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Kinematic Analysis of Hip and Knee Joints between Barefoot and Shod Treadmill Running

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Abstract

Running shoes have recently been designed to mimic barefoot walking or running, and they are marketed with promises that runners will benefit from the effects of barefoot running. Studying gait analysis with particular running shoes is extremely important because the ankle and foot serve as the foundation of structural balance, support, and propulsion. In this study, the knee and hip joint motions will be addressed while wearing Vibram FiveFinger and Nike Free Run shoes, which are designed to imitate barefoot running while providing protection from the elements. The purpose of this current study was to investigate the movement kinematics in the hip and knee joint while running on the treadmill at 0%, 4%, and 8% inclines in the barefoot condition as well as in Nike Free Run and Vibram FiveFinger shoes. Five experienced distance runners with a heel strike landing style in the traditional cushioned shoe were selected to participate in the study. During the testing each participant ran at 3.0 m/s on a slope of 0%, 4% and 8% in all three types of footwear. A two-way repeated measures ANOVA test was conducted at $\alpha = 0.05$ followed by a t-test with a Bonferroni adjustment if a significant difference was found. The results of the study showed a significant difference in slope was observed between the 0% incline and the 8% incline during the heel strike phase in the hip joint and the mid support phase of the knee joint, and a significant difference in footwear was found between the barefoot and Nike shoe during the mid support phase of gait in the hip joint. Also during the mid support phase of gait, a significant difference was found between the barefoot and Nike shoe as well as the Vibram and Nike shoe in the knee joint. No significant differences were found when comparing shoe or slope in regards to angular velocity in both hip and knee joints. The

findings of this study show that when looking at the phases of the gait cycle, the mid support phase of gait is the most crucial phase of gait. The toe off phase was found to be the least important phase of gait to be examined. Running slope is important because the slope can affect the running kinematics when the gradient is substantial (0% to 8%). It is critical that when developing new footwear that the mid support phase should be the most important phase of gait to be examined, particularly in respect to the knee joint.

Although humans have been walking and running for millions of years, the majority of people ran barefoot or in minimalist footwear until the 1970’s. Barefoot running has recently become a fad in the past few years, but is it really considered an innovative way to run when humans’ ancestors have been running barefoot for centuries? When studying human gait, researchers can learn a tremendous amount simply by studying our human ancestors’ movement mechanics. It is important to keep in mind that it is incorrect to consider barefoot running a fad or even intrinsically dangerous (Lieberman, 2012).

Lieberman (2012) relies on the evolution of the human race in order to point out what should be obvious ideas. First, Lieberman (2012) makes the observation that there is no such thing as barefoot running shoes, because how could one be considered barefoot if they are wearing footwear, no matter how minimalistic. Second, Lieberman (2012) states that while studying the kinematics of running, one should focus on how one runs, as opposed to what is on one’s feet. It is noted that what is on one’s feet may affect how one runs; however, Lieberman focused mainly on the evolution of human gait, which is important in understanding the mechanics of running.

Lieberman (2012) states three novel consequences of wearing running shoes in relation to injury. The first claim he makes is that shoes limit proprioception. Proprioception is important while running because it provides the individual with feedback that increases stability and in turn decreases risk of injury. When running shod, the sensory feedback areas of the feet are covered, which decreases the sensation in the foot and prohibits the body to sense possible dangers on the ground below it.

The next claim made is that modern shoes with cushioning and support may either force or promote a running pattern that is not common to habitual barefoot runners (Lieberman, 2012). The human body has adapted over millions of years to perform barefoot, so why should this natural instinct be forbidden. Lieberman (2012) notices that individuals may be receiving more injuries by wearing shoes, as opposed to running barefoot. While this seems like a logical claim, Nigg (2009) rejects it because there is not enough evidence to support that people running barefoot will have fewer injuries than people running shod. While it was natural for humans to walk and run barefoot, is it still natural for people of the 21st century to follow this notion?

The third claim made by Lieberman (2012) is that running shoes may cause weak and inflexible foot development in today's lifestyle. Well cushioned shoes with arch support and stiff soles designed to control pronation and supination prevent the muscles and bones of the foot from adapting to natural foot stresses (Lieberman, 2012). When shoes are highly supportive, the muscles in the lower extremity have a lighter load; therefore, they do not adapt to strenuous activity while wearing footwear. A weakened state of muscle in the foot prohibits the foot from stabilizing itself to the best ability. Some running injuries may be prevented with a strong and flexible foot to control pronation and other harmful foot movements (Lieberman, 2012). Jones, Barton, and Morrissey (2012) have also found increased strength of the intrinsic musculature of the foot while running barefoot. Jones et al. (2012) argued some modern footwear can act as a cast that causes intrinsic muscles to weaken gradually. With less confirmation of this idea, Nigg (2009) has found that there is indirect evidence that barefoot running strengthens muscles crossing the ankle joint. Nigg (2009) also argues there are energetic advantages of barefoot running, but there is no evidence that barefoot running would prevent or enable running injuries. Although there are many researchers who have seen an increase in muscle mass during barefoot running, more research is needed to directly support this hypothesis.

More research is needed in the up and coming area of barefoot running. It is astonishing that something as natural and innate as running barefoot can be so under researched in today's fitness world. While barefoot running has been around for millions of years, the fitness world uses it as a marketing strategy without really knowing the benefits or consequences. The purpose of this current study was to investigate the movement kinematics in the hip and knee joint while running on the treadmill at 0%, 4%, and 8% inclines in the barefoot condition as well as in Nike Free Run and Vibram FiveFinger shoes.

Review of Literature

Gait Cycle

The phases of human gait include the stance phase and the swing phase. The stance phase accounts for 60% of the human gait cycle, and it is generally categorized by the time period when the foot is in contact with the ground. The swing phase accounts for the rest of the 40% of the human gait cycle, and it is defined as the period of time where the foot is not in contact with the ground. For the purposes of this study, the part of the gait cycle which was focused on was the stance phase.

The stance phase in human gait starts when the heel strikes the ground until the toe leaves the ground. The stance phase can be divided into events which include heel strike, foot flat, midstance, heel off, and toe off. Heel strike is the initial contact of the heel with the ground. Foot flat is the time frame when the full foot contacts the ground. Midstance is defined as the body weight being directly over the supporting leg. Heel off is the period when the heel lifts off the ground. Finally, toe off is the last remaining contact of the foot being removed from the ground. The stance phase is important to research in biomechanics because it comprises the majority of the gait cycle, as well as it is the only time period in which the foot contacts the ground (Levangie & Norkin, 2001).

Winter (1980) defines the purpose of the stance phase as the lower extremity resisting collapse and then extending to push-off from the ground. Flexion of the knee, ankle, and hip is required for the collapse, subsequently followed by the extension of the knee, ankle, and hip to push-off (Winter, 1980). In a study of 24 subjects walking at a fast, natural, and slow cadence, and 9 patients with various knee and hip issues, Winter (1980) found that runners experienced variability in the knee and hip throughout the stance phase. This variability was seen at the various joint angles as well as the moments of force at these individual joints. This research is relevant to the current study because by measuring the degree of hip and knee movement while running, researchers can determine the timing of collapse and push-off of the stance phase.

The stance phase is crucial to this study because it is a phase of gait where injury is prevalent. Stanton and Purdham (1989) found that hamstring injuries occur in the late swing and early stance phase of sprinting. It is unknown if the same injuries are as prevalent in running as opposed to sprinting. Besier, Lloyd, Cochrane, and Ackland (2001) also have found that there is an external flexion and extension load at the knee joint during running and cutting. In the research of Besier et al. (2001), 11 healthy males were studied during running, sidestepping and cutting. A force plate and a kinematic model were used to determine the loads at the knee joint during the stance phase. An external flexion movement at the knee joint was captured, which is believed to put ligaments, especially the anterior cruciate ligament, prone to injuries particularly between knee flexion angles of 0° and 40° (Besier et al., 2001). The importance of the stance phase in running is directly correlated to decreasing the risk of running injuries.

Inclined Running

Knowledge of the mechanics of running on an incline is important because it examines adaptive gait control mechanisms the body endures while on a slope (Telhan et al., 2010). Studying sloped running also allows researchers to examine the changes in mechanics of the lower extremity and possibly determine risk factors of injuries. Sloped running is important in modern society because uphill and downhill gradients are common to competitive races such as cross-country competitions and marathons (Padulo et al., 2012). If research allows runners to understand how slope affects running mechanics, an athlete may be able to improve their overall performance.

Padulo et al. (2012) studied 65 male marathon runners at slopes of 0%, 2%, and 7% at iso-efficiency speed on the treadmill. The parameters measured in this study were step length, flight time, step frequency, contact time, and heart rate. All of these parameters play a role in an athlete's performance. The results of this study indicated that step length, flight time and step frequency decreased in respect to the increasing treadmill gradient (Padulo et al., 2012). This is important to the current study because with the decrease in step length, flight time and step frequency, a change in hip and knee joint motion would be expected. To decrease step length and flight time, it is expected that hip and/or knee extension would also be decreased.

Telhan et al. (2010) tested nineteen healthy young runners on the treadmill at a speed of 3.13 m/s at a 4% decline, level, and a 4% incline. In relation to this study, Telhan et al. (2010) examined the lower extremity joint movements at a similar speed and incline. The results of Telhan et al. (2010) indicated that moderate changes in slope had a minimal effect on ankle, knee, and hip joints kinetics at a constant velocity. It was concluded that both level ground running and moderately sloped running were considered safe in terms of maintaining similar joint angles at 3.13 m/s.

Barefoot Versus Shod Running

Although human ancestors have been running barefoot for years, running in shoes has only been a trend since the 1970's when well-cushioned heels, arch support and a stiff sole was created (Lieberman, 2012). For the purpose of this study, shod is defined as wearing shoes on the feet, whether they are minimal or well cushioned. Griffiths (2012) classifies running shoes into three categories: motion control, stability, and neutral or cushioned shoes. With the up and coming trend of barefoot shoes such as Vibram's

FiveFinger shoe, it may be necessary to add a category to Griffith's list for minimalist shoes.

While it would be cost effective to run barefoot nowadays, researchers say that there may not be enough evidence to switch to barefoot running yet. Jones et al. (2012) believes that while studies of barefoot running may suggest a reduction in running injuries, much research is still needed to make that vast of a conclusion. If one opts out of purchasing an expensive pair of running shoes to go barefoot, a gradual transition is suggested to reduce as many complications as possible such as sudden change in strike pattern, new muscle activation patterns, or overuse injuries.

Minimalist Shoes

Lieberman (2012) reports that a minimalist shoe may provide an individual with the same mechanics of running as experienced while running barefoot. These similarities include a forefoot striking pattern, lower ground contact time, a lower peak impact force, and an increase in step rate as opposed to the traditional running shoe. The American Council on Exercise (2011) tested 16 healthy, injury free female subjects of the ages of 19 to 25. All of the subjects were considered recreational joggers. After two weeks of running in Vibram's FiveFinger shoe for three times a week for 20 minutes in duration, The American Council on Exercise (2011) found that all of their subjects were heel strikers when they wore neutral running shoes, but when wearing Vibram's FiveFinger barefoot running shoes, half of the group switched to a forefoot strike pattern. These individuals who adopted the new forefoot-style foot strike pattern were better suited to absorb the impact forces of running (The American Council on Exercise, 2011). These participants also experienced reduced knee flexion while wearing Vibrams and running barefoot, which is often associated with lower risk of running injury (American Council on Exercise, 2011). Although many studies find that individuals switch their foot strike pattern from heel strike to forefoot, more research is warranted to determine if this is the case for all minimalist shoes.

Scientific Objectives

With little research available on the kinematics of running on the treadmill especially at various inclines in various types of footwear, there is a dire need of biomechanical research. This information is relevant because the most common site of lower extremity injuries while running is the knee (Gent et al., 2007). In order to better understand why the knee is so receptive to running injuries, evaluating the range of motion is important. Various types of footwear will also be studied to determine if one type of footwear allows a greater or lesser range of motion at the hip and knee joints. If knee flexion is reduced, there is a possibility that there will be lower injury rates seen according to American Council on Exercise (2011). This study could potentially benefit athletes by educating them on the most appropriate form of footwear. Therefore, the purpose of this study was to examine the hip and knee joint motions among Vibram and Nike minimalist footwear and barefoot running condition while running on different slopes on a treadmill. The researcher hypothesized that there would be significant kinematic differences in range of motion in the hip and knee joints between shod and barefoot conditions on an incline.

Methods

Participants

Five participants with a mean age of 21 ± 1.0 years, a mean height of 1.7 ± 0.1 m, a mean mass of 58.8 ± 4.4 kg and a mean running experience of 8.8 ± 1.8 years volunteered to participate in the study. Participants were recruited from the Varsity athletic teams at Bridgewater State University, and they had a minimum of five years of running experience. All participants had a heel strike landing style with traditional cushioned running shoes. Approval from the Institution Review Board (IRB) at Bridgewater State University was obtained prior to the study, and written informed consent was obtained from each participant before the testing. All participants were fully briefed on the study and were able to withdraw from the study at any time without any penalty.

Protocols and Experimental Set Up

All participants arrived at the Exercise Physiology Laboratory in the Adrian Tinsley Center at Bridgewater State University. Each participant was allowed to warm up with their regular warm up routine on the suspended track for approximately 10 to 15 minutes. After the warm up routine, each participant was given a chance to run in each type of footwear on the treadmill to allow them to feel comfortable with their running shoes. Five joint reflective markers were placed on the right side of the participant at the shoulder (acromion), hip (greater trochanter), knee (lateral epicondyle of femur), ankle (lateral malleolus) and toe (base of fifth metatarsal), Figure 1. During the testing each participant ran 30 seconds at the speed of 3 m/s on each incline treadmill slope of 0%, 4%, and 8% for the Vibram shoe, Nike shoe, and barefoot condition. The running speed of 3 m/s was selected due to its prevalence in a similar previous running research study, which tested similar kinetics (Telhan et al., 2010). Gottschall and Kram (2005) also selected the speed of 3 m/s on the treadmill at inclines of 3°, 6°, and 9°. Participants had three minutes to rest between each incline treadmill slope and five minutes to rest between each type of footwear. The order of the incline treadmill slope and type of footwear were randomized to reduce any order effect. Data collection was concluded in one day for an hour in duration per subject.

Figure 1. Shod mid support phase of gait with joint reflective markers at 0% slope (Note: Reflective markers on shoe appear twice due to reflectiveness of footwear).

Instrumentation and Statistical Analysis

A JVC (model: GR-D371V) video camera was positioned in conjunction with a 650W artificial light to capture the sagittal view of running motion at 60Hz. All video trials were then transferred onto a Bridgewater State University computer in the

Biomechanics Lab for gait analysis with Ariel Performance Analysis System (APAS). Several two-dimensional kinematic analyses were conducted for hip and knee joint angles and angular velocities from five successful trials at the heel strike, mid support, and toe off for each type of footwear in each incline slope. A total of 675 trials (3 types of footwear x 3 treadmill angles x 3 instances of gait cycle x 5 trials x 5 participants) were filtered and analyzed in this study. Digital filter function was applied to the data with cut off frequency at 9 Hz. A series of two-way (3 types of footwear x 3 treadmill angles) repeated measures ANOVA tests were conducted at $\alpha = 0.05$ and followed by t-tests with a Bonferroni adjustment if a significant difference was found. All statistical analyses were conducted with SPSS (v. 18) software.

Results

Heel Strike

To conclude this research study, SPSS software was used to compare different types of footwear on similar inclines. At a 0%, 4%, and 8% incline the hip angles between barefoot, Vibram and Nike conditions were compared during the heel strike phase, Table 1.

Table 1.
Descriptive statistics between different incline angles and types of footwear during the heel strike phase in the hip joint. Data are means ± standard deviation.

Incline	0%	4%	8%
Barefoot	163.2° (7.3°)	158.9° (7.8°)	152.8° (6.7°)
Vibram	161.5° (6.9°)	159.0° (8.1°)	153.8° (8.3°)
Nike	161.0° (9.2°)	157.8° (7.9°)	151.3° (8.1°)

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at $\alpha = 0.05$ for the hip joint angle at the heel strike phase. The results showed that there were no significant differences found in the hip joint between the three types of footwear. However, a significant difference was found in the treadmill angle, so a post hoc t-test with Bonferroni adjustment ($\alpha = 0.05 / 3 = 0.017$) was conducted. The results showed a significant difference was found between the 0% and 8% slope (p = 0.003). There was no significant difference found in the interaction effect (types of footwear x treadmill angle). In addition, the researcher observed a noticeable increment of hip flexion from a 0% incline to an 8% incline in all three footwear conditions, particularly an increased flexion of 10.4° in the barefoot condition, Table 1.

At a 0%, 4%, and 8% incline the knee angles between barefoot, Vibram and Nike conditions were compared during the heel strike phase, Table 2.

Table 2.
Descriptive statistics between different incline angles and types of footwear during the heel strike phase in the knee joint. Data are means ± standard deviation.

Incline	0%	4%	8%
Barefoot	156.2° (6.2°)	150.8° (5.0°)	148.0° (5.4°)
Vibram	155.1° (6.7°)	153.0° (7.6°)	150.3° (5.3°)
Nike	155.3° (5.5°)	151.8° (5.8°)	148.3° (6.2°)

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at $\alpha = 0.05$ at the knee joint during the heel strike phase, and the results showed that there were no significant differences found in footwear in the knee joint during different inclines among barefoot, Nike or Vibram shoes. There were no significant differences found among any of the slopes for the three footwear conditions as well. Even though there were no statistical significant differences, the researcher observed that barefoot, Nike and Vibram footwear all showed a slight increment in knee flexion as the incline increased from 0% to 4% and 8%.

Hip and knee angular velocity was also assessed as a part of this research study. After a two-way (3 types of footwear x 3 treadmill angles) repeated measures ANOVA test was conducted at $\alpha = 0.05$ and followed by t-test with Bonferroni adjustment, there were no significant differences found in hip velocity or knee velocity on a 0%, 4%, or 8% incline with regards to the hip joint or the knee joint in the barefoot or shod condition among slopes, shoes or between in the interaction effect.

While no significant differences were found in the hip joint angular velocity during the heel strike phase, an interesting point is the hip's angular velocity was relatively small on an 8% incline as compared to the flat condition and a 4% incline, Figure 2.

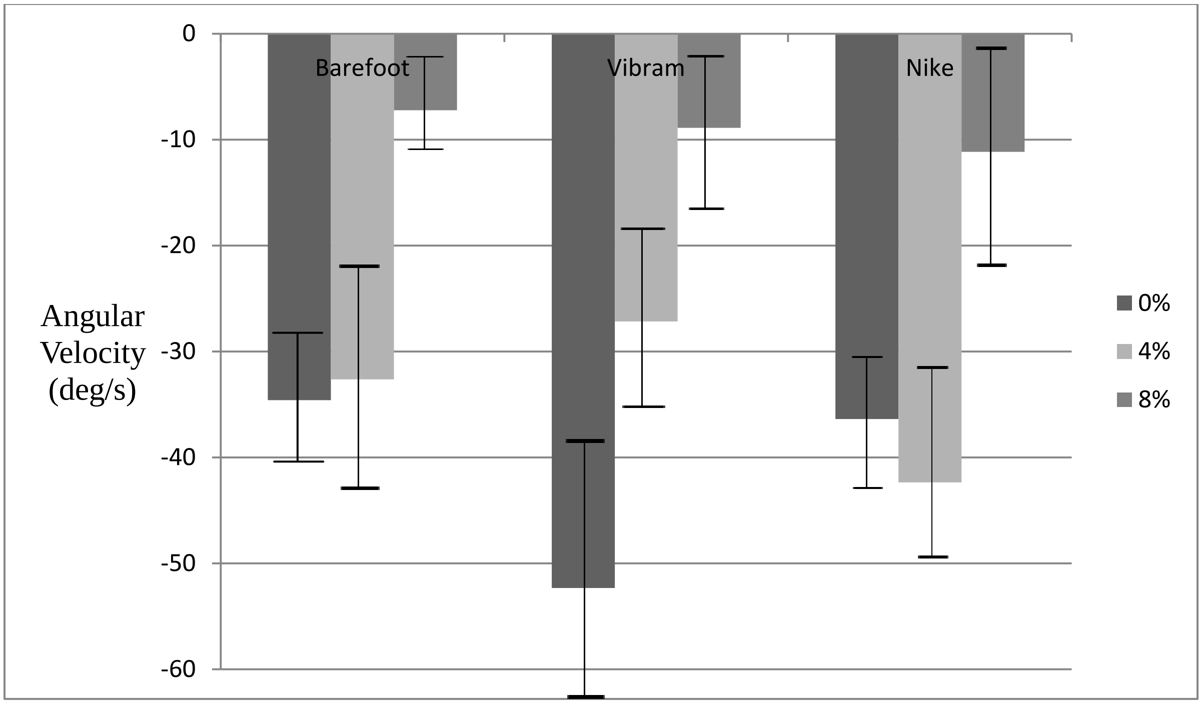

Figure 2. Means ± standard deviation of heel strike angular velocities in the hip joint.

When the angular velocity of the knee joint was examined, no statistical differences were found between barefoot, Vibram or the Nike shoe. An interesting point to consider is the barefoot condition produced smaller angular velocities at the 4% and 8% incline when compared to both Vibram and Nike, -16.6 degrees/second and -39.8 degrees/second respectively, Figure 3. The Vibram shoe produced the overall highest angular velocity on the flat condition of -151.2 degrees/second, Figure 3. For both the barefoot condition and the Vibram shoe, the angular velocity on the flat condition was highest, but for Nike the 4% incline produced the highest angular velocity of -126.7 degrees/second, Figure 3.

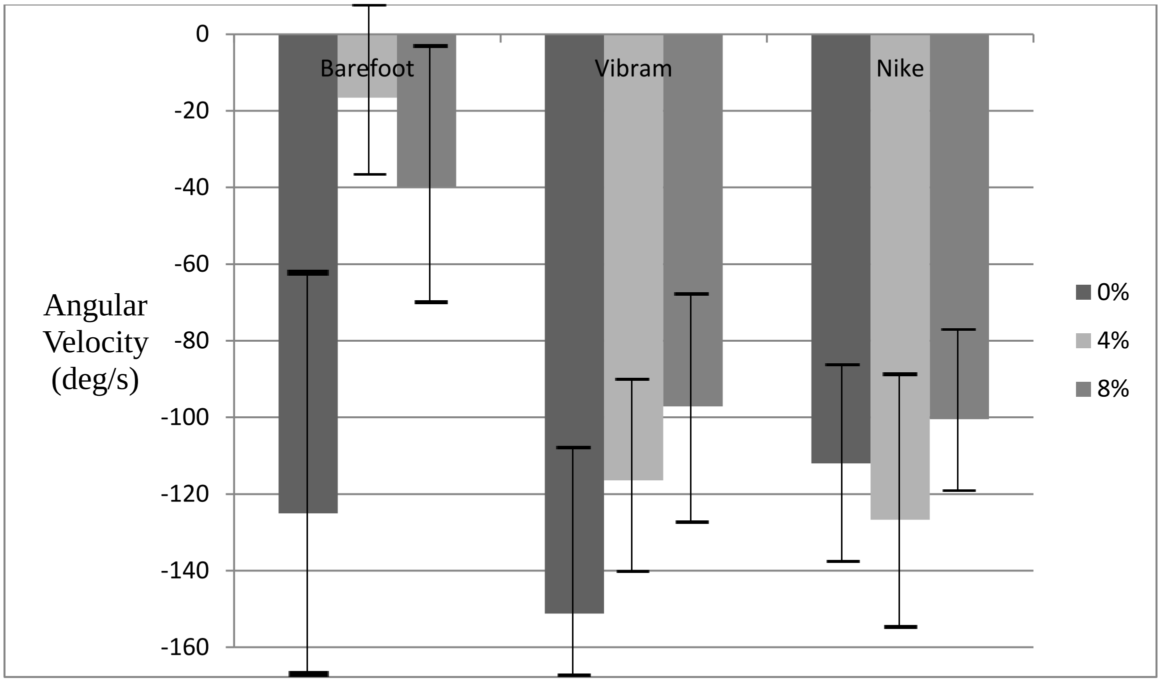

Figure 3. Means ± standard deviation of heel strike angular velocities in the knee joint.

Mid Support

At a 0%, 4%, and 8% incline the hip angles among Barefoot, Vibram and Nike conditions were compared during the mid support phase, Table 3.

Table 3.
Descriptive statistics between different incline angles and types of footwear during the mid support phase in the hip joint. Data are means ± standard deviation.

Incline	0%	4%	8%
Barefoot	154.8° (7.8°)	153.1° (7.5°)	149.9° (8.4°)
Vibram	154.0° (4.9°)	150.4° (7.1°)	149.6° (7.8°)
Nike	151.5° (6.8°)	147.7° (7.3°)	145.1° (8.6°)

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at $\alpha = 0.05$ at the hip joint during the mid support phase of the gait cycle. The results showed that during the mid support phase there was a significant difference found in the hip joint between different types of footwear. A t-test with Bonferroni adjustment was then conducted at $\alpha = 0.05 / 3 = 0.0167$, and the significant difference was found between the barefoot and Nike footwear ($p = 0.006$), Figure 4. The Vibram and Nike shoe approached significance (p = 0.028) but was not quite significant. While there was a significant difference between shoes, there was no significant difference found between inclines during this mid support phase of the hip joint.

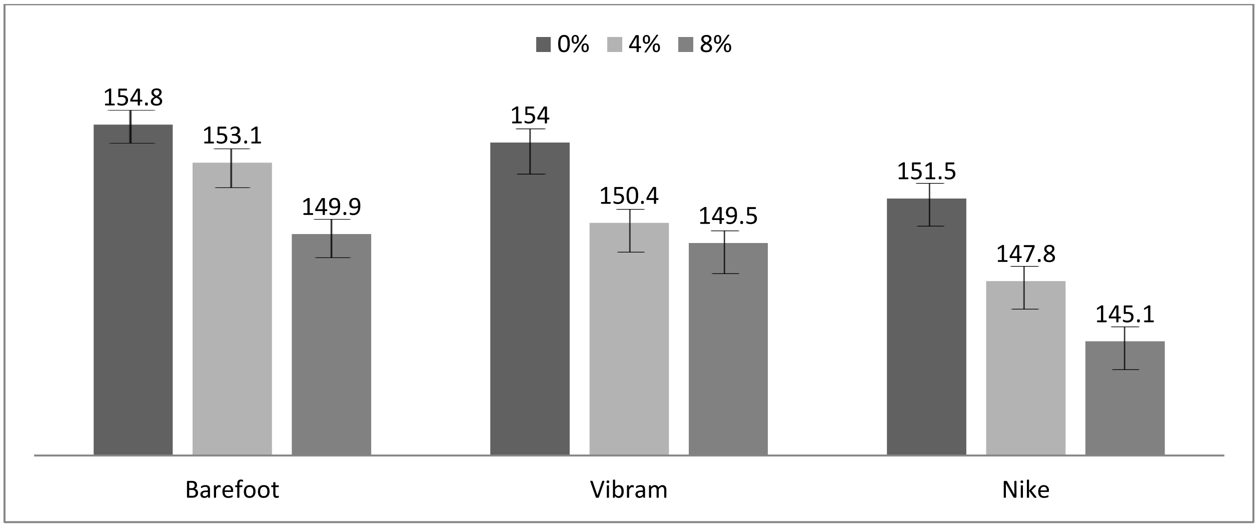

Figure 4. Means ± standard deviation of hip angles during the mid support phase of gait for each type of footwear and barefoot condition.

At a 0%, 4%, and 8% incline the knee angles between Barefoot, Vibram and Nike conditions were compared during the mid support phase, Table 4.

Table 4.
Descriptive statistics between different incline angles and types of footwear during the mid support phase in the knee joint. Data are means ± standard deviation.

Incline	0%	4%	8%
Barefoot	132.4° (3.5°)	132.5° (4.6°)	130.5° (3.0°)
Vibram	132.7° (3.6°)	129.4° (3.4°)	131.1° (3.7°)
Nike	128.5° (3.5°)	126.9° (3.7°)	124.9° (3.7°)

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at $\alpha = 0.05$ at the knee joint during the mid support phase of the gait cycle. The results showed that during the mid support phase there was a significant difference found in the knee joint between different types of footwear. A t-test with Bonferroni adjustment was then conducted at $\alpha = 0.05 / 3 = 0.0167$, and the significant difference was found between the barefoot and Nike shoe (*p* = 0.000) and a significant difference was found between the Vibram and Nike shoe (*p* = 0.008). The barefoot condition and Vibram shoe displayed similar knee angles during the mid support phase, Table 4. A significant difference was found between slopes during the mid support phase in the knee. A t-test with Bonferroni adjustment was then conducted at α= 0.05 / 3= 0.0167, and the significant difference was found between the 0% and the 8% slope (p = 0.001). No significant difference was found in the interaction effect. However, an interesting point to note is that Vibram produced a greater knee angle than barefoot on the 0% and 8% incline, but barefoot showed a larger knee angle on the 4% incline by 3.1°, Table 4.

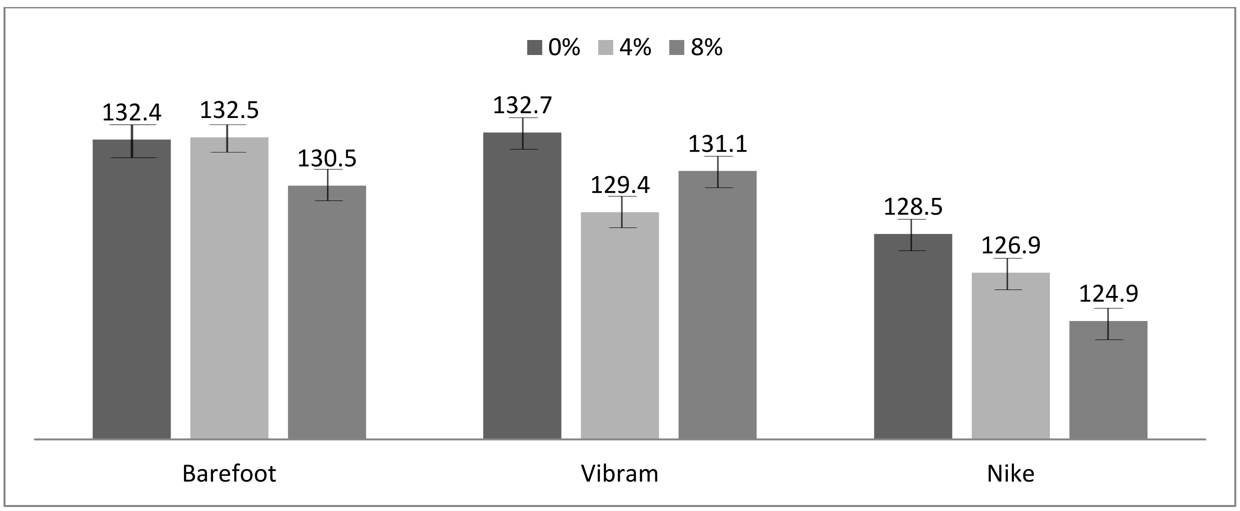

Figure 5. Means ± standard deviation of knee angles during the mid support phase of gait.

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at α = 0.05 during the mid support phase of the gait cycle for the hip angular velocity, and no significant differences were found in the mid support phase of the angular velocity in the hip joint. An interesting point was the relatively high angular velocity in the hip joint during a 4% incline while barefoot, which was 18.7 degrees/second, Figure 6. One possible explanation for this high velocity is the hip joint is able to move unrestricted without being weighed down by a pair of running shoes. This would not however explain the hip joints angular velocity at an 8% incline.

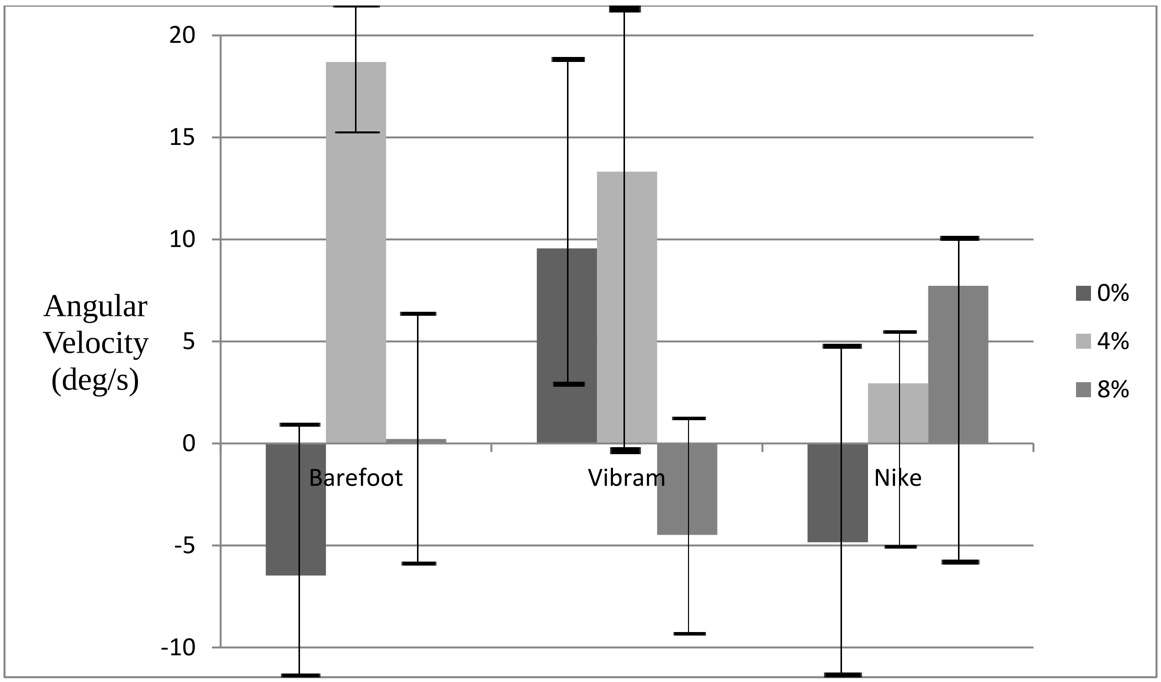

Figure 6. Means ± standard deviation of mid support angular velocities in the hip joint.

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at $\alpha = 0.05$ during the mid support phase of the gait cycle for the knee angular velocity, and there were no statistical significant differences found in the main effects of slope and footwear and the interaction effect (slope x footwear). Interestingly, the barefoot condition and the Vibram and Nike shoes showed similar velocities on all three inclines, except for the barefoot 4% incline velocity. The angular velocity for the knee joint on the 4% incline while barefoot was -16.6 degrees/second, while the Nike shoes angular velocity was -116.44 degrees/second and the Vibram shoes angular velocity was -126.7 degrees/second, Figure 7.

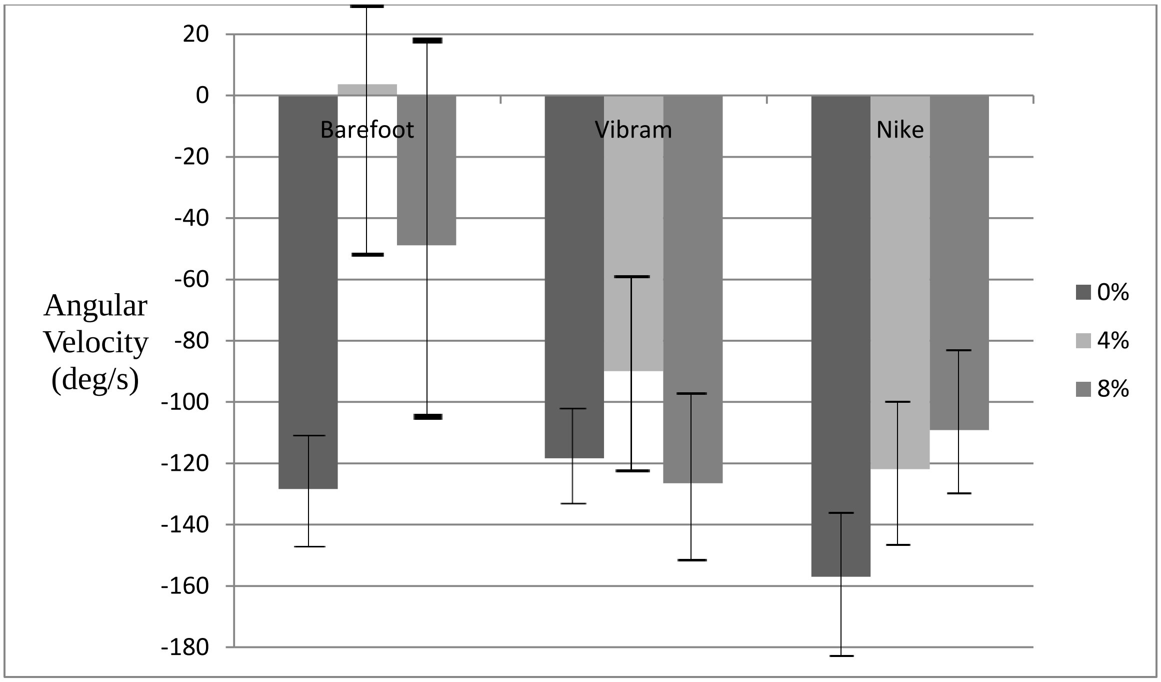

Figure 7. Means ± standard deviation of mid support angular velocities in the knee joint.

Toe Off

At a 0%, 4%, and 8% incline the hip angles between Barefoot, Vibram and Nike conditions were compared during the toe off phase, Table 5.

Table 5.
Descriptive statistics between different incline angles and types of footwear during the toe off phase in the hip joint. Data are means (SD).

Incline	0%	4%	8%
Barefoot	173.0° (6.1°)	173.4° (4.4°)	174.6° (4.3°)
Vibram	173.4° (4.4°)	173.5° (3.3°)	173.1° (6.2°)
Nike	172.7° (5.8°)	174.3° (4.7°)	174.5° (4.8°)

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at $\alpha = 0.05$ during the toe off phase of the gait cycle for the hip angular displacement. The results showed that during the toe off phase there were no significant differences found between either the shoes or the slope in the hip joint. The hip angle did not increase or decrease a significant amount from the 0% to the 4% and 8% incline. The barefoot condition showed a 1.6° increase from the 0% incline to the 8% incline, Table 5.

The Vibram shoe only varied by 0.4° between its largest hip angle (173.5° at 4%) and its smallest hip angle (173.1° at 8%), Table 5. The Nike shoe showed the largest variability, increasing by 1.8° from 0% incline to 8% incline, but no significant differences were found, Table 5. Further, no significant difference was found in the interaction effect between the shoe and slope during the toe off phase of the gait cycle for the hip angular displacement.

At a 0%, 4%, and 8% incline the knee angles between Barefoot, Vibram and Nike conditions were compared during the toe off phase, Table 6.

Table 6.
Descriptive statistics between different incline angles and types of footwear during the toe off phase in the knee joint. Data are means (SD).

Incline	0%	4%	8%
Barefoot	145.2° (8.5°)	145.6° (6.5°)	147.4° (7.8°)
Vibram	144.3° (4.0°)	144.7° (4.9°)	148.9° (6.7°)
Nike	146.0° (8.0°)	144.5° (3.3°)	146.5° (4.2°)

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at $\alpha = 0.05$ during the toe off phase of the gait cycle for the knee angular displacement. During the toe off phase there were no significant differences found between the shoes in relation to the knee joint angular displacement, and there were no significant differences found between the slopes in relation to the knee joint angular displacement as well. Additionally, no significant difference was found in the interaction effect between the shoe and slope during the toe off phase of the gait cycle for the knee angular displacement. Nevertheless, it is interesting that both the barefoot and Vibram shoes knee angle increased as the incline increased, but the Nike shoe did not follow this suit. The Nike shoe decreased by 1.5° from a 0% incline to a 4% incline, but then increased by 2.0° from a 4% incline to a 8% incline, Table 6.

A two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at α = 0.05 during the toe off phase of the gait cycle for the hip angular displacement, and no significant differences were found in the main effects of shoe and slope and the interaction effect between the shoe and slope. It is important to note the barefoot condition showed the greatest angular velocity at an 8% incline of -72.50 degrees/second, Figure 8. Vibram displayed the smallest angular velocity of 2.5 degrees/second during the 4% incline, Figure 8. Slightly larger than Vibram's smallest angular velocity of 2.5 degrees/second, Nike displayed its smallest angular velocity of 3.1 degrees/second on an incline of 8%, Figure 8.

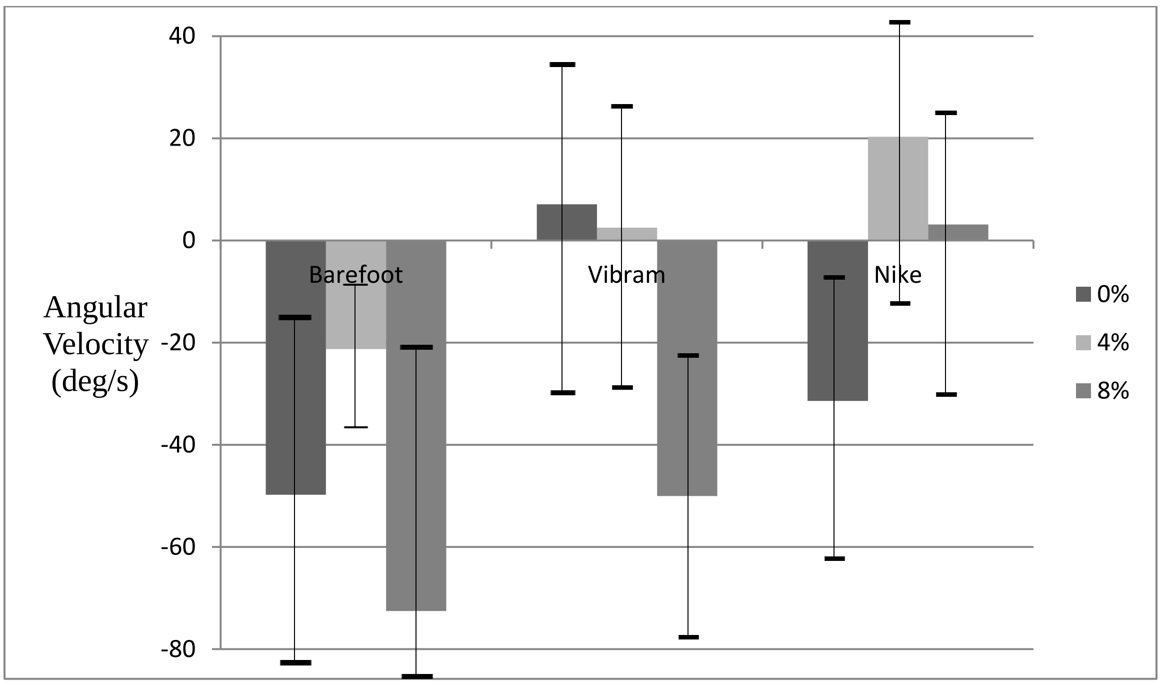

Figure 8. Toe off angular velocities in the hip joint. Data are means.

Finally, a two-way (3 types of footwear x 3 treadmill angles) repeated measure ANOVA was conducted at α = 0.05 during the toe off phase of the gait cycle for the knee angular displacement. In the final stance phase of running gait, toe off, no significant statistical differences were found in the angular velocity of the knee joint in the main effects of shoe and slope and the interaction effect between the shoe and slope. In this phase of gait the Vibram and the Nike shoe produced higher velocities than produced in the barefoot condition on a 0% incline, 4% incline and an 8% incline. Both the Vibram and Nike shoes produced the highest angular velocities on a 4% incline, -340.1 degrees/second and -352.7 degrees/second respectively, Figure 9. With an angular velocity of 268.1 degrees/second on the flat incline, the barefoot condition produced an angular velocity nearly 85 degrees/second lower than the Vibram and Nike shoes, Figure 9.

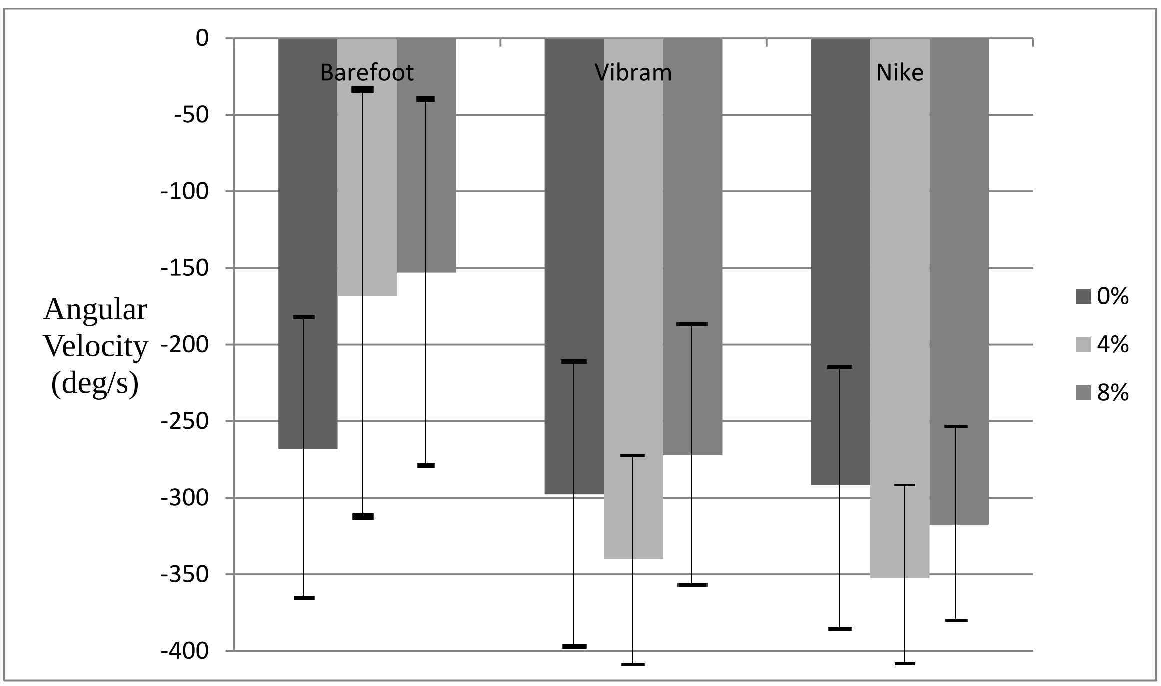

Figure 9. Means ± standard deviation of toe off angular velocities in the knee joint.

Discussion

The purpose of this study was to examine the hip and knee motion on a 0%, 4% and 8% incline in the barefoot and shod conditions. From the results, this study found that there was a significant difference between the 0% and 8% slopes during the heel strike phase of gait in respect to the hip flexion angle. A significant difference between the 0% and 8% slopes during the mid support phase of gait in respect to the knee flexion angle was also found. The results of this study also found that there were significant differences between the barefoot and Nike shoes and the Vibram and Nike shoes at the mid support phase in the knee flexion angle. A significant difference was found between the barefoot and Nike shoe during the mid support phase in the hip flexion angle. No significant differences were found in either slope or shoe during the toe off phase in regards to the hip or knee joint motion. No significant differences were found in the angular velocity of the hip or knee joints.

When looking at the phases of the gait cycle, the current study has found that the mid support phase of gait is the most crucial phase because it was where the most significant differences were found, while the toe off phase was the least important because no significant differences were found. It is important to recognize that the slope can affect the running kinematics at the heel strike in the hip joint, as well as the mid support phase in the knee joint, but only when the gradient is substantial (0% to 8%). When selecting the type of footwear, the current study found that the footwear has the most impact during the mid support phase of gait, at both the hip and the knee joint. The current study found the Vibram shoe to be more similar to the barefoot condition than the Nike shoe, and the type of footwear used for inclined running should be carefully chosen to address the hip and knee joints during the mid support phase of gait. It is critical that when developing new footwear that the mid support phase should be the most important phase of gait to be examined, particularly in respect to the knee joint.

In a study completed by Telhan et al. (2010), joint kinetics during moderately sloped decline, flat, and an inclined running surface were studied in respect to both the hip and knee joints. Participants ran at 3.13 m/s on the treadmill at a 4° decline, level and a 4° incline. Telhan et al. concluded that moderate changes in the slope of the running surface had minimal effect on the knee and hip joints at a constant velocity. Although the study done by Telhan et al. used a similar running speed, the results of that study are not congruent with the results of this study because Telhan et al. focused on kinetics, while this study focused on kinematics.

The barefoot, Vibram, and Nike shoes all showed significantly more flexion, from 0% incline to a 4% incline and again to an 8% incline which would imply that the knee is displaying greater flexion as the gradient increases. In the study by the American Council on Exercise (2011), all of the participants experienced more knee extension which is typically associated with lower injury. It is unknown if the greater knee flexion in the current study was an adaptation to slope or an adaptation to the shoe. By reducing the knee flexion angle, stride length and duration may be decreased, which is in line with Rothschild's (2012) study who noticed a decrease in stride length and duration while barefoot. Future studies are warranted to measure knee flexion angles on a gradient as well as stride length and duration.

In a study by Li, Van Den Bogert, Caldwell, Van Emmerik, and Hamill (1999), six male graduate students were selected to walk and run at a speed of 2.24 m/s for 6 minutes. A knee angle of 163 ± 3° was seen while running during the heel strike phase (Li et al., 1999). In this study, a similar knee angle of 155.5 ± 1° was seen while running during the heel strike phase on the 0% incline. Li et al. (1999) found a knee angle of 159 ± 5° during the toe off phase, while this study found a slightly smaller knee angle of 145.2 ± 1° during the toe off phase of gait on a 0% incline.

Similar knee angles were examined by Grimmer, Ernst, Gunther, and Blickhan (2008) in comparison to this study. Both Grimmer et al. (2008) and the present study display a knee angle between 145° and 157° during heel strike, and a mid support angle of approximately 124° to 133°, Figure 10.

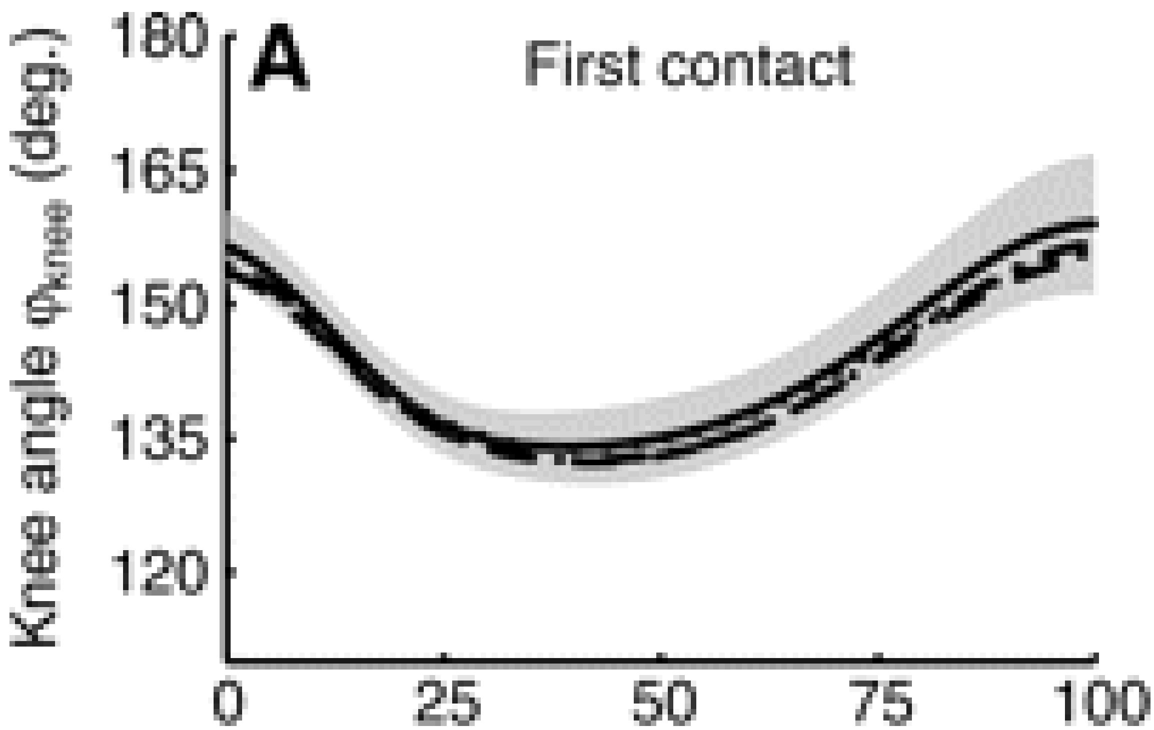

Figure 10. Knee joint angles during the first contact of the stance phase (Grimmer et al., 2008).

Lewis, Sahrmann, and Moran (2010) studied the hip joint in respect to hip extension during gait. While Lewis et al. (2010) studied hip extension while walking not running, the results were similar to this study, Figure 11. It is important to keep in mind that Lewis et al. (2010) used full hip extension as the 0° marker, while this study used full hip extension as 180°. The results of this study were compatible with the study of Lewis et al. (2010) because we noticed the hip angle approached 180° or 0° from heel strike to mid support, and then approached 180° or 0° again from mid support to toe off, Figure 11.

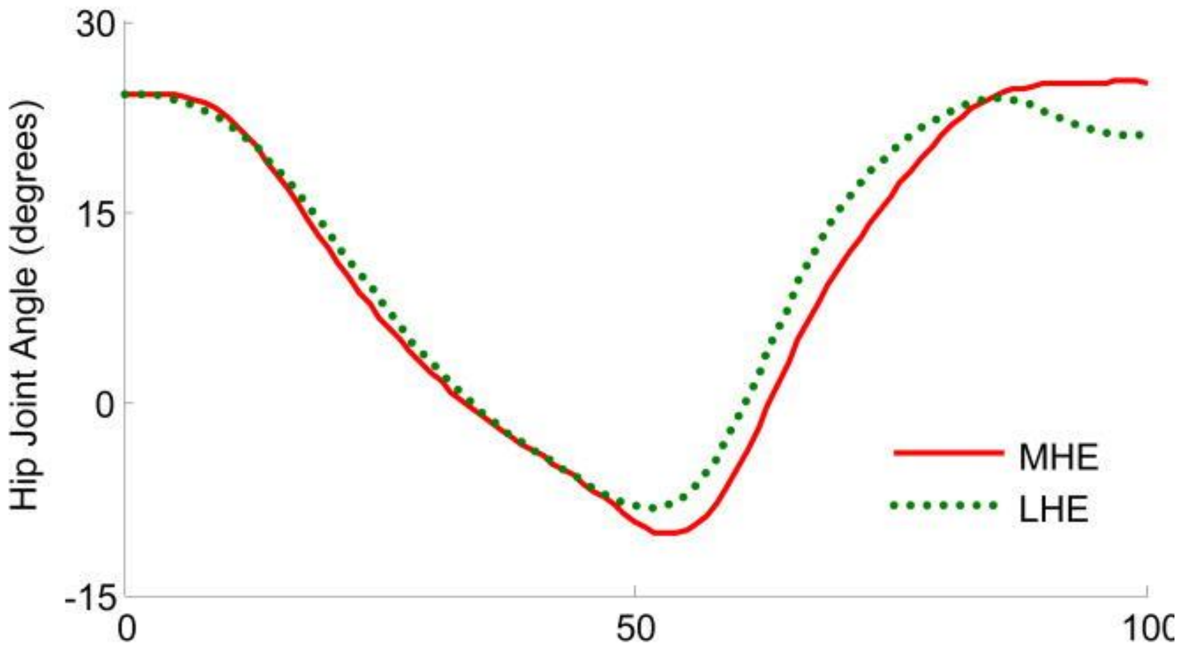

Figure 11. Hip joint angles during walking. MHE represents most hip extension while LHE represents least hip extension. (Lewis et al., 2010).

No statistical significances were found in the angular velocity between the hip joint or the knee joint on any of the inclines in any of the footwear conditions. This information is incongruent with Li et al. (1999) who found a significant difference at the toe off phase in the angle and angular velocity of the thigh and leg. This information however is still relevant because Hardin, Van Den Bogert, and Hamill (2004) found shoes with minimal cushioning produced an increased knee flexion velocity, but no significant increase or decrease was seen in the current study. In the study by Hardin et al. (2004) midsole hardness, joint angular velocities, surface stiffness, and a gradient were all examined to determine how they affected kinematics. Hardin et al. (2004) found that harder midsoles can cause an increase in knee flexion velocity, but they did not find any statistical significance (p = 0.099). The results of that study are congruent with the results of this study.

In a study by Ferber, Davis, and Williams (2003), 20 female recreational runners were tested at 3.65 m/s for 25 m to determine the differences in hip and knee kinematics and kinetics. The peak angular velocity in the hip in the runners was determined to be 129 degrees/second (Ferber et al., 2003). The results of this study did not show a hip velocity of quite that high, but it is unknown if Ferber et al. (2003) tested strictly the stance phase, as well as there was slightly an incongruence in speeds. Ferber et al. (2003) also found a peak angular velocity of the knee to be -509 degrees/second, which was higher than the peak angular velocity in the current study of -352 degrees/second. Perhaps the increase of 0.65 m/s in speed caused the higher velocity.

There were several limitations of this study in which future studies are warranted. The first limitation is in the number of subjects. This study used five subjects, but in future warranted studies, ten or fifteen subjects would increase the strength of the study. In this study, the phases of gait were not used as an independent factor in statistical analysis, however in future studies with a larger population size the phases of gait may be used as an independent factor in statistical analysis. This would allow us to validate that the mid support phase is the most important phase of the gait cycle. Another limitation of this study is the running speed. A faster running speed would be beneficial to research because most elite athletes perform at a faster running speed than 3 m/s. Future studies are warranted in which they would introduce a control shoe which would be well cushioned and supportive, in order to compare the minimalistic shoes to a control shoe. Future studies are also warranted in which a larger slope is examined, because in this study slope did influence running kinematics only at a large gradient. While there were some limitations of this study, this study provided a strong preliminary understanding on how running on an incline in minimalistic footwear and barefoot affects hip and knee angular displacements and velocities.

Conclusion

In this study the hip and knee motions were examined with five elite female runners. Each runner ran in two types of minimalist shoes (Nike Free Run and Vibram FiveFingers) and in a barefoot condition on a flat treadmill, 4%, and 8% inclines at 3 m/s. From the results, this study found that there was a significant difference between the 0% and 8% slopes during the heel strike phase of gait in respect to the hip flexion angles. A significant difference between the 0% and 8% slopes during the mid support phase of gait in respect to the knee flexion angles was also found. The results of this study also found that there were significant differences found between the barefoot and Nike shoes and the Vibram and Nike shoes at the mid support phase in the knee flexion angles. A significant difference was found between the barefoot and Nike shoe during the mid support phase in the hip flexion angles. No significant differences were found in either slope or shoe during the toe off phase in regards to the hip or knee joint motion.

Overall, when looking at the phases of the gait cycle, the current study has found that the mid support phase of gait is the most crucial phase of gait. The toe off phase was found to be the least important phase of gait to be examined. Running slope is also important because the slope can affect the running kinematics when the gradient is substantial (0% to 8%). It is critical that when developing new footwear that the mid support phase should be the most important phase of gait to be examined, particularly in respect to the knee joint.

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