prolonged bouts of running, chronic overuse injuries appear to be much more common. A number of factors have been associated with increased injury risk, including age, sex, structural variances, distance per training session, frequency of training sessions, shoe structure and running surface. Ground reaction force attenuation is believed to be linked with a variety of injuries, although the mechanism is not completely understood. Runners generally experience 50 to 70 foot strikes per minute, with forces ranging from three to eight times the runner’s bodyweight. Roughly 75% of runners experience either a moderate or severe repetitive stress injury.

During rearfoot running, an initial impact peak is present as the heel strikes the ground. Because these ground reaction forces occur too quickly to be absorbed by muscle, ground reaction forces during impact are absorbed through passive mechanisms, such as heel fat pads, ligaments and bones, possibly resulting in a number of injuries, including tibial stress fractures and plantar fasciitis. Hamill, Moses & Seay (2009) found that runners with idiopathic lower extremity pain had stiffer knee joints. Pain was believed to be caused by poor force attenuation by the lower extremity, resulting in larger loads being translated into the axial skeleton.

Many have proposed that forefoot running reduces the risk of injury. In a retrospective cohort study, rearfoot runners, when compared with forefoot runners, experienced nearly twice as many moderate and severe injuries, with injuries above the ankle being as much as 2-4 times more prevalent.

Stress Fractures and Medial Tibial Stress Syndrome

Stress fractures and stress reactions are one of the most common injuries seen in athletes, and even more common in distance runners. Fredericson, Jennings, Beaulieu & Matheson,
(2006) found that up to 20% of all sports medicine injuries are lower limb stress fractures. The tibia is generally the most common spot for stress fractures, making up 33-55% of all incidences. Stress fractures are a result of repetitive strain, where bone adaptations do not keep pace with tissue damage. The cause of the strain is less understood. Some believe that it is caused by the active peak vertical ground reaction forces while others believe that stress fractures are a result of the initial impact peak. Several studies have shown that injured runners tend to produce larger vertical ground reaction forces. If stress fractures are truly caused by an impact peak, it is within reason to suggest that midfoot and forefoot running could decrease incidences of tibial stress fractures due to the absence the initial impact peak seen with this style of running.

Female runners with a history of tibial stress injuries have been shown to have greater rates of instantaneous and average vertical loading when compared to healthy controls.

Medial tibial stress syndrome is another common injury found in runners, characterized as a painful stress reaction. Studies have shown that between 4%-35% of military recruits experience medial tibial stress syndrome as a result of running activity and suggested that more injuries were likely undiagnosed, because recruits will often hide medical conditions and injuries. Studies on civilian populations indicated that 12% of high school runners will experience medial tibial stress syndrome as a result of distance running.

Some studies suggest that it is not the magnitude of ground reaction forces that result in stress fractures, but the rate of loading which causes injury. The micro-trauma that results from each initial impact is not typically enough to cause a fracture, however repeated loading with insufficient recovery time could be a factor in injury.
Anterior Compartment Syndrome

A study examining patients with anterior compartment syndrome found that a forefoot running training protocol decreased lower leg intra-compartmental pressure and decreased perceived pain with running.\textsuperscript{15} This is probably a result of decreased eccentric activity of the tibialis anterior with a forefoot strike.\textsuperscript{29,57}

IT Band Syndrome

Forefoot runners have been shown to have shorter stride length than rearfoot runners.\textsuperscript{28} A shorter stride length has shown to reduce step width.\textsuperscript{9} Although a reduced step width is associated with an increase in IT band strain and strain rate,\textsuperscript{43} the narrower step width exhibited by forefoot strikers did not result in an increase in peak IT band strain\textsuperscript{9} therefore it is unlikely that changing footstrike would reduce the risk of developing IT band pathology.

Patellofemoral Pain Syndrome

Forefoot strike has been shown to reduce peak patellofemoral joint stress by 14.6\% when compared to rearfoot strike,\textsuperscript{34} while barefoot running has been shown to have a 12\% reduction when compared to shod running.\textsuperscript{8} This may be explained by forefoot runners having a shorter stride length and increased step rate compared to rearfoot runners.\textsuperscript{28} Increasing step rate by 10\% reduces peak patellofemoral joint stress by 14\% \textsuperscript{39} and may be the mechanism responsible for the decrease in patellofemoral stress.

Forefoot Running and Injuries

While forefoot running may decrease incidence of many of the common injuries associated with rearfoot running, there is also a possibility that it may increase the incidence of injuries not typically seen with rearfoot running. A rearfoot impact utilizes the heel fat pad to attenuate some force.\textsuperscript{7} A forefoot strike does not utilize this mechanism, so it is possible that
repetitive impact force can cause injury to the metatarsals. In addition, greater moments at the ankle seen during forefoot running could increase injury, although it has not yet been proven whether or not joint moments are associated with injury risk. It is also likely that increased strain on posterior musculature would increase the injury incidence of the triceps surae as well as Achilles tendon.

Fuller et al. (2016) found that runners who adopted a midfoot strike were more likely to have reduced stride interval structure. It has been observed that fatigued and recently injured runners run with weaker stride interval correlations when compared to healthy runners, although further research is needed to determine causation.
Chapter 3

Methods

Participants

Sixteen healthy, rearfoot runners (8 males, 8 females, height 172.8 ± 9.0 cm, mass 75.4 ± 16.4 kg) participated in this study. Participants were excluded if they were not rearfoot runners, had previous training in forefoot running, had a BMI of over 30, had a surgery within the last two years or had a current injury that would be exacerbated by exercise. Participants were recruited by emailing the Pennsylvania State University Kinesiology undergraduate listserv. All work was reviewed and approved by the Pennsylvania State University Internal Review Board.

Testing Protocol

Participants underwent one data collection session in the gait lab of the Pennsylvania State University Biomechanics Lab. Prior to the testing session, participant’s height, weight and shoe size were recorded. Participants were given time to warm-up on their own. Participants were then fitted with 10 reflective markers. Marker clusters were placed on the mid shaft of the left tibia and the dorsal portion of the left shoe. A 3D photogrammetry system (Cortex, Motion Analysis Corporation, Santa Rosa, CA) was used to record the marker data at 100 Hz. Ground reaction forces were measured using a force plate (Kistler, Amherst, NY) in synchronization with the marker data with a 1000 Hz sample rate. Analysis was done on one cycle of stance phase when the participant made contact with the force plate.
The participants were then instructed to walk down a runway across a force plate using their normal gait. Participants were not given the specific location of the force plate in order to avoid alterations in gait to accurately strike the plate. Participants performed five trials of walking. If a participant completed a trial and did not cleanly strike the force plate, the participant was required to perform the trial again.

Following the walking trials, participants were instructed to perform five running trials using their normal running gait. Visual analysis was used to exclude any participants using a midfoot or forefoot running style. Similar to the walking trials, if a participant did not cleanly strike the force plate, they were required to perform the trial again.
Participants were then asked to complete another five trials, this time using a forefoot strike. They were instructed to land on the balls of their feet. No other instructions were provided. They were given a few trials to familiarize themselves with the technique, but no additional practice. The trials were performed using the same protocol as described above. If a participant did not cleanly strike the force plate, they were instructed to repeat the trial.

**Data Processing**

The Cortex software was used to post-process the marker data prior to exporting to MATLAB (the Mathworks, Natik, MA). Noise in marker data was reduced by using a dual-pass 4th-order, lowpass (Butterworth) filter with a cutoff frequency of 6 Hz. Ankle plantarflexion/dorsiflexion angle was calculated by using a purpose-written MATLAB program.

Of the 16 participants that completed the testing protocol, 2 male subject’s data were excluded due to corrupted data. Following the analysis in MATLAB, subject’s data from each of the 5 trials were averaged for each variable.

**Statistics**

Descriptive statistics were used to compare subject’s demographic data (Appendix E). Microsoft excel was used to perform paired t-tests to compare across subject means (± standard deviation) for impact peak ground reaction force, active peak ground reaction force, impact peak occurrence at percent of stance phase, total ankle range of motion during stance phase, peak plantarflexion and dorsiflexion angles during stance phase, ankle angle during initial contact and stance phase duration between rearfoot and forefoot conditions. T-Tests were used to compare range of motion and ground reaction force data between male and female subjects. F-tests were used to calculate variance. The p-value was set at p <0.05.
Chapter 4

Results

All subjects recruited completed their initial trials with a heel-strike at impact, so no
subjects were disqualified. After verbal instruction, visual assessment indicated all runners
adopted the forefoot strike at impact. Stance phase for rearfoot striking lasted for a duration of
0.30 ± 0.04 seconds and for 0.27 ± 0.02 seconds in forefoot striking. This 0.03 second difference
was significant (p<0.001).

Range of Motion

When subjects were asked to land with a forefoot strike, peak dorsiflexion of the stance
phase occurred at 20.6 ± 4.9 degrees, compared to 24.2 ± 3.8 degrees with a rearfoot strike
(p<0.001). Peak plantar flexion of the stance phase occurred at 30.9 ± 7.6 degrees in forefoot
strikes and 24.8 ± 7.6 degrees in rearfoot strikes, (p<0.001). Total ankle joint excursion during
the stance phase was significantly larger in forefoot running than rearfoot running (p=0.02) with
joint excursion being 51.5 ± 9.8 degrees with forefoot running and 49.0 ± 9.0 degrees with
rearfoot running.

Ankle angle at impact was 10.9 ± 4.0 degrees of dorsiflexion with rearfoot strike. Ankle
angle at impact with a forefoot strike was 22.8 ± 8.1 degrees of plantarflexion. This difference
was significant (p<0.001). Motion data is summarized in Table 4-1.
Table 4-1. Motion Data During Stance Phase for Rearfoot and Forefoot Conditions

<table>
<thead>
<tr>
<th>Impact Angle*</th>
<th>Peak Plantar flexion*</th>
<th>Peak Dorsiflexion*</th>
<th>Total Joint Excursion*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rearfoot</td>
<td>10.9 (± 4.0)</td>
<td>-24.8 (± 7.6)</td>
<td>24.2 (± 3.8)</td>
</tr>
<tr>
<td>Forefoot</td>
<td>-22.8 (± 8.1)</td>
<td>-30.9 (± 7.6)</td>
<td>20.6 (± 4.9)</td>
</tr>
</tbody>
</table>

Mean (± S.D.) motion data for rearfoot and forefoot strike trials for 14 subjects. – denotes plantarflexion. *significance at (p<0.05)

Figure 4-1. Ankle Range of Motion Through Stance Phase

Average angle of dorsiflexion (with SD) throughout stance phase for 14 subjects.
When grouping participants by gender, there were no significant differences in any of the range of motion variables. Peak dorsiflexion occurred at 23.6 ± 4.8 degrees for males and 24.6 ± 3.2 degrees for females with rearfoot strikes (p=0.64) and 21.34 ± 6.3 degrees for males and 20.0 ± 3.9 degrees for females with forefoot strikes (p=0.78). Peak plantar flexion occurred at 24.8 ± 9.9 degrees in male and 24.8 ± 6.1 degrees in females during rearfoot running (p=0.99) and 30.7 ± 8.0 degrees in males and 31.2 ± 7.7 degrees in females during forefoot running (p=0.91). Total joint excursion was 48.2 ± 12.5 degrees in males and 49.4 ± 6.3 degrees in females during rearfoot striking (p=0.85) and 52.0 ± 13.7 degrees in males and 51.1 ± 6.5 degrees in females during forefoot striking (p=0.89). During rearfoot running, angle at impact occurred at 13.1 ± 2.4 degrees of dorsiflexion in males, and 9.2 ± 4.3 degrees of dorsiflexion in females (p=0.05). Angle of impact during forefoot running at 21.5 ± 8.9 degrees of plantar flexion in males and 23.9 ± 7.8 degrees of plantar flexion in females. (p=0.61). Gender range of motion data is summarized in table 4-2.

Table 4-2. Gender Differences in Motion Data Between Rearfoot and Forefoot Conditions

<table>
<thead>
<tr>
<th></th>
<th>Rearfoot</th>
<th></th>
<th></th>
<th>Forefoot</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Impact Angle</td>
<td>Peak Plantar Flexion</td>
<td>Peak Dorsiflexion</td>
<td>Joint Excursion</td>
<td>Impact Angle</td>
<td>Peak Plantar Flexion</td>
<td>Peak Dorsiflexion</td>
<td>Joint Excursion</td>
</tr>
<tr>
<td>Males</td>
<td>13.1 (± 2.4)</td>
<td>-24.8 (± 9.9)</td>
<td>23.6 (± 4.8)</td>
<td>48.4 (± 12.5)</td>
<td>-21.5 (± 8.9)</td>
<td>-30.7 (± 8.0)</td>
<td>21.3 (± 6.3)</td>
<td>52.0 (± 13.7)</td>
</tr>
<tr>
<td>Females</td>
<td>9.2 (± 4.3)</td>
<td>-24.8 (± 6.1)</td>
<td>23.0 (± 3.2)</td>
<td>49.4 (± 6.3)</td>
<td>-23.9 (± 7.8)</td>
<td>-31.2 (± 7.7)</td>
<td>20.0 (± 3.9)</td>
<td>51.1 (± 6.5)</td>
</tr>
</tbody>
</table>

Mean (± S.D.) motion data for rearfoot and forefoot strike trials when subjects were separated by gender (6 males, 8 females). – denotes plantarflexion.
Ground Reaction Forces

Not all subjects exhibited impact peak ground reaction forces in the forefoot condition. During instances where a trial was missing an impact peak, the participant’s trial was excluded from the average. Two participants did not exhibit any impact peak ground reaction force at all during forefoot strike. When comparing impact ground reaction forces, only subjects that exhibited a discernable impact peak were utilized. Impact peak ground reaction forces were significantly larger in rearfoot strikes when compared to forefoot strikes (p<0.001). When an impact peak occurred, the average impact peak for rearfoot strikes was 1.56 x bodyweight, while the average impact peak when present in forefoot strikes was 0.86 x bodyweight.

Active peak ground reaction forces were significantly larger with a forefoot strike (p<0.001). Active peak ground reaction forces with rearfoot strikes was 2.34 x bodyweight, while forces with a forefoot strike were 2.52 x bodyweight.
Average for ground reaction forces (with SD) for the duration of stance phase for the 14 subjects normalized with bodyweight

There were no significant differences in ground reaction forces when subjects were grouped by gender. Male participants utilizing a rearfoot strike exhibited an impact peak ground reaction force of $1.58 \pm 0.21 \times \text{bodyweight}$ compared to $1.51 \pm 0.20 \times \text{bodyweight}$ observed in female participants ($p=0.61$). Impact peak in forefoot strikes was observed at $0.85 \pm 0.20 \times \text{bodyweight}$ in males and $0.86 \pm 0.17$ in females ($p=0.92$). Active peak during rearfoot striking occurred $2.35 \pm 0.20 \times \text{bodyweight}$ in males and $2.33 \pm 0.16 \times \text{bodyweight}$ in females ($p=0.86$) while active peak during forefoot striking occurred at $2.53 \pm 0.27 \times \text{bodyweight}$ for males and $2.50 \pm 0.20 \times \text{bodyweight}$ for females ($p=0.78$). Gender ground reaction force data is summarized in table 4-3.
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<td>Forefoot</td>
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<td>0.86 (± 0.20)</td>
<td>2.35 (± 0.20)</td>
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<td>Females</td>
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<td>0.87 (± 0.17)*</td>
<td>2.33 (± 0.16)</td>
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</table>

Mean (± SD) ground reaction force data for rearfoot and forefoot strike trials when subjects were separated by gender (6 males, 8 females). Ground reaction forces were normalized and expressed by bodyweight. Only trials that expressed a discernable impact peak were used for analysis.

* only 6 female participants exhibited impact peak ground reaction forces

There was a significant difference in timing of impact peaks between the two conditions. Impact peak during rearfoot striking occurred at 13.70 ± 1.69% of stance phase and at 7.78 ± 1.89% of stance phase (p<0.001).
Chapter 5

Discussion

Range of Motion

There was a significant difference in the ankle angle at impact. Rearfoot strikers had an average of 10.87 degrees of dorsiflexion at impact, compared to 22.84 degrees of plantar flexion during forefoot strike. The difference in angle at impact was statistically insignificant, but was borderline with a p-value just over 0.05. This confirmed the first hypothesis that forefoot runners make contact in a position of plantar flexion. It also confirmed the visual assessment that all runners were able to adopt a forefoot strike during the running trials and is consistent with research showing that a single session of simple verbal instruction is enough to elicit a forefoot strike in untrained runners.37

The results of this study are consistent with previous research showing that runners that demonstrate a rearfoot strike land in a position of dorsiflexion,56 requiring greater activation of the tibialis anterior prior to impact,54,66 while runners contacting the ground with a forefoot strike results in impact being made in a plantar flexed position and having a higher peak plantar flexion angle, placing more demand on the triceps surae and Achilles tendon.2,34,66 Reduced eccentric activity of the tibialis anterior is likely why individuals suffering from anterior compartment syndrome have reported alleviated symptoms when converting to a forefoot strike.29 It was also found that trials in which the participant utilized a rearfoot strike, a significant larger peak dorsiflexion angle was exhibited when compared to forefoot strikes. Peak dorsiflexion angle occurred in the mid stance phase and peak plantarfexion angle occurred at toe-off in both conditions, with the exception of two trials where peak plantarfexion occurred at impact in the forefoot condition.
It has been suggested that greater work being imposed on the triceps surae and Achilles tendon during forefoot strike, may increase injury incidence on these structures, although research is needed to examine the effects of joint moments at the ankle on these structures.\textsuperscript{2,33}

The second hypothesis was accepted as the results of this study showed there was a significant increase between total joint excursion at the ankle when runners switched to a forefoot strike. This aligns with previous research demonstrating larger ankle range of motion during stance phase when landing with a forefoot strike when compared to a rearfoot strike, while hip and knee range of motion is larger when landing with a rearfoot strike.\textsuperscript{58,64} This provides further evidence that demand during forefoot running shifts from the knee and hip joints towards the ankle joint. A shift in demand from the knee and hip to the ankle could possibly lead to a decrease in knee and hip injuries and an increase in incidence of ankle injuries, especially for individuals that do not possess adequate ankle ROM to adopt a forefoot running pattern.\textsuperscript{64} There were no significant differences in total range of motion between male and female participants.

Ground Reaction Forces

The final hypothesis that impact peak ground reaction forces would be eliminated and active peak ground reaction forces would be larger was partially accepted. The results of this study indicated that acute adaptations resulted in an altered impact peak, although an impact peak was still present in several trials for all but two participants. Impact peak was significantly smaller and occurred significantly earlier in stance phase in forefoot striking. Similar results were shown by Laughton et al. (2003), where an impact peak occurred earlier with forefoot running and was smaller in magnitude than in rearfoot running. This does not align with the observations of Williams et al. (2000), where forefoot runners exhibited a single, active peak ground reaction force and no impact peak.\textsuperscript{64} This suggests that there is a learning curve when
converting foot strikes, and conflicts with previous research where impact peak was eliminated when habitual rearfoot runners were instructed to run with a forefoot strike. Both studies allowed the participants several trials to practice the forefoot strike pattern, while this study did not. It is possible that a short practice session could eliminate impact transients noted with the forefoot strike pattern in this study. Strength of the triceps surae was not assessed prior to the trials. It is also possible that strength and conditioning of the gastrocnemius and soleus play a role in muscle tuning and participants with weaker musculature were not able to fully attenuate force in soft tissue, resulting in an impact peak. Male and female subjects did not exhibit significantly different impact peaks.

If impact peak is responsible for stress fractures as has been suggested it is possible that running with a forefoot strike and still possessing an impact peak could become problematic. A forefoot strike would bypass many of the passive structures that are thought to attenuate the impact peak, such as the heel fat pad. Modern day running shoes are also designed with a cushioned heel in an effort to reduce the impact transient with rearfoot running, while providing little cushion in the mid and forefoot. Long distance running has already been shown to increase peak pressures under the metatarsal heads in rearfoot runners, likely a result of fatigue in the musculature. It is plausible that these factors compounding could place enough stress on the metatarsals to increase injury incidence, although further research examining metatarsal loading in forefoot runners is needed.

Active peak ground reaction forces were larger in trials with a forefoot strike (2.52 x bodyweight) when compared to trials with a rearfoot strike (2.34 x bodyweight). This is supported by the literature, where converted rearfoot strikers exhibited similar active peak ground reaction forces. It is also consistent with research demonstrating larger active peak
ground reaction forces found with habitually forefoot runners when comparing to rearfoot
runners. There were no significant differences in active peak ground reaction forces when
comparing by gender.

It is difficult to say how an increase in active peaks would affect injury rate in forefoot
strikers, because much of the soft tissue utilized is different between techniques. It has been
proposed that the longitudinal arch plays a role in force attenuation in forefoot runners because
of its elasticity, as well as the triceps surae and Achilles tendon. The threshold of force required
to cause injury to these structures during running is still unclear, and it is yet to be determined if
the increase in peak magnitude of force seen in forefoot running exceeds this threshold. More
research needs to be done examining loads among the triceps surae, Achilles tendon, plantar
fascia and longitudinal arch, and the incidence of injuries in these structures among forefoot
runners.

Forefoot striking had a significant decrease in total stance time compared to rearfoot
striking. It has been shown previously that forefoot strikers have reduced contact time when
compared to rearfoot runners, although Almonroeder et al. (2013) found no change in total
stance time between rearfoot and forefoot running. Because speed was not controlled in this
study, it is possible that subjects altered running velocity between conditions, effecting stance
times.

Limitations

This study had several limitations. Participant’s shoes were not controlled. Pre-test
normative values for ankle range of motion and strength were not established. Structural
abnormalities were not controlled. While recent injury excluded participants from the study,
previous injury history was not controlled. Because participants were told to run at a comfortable
jog, speed was not controlled in this study. It is possible that individual running speeds may have altered ground reaction forces between styles of running.

**Conclusion**

In conclusion, this study has shown that runners engaging in a forefoot strike contact the ground in a position of ankle plantar flexion and had a much greater demand for ankle range of motion than rearfoot strike, confirming our hypotheses. We were able to accept our hypothesis that acute changes in foot strike resulted in a larger active peak ground reaction force than rearfoot strikes. Our hypothesis was incorrect in predicting that forefoot striking would eliminate impact peak ground reactions forces. Forefoot striking did not eliminate all impact ground reaction forces in a majority of participants, although impact transients were smaller in magnitude than rearfoot striking. Furthermore, male and female participants did not exhibit any differences in the kinematic and kinetic variables measured.

Further research into examining the effects of ground reaction forces and their relationship to injury is needed, as well as loading patterns in the metatarsals, tarsals and tibia in forefoot striking. It is likely that not a single cause is responsible for injury, and forefoot running may be beneficial to some runners, while contraindicated for others in regards to injury prevention.


Informed Consent Form for Biomedical Research
The Pennsylvania State University

Title of Project: Comparison of heel-toe and forefoot running.

Principal Investigator: Chris Matarazzo
147 D Rec Hall Athletic Training Room
State College, PA 16802
e-mail: cpm1989@psu.edu
phone: 201-575-1579

Advisor: Neil Sharkey Ph. D.
201 Henderson Building
State College, PA 16802
e-mail: nas5@psu.edu
phone: 863-2426

Other Investigator(s): Thomas J. Whipple, Dr. William Buckley, Dr. John Miller.

1. **Purpose of the Study:** The purpose of this research is to compare normal heel strike running with forefoot running. Forefoot running is classified as landing on the toes, and having minimal heel-strike, if any.

2. **Procedures to be followed:** You will be asked to attend one session, lasting no longer than one and a half hours. On your visit to the lab you will be assessed to make sure that you are a heel strike runner. Your height, weight, foot size and date of birth will be recorded. Plastic reflective markers and EMG electrode pads will be attached to your skin and clothing using hypo-allergenic sticky tape and Coban bandages. You will be given a chance to warm up and familiarize yourself with the equipment. You will then be asked to run across a force plate in our gait analysis laboratory in order to collect three dimensional data for single steps while we record your body’s motions. As you run across the force plate, joint angles will be recorded and ground reaction forces will be measured. Following several trials using a heel-toe method, you will be asked to perform several trials using a forefoot method.

3. **Discomforts and Risks:** As a result of the running activity there is a slight risk of muscle strain, sprains and muscle soreness diminishing over 48 hours following exercise that may temporarily restrict movement slightly. This is likely to be no more than you would experience as a result of your normal running training. You may experience some slight reddening of the skin as a result of the tape used to attach the plastic motion analysis markers and EMG electrodes.
If you experience discomfort and wish to stop you may indicate this at any time to any of the research personnel. You do not have to provide a reason.

4. **Benefits:** The benefits to you are that you may feel more comfortable running with the forefoot technique and may choose to use this technique in the future.

The benefits to society include a greater understanding of the effect of different running styles on biomechanical variables associated with running and a greater understanding of an alternative style of running that may cause less injuries.

5. **Duration/Time:** You will be involved in the study for a one day session. You will be asked to attend an initial testing session that will last one hour and a half.

6. **Statement of Confidentiality:** Your participation in this research is confidential. The data will be stored and secured in the Biomechanics Laboratory in a password protected file. Penn State’s Office for Research Protections, the Institutional Review Board, and the Office for Human Research Protections in the Department of Health and Human Services may review records related to this project. In the event of a publication or presentation resulting from the research, no personally identifiable information will be shared.

7. **Right to Ask Questions:** Please contact Chris Matarazzo at (201) 575-1579 or Dr. Neil Sharkey at (814) 863-2426 with questions, complaints or concerns about this research. You can also call this number if you feel this study has harmed you. If you have any questions, concerns, problems about your rights as a research participant or would like to offer input, please contact Penn State University’s Office for Research Protections (ORP) at (814) 865-1775. The ORP cannot answer questions about research procedures. Questions about research procedures can be answered by the research team.

8. **Voluntary Participation:** Your decision to be in this research is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would receive otherwise.

In the unlikely event you become injured as a result of your participation in this study, medical care is available but neither financial compensation nor free medical treatment is provided. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

You must be 18 years of age or older to consent to take part in this research study. If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

Data obtained during this study may be utilized in future studies and publications:
_____ I agree to allow the researchers to keep the data recordings of my participation in this research study indefinitely to use in the future studies and publications

_____ I DO NOT agree to allow the researchers to keep the data recordings of my participation in this research study indefinitely. The recordings/photographs will be destroyed on _______________.

______________________________________________
Participant Signature                                      Date

______________________________________________
Person Obtaining Consent                                   Date
Appendix B

Subject: Forefoot Running Research

Hello Everyone,

The Penn State Biomechanics Lab is currently looking for participants to engage in a study examining the differences between normal running (heel toe running) and forefoot running. The forefoot running technique may reduce the risk of injuries associated with prolonged periods of running.

In order to participate in the study, you must be:

Between the age of 18-45

Have no previous training in POSE or forefoot running

No injuries in the past 2 years that required surgery of the ankle, knee, hip, shoulder or spine.

Be in overall good physical health

Participation will include 1 session lasting an hour and a half in duration.

This is a research study being conducted at the Penn State University by graduate assistant athletic trainer Chris Matarazzo and Dr. Neil Sharkey. For more information, please contact Chris by phone (201-575-1579) or by email (cpm189@psu.edu).
Appendix C

Heel-Toe Evaluation

Participants will be brought into the Gait Analysis Lab of the Biomechanics Laboratory and be evaluated to determine that each individual is a heel-toe runner. Initial assessment will be done visually, and then confirmed during the initial data collection while running across the force plate.

Heel-toe runners are defined as:
Initial contact being made with the rear one third of the foot, while neither the mid foot or forefoot contact the ground during foot strike.

Mid foot runners are defined as:
Initial contact occurring with both the rear foot and the entire sole.

Forefoot runners are defined as:
Initial contact occurring on the front third of the food with no contact by the rear or midfoot.

Only runners that are determined to be heel-toe runners will be utilized in this study.

Appendix D

GENERAL HEALTH SCREEN

Title of Project: Differences in joint kinematics and ground reaction forces between heel-strike and forefoot running.

Principal Investigator: Chris Matarazzo ATC

Co-Investigators: Dr. Neil Sharkey, Dr. William Buckley, Dr. John Miller,

Screening Checklist: Healthy Participants between the ages of 18-45 years old

Participant Identification Number ________________________________

As a general health screen, you must be able to answer ‘YES’ to the following questions.

1. Are you between 18 to 45 years old? Yes No

2. Do you speak English? Yes No

3. Are you generally healthy (BMI\(^1\) under 30)? Yes No

As a general health screen, you must be able to answer ‘NO’ to the following questions.

1. Do you have a history of musculoskeletal or neurological injury within the last two years that resulted in surgery and withdrawal from activity lasting longer than 3 months? Yes No

2. Do you have a current musculoskeletal or neurological injury that is exacerbated by running? Yes No
3. Do you have any of the following conditions:

- Multiple Sclerosis?  **Yes**  **No**
- History of severe head injury?  **Yes**  **No**
- Partial Paralysis?  **Yes**  **No**
- Parkinson’s Disease?  **Yes**  **No**
- High Blood Pressure?  **Yes**  **No**
- Other musculoskeletal or neurological diseases?  **Yes**  **No**

4. Are you pregnant?  **Yes**  **No**

5. Have you had any previous training in Pose or forefoot running?  **Yes**  **No**


Body Mass Index = (Weight in lbs x 703) / (height in inches x height in inches).
### Subject Demographic Data

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|       | Mean  | 68.0  | 172.8  | 166.2 | 75.4  |
|       | SD    | 3.6   | 9.0    | 36.2  | 16.4  |