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Lower Extremity Joint Moments During the Active Peak Vertical Ground Reaction Force in Three Different Running Conditions

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Lower Extremity Joint Moments During the Active Peak Vertical Ground Reaction Force in
Three Different Running Conditions

Tyler Standifird

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

Lower Extremity Joint Moments During the Active Peak Vertical Ground Reaction Force in Three Different Running Conditions

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The purpose of this study was to compare joint moments during the active peak vertical ground reaction force (PVGRF) when running in three conditions. Twenty-five subjects, sixteen male and nine female, were measured using 3-dimensional motion analysis while running barefoot, in Vibram FiveFingers[®] (VF[®]) minimalist running shoes and in traditional running shoes at a 7-minute-mile pace (3.84 m/s). Joint moment differences were calculated and compared using a mixed model analysis of variance. Results showed the VF[®] was effective at mimicking both the kinetic and kinematic attributes of barefoot running. The only significant difference found when comparing barefoot and VF[®] running was in the ankle angle ($p < .005$). All other variables in the lower extremity were the same for the two conditions. Though the subjects in our study had no previous experience with VF[®] (or barefoot) running they were able to closely mimic barefoot running upon initial running trials. Joint moments at the ankle were higher for barefoot and VF[®] running ($p < .001$) when compared with shod running. This may potentially lead to a greater risk of injury at the ankle joint when running barefoot or in VF[®]. The hip joint moments were only different when comparing the barefoot condition to the shod condition ($p = .002$), with the barefoot condition higher than shod running. The knee joint moment was smaller during the VF[®] and barefoot conditions when compared with shod running ($p < .001$) and may lead to a decrease in injury rates at the knee. Though a reduction in moments of the lower extremity may lead to a decrease of injury at the corresponding joint, it is important to consider the adaptations that take place as a result of varying stresses. According to Wolff's law, bone and surrounding tissue will adapt to the loads it is placed under. Taking this into consideration, it is important to remember that lower moments may lead to weaker bones and surrounding tissues and without compensation for these reduced loads, injury rates may remain the same over time.

Keywords: joint moment, active peak vertical ground reaction force

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Introduction

Running, once primarily used for transportation, has now become one of the primary forms of exercise. The benefits of cardiovascular exercise, such as running, are numerous and include: decreased depression and increased emotional well-being (Galper, Trivedi, Barlow, Dunn, & Kampert, 2006), reduced risk for heart attack and stroke (Fentem, 1994) reduction in blood pressure (Fentem, 1994; King, Hopkins, Caudwell, Stubbs, & Blundell, 2009; Myers, 2003), improved treatment and reduced risk for diabetes (Fentem, 1994; Gulve, 2008; Manders, Van Dijk, & van Loon, 2010) and reduction in coronary heart disease (Hatziandreu, Koplán, Weinstein, Caspersen, & Warner, 1988; Thompson et al., 2007). These studies, along with many others show numerous health benefits associated with habitual exercise.

Over 36 million Americans ran at least once in 2003 and over 10.5 million ran at least 100 days (Paluska, 2005). As the number of runners increase, the incidence of running injuries goes up as well. Many runners sustain lower extremity running injuries (van Gent et al., 2007), with some reported incidence rates as high as 79% in recreational runners (Lun, Meeuwisse, Stergiou, & Stefanyshyn, 2004).

Barefoot running is one of the areas of running research that has gained popularity in recent years. During running a runner will need to withstand forces up to 3 times their body weight in the first 50 ms of the stance phase (Lieberman et al., 2010). These forces quickly travel up the body and can contribute to the high incidence of injury in runners, including plantar fasciitis and tibial stress fractures (Lieberman et al., 2010; Milner, Ferber, Pollard, Hamill, & Davis, 2006; Pohl, Hamill, & Davis, 2009; van Gent et al., 2007). Barefoot running has been found to reduce these impact forces as a result of a flatter foot placement and no rear foot strike (Lieberman et al., 2010; Squadrone & Gallozzi, 2009). Barefoot runners have a lower peak

impact force than their shod counterparts (1.62 times BW and 1.72 times BW respectively) at 3.33 m/s (Squadrone & Gallozzi, 2009).

Peak impact forces are not the only area that differences are seen during barefoot running. Joint moments of the lower extremity were found to be significantly lower at the hip for adduction and internal rotation torques, at the knee for flexion, varus and internal rotation torques and at the ankle for internal rotation torques (Kerrigan et al., 2009). These joint torques, or moments, are an important aspect of running that must be considered in relation to running injury. Joint moments can be an effective indicator of the stresses placed on the neuromuscular system (Winter, 1983) and elevated joint moments at the knee can lead to lower extremity joint injuries (McClay & Manal, 1999; Scott & Winter, 1990). Further research has suggested that increased knee extension moments could lead to overuse injuries (Messier et al., 2008) with overuse stress fractures being a common injury of the lower extremity (Ferber RI, 2002). In addition, increased frontal (ab-adduction) and transverse (external-internal rotation) moments at the knee might be related to the development of patellofemoral pain syndrome in runners (Stefanyshyn, 1999).

Barefoot running does have some limitations. Someone who chooses to participate in a barefoot running program may need to find areas that have soft surfaces free of sharp objects to perform their running. Though the skin on the sole of the foot is stronger and thicker than other areas, injuries, such as puncture wounds, can still occur at the foot. This problem has led to the development of the FiveFingers running shoe from Vibram[®]. This shoe is designed to mimic barefoot running while giving the runner protection from objects encountered while running ("Barefoot Running," 2012). Research on the Vibram FiveFingers[®] (VF[®]) running shoe is minimal, but does include a study performed in 2009 that concluded that the VF[®] was effective

at mimicking the barefoot running condition while offering protection to the feet of the runner (Squadrone & Gallozzi, 2009). Additionally the study showed that the VF[®] did significantly reduce peak impact forces in comparison with running shoes (1.59 times BW and 1.72 times BW respectively) and that the impact forces of the VF[®] was less than the 1.62 times BW reported during barefoot running.

After an extensive search of the literature, no study has been found that investigated the joint moments associated with the VF[®] running shoe. The purpose of this study was to determine the effects of VF[®] running shoes on ankle, knee and hip joint moments during the active peak vertical ground reaction force in experienced, recreational runners with no previous experience running barefoot or in VF[®] running shoes and how these joint moments compare both to barefoot and shod running.

Methods

Subjects

Sixteen healthy males and nine healthy female recreational runners participated in the study (175.7 ± 10.5 cm, 72.08 ± 12.6 kg). The subjects had no lower extremity injuries that had prevented them from running at least 3 days/week in the prior 12 weeks and had been running consistently between 15 and 30 miles/week for the last six months. Each subject signed a consent form, which was approved by the appropriate institutional review board.

Testing Procedures

Following a brief warm up of running the length of the lab, each subject ran barefoot, in VF[®] and in running shoes (Nike Air Pegasus). Subjects ran at seven-minute-mile pace (3.84m/s) across two force plates (AMTI OR6-5, Advanced Mechanical Technology Inc., Newton, MA), collecting at 960 Hz. A motion analysis system (Vicon, Centennial, CO) recorded the positions

of reflective markers on the runner at 240 Hz. Subjects drew out of a bag a random order of shoe conditions prior to beginning their trials. Timing lights (Brower, Draper, UT) positioned at head height were used to verify that seven-minute-mile pace $\pm 5.0\%$ was achieved through a 2 m section around the location of the force plate. Each subject ran a 10-meter approach in order to reach seven-minute-mile pace. Trials were only analyzed when it was determined that the right foot landed completely on the force plate and the subject achieved a normal gait pattern as determined by a trained researcher reviewing each run for consistency. Trials were performed until the criteria had been met three times. Visual 3d (C-Motion Inc., Germantown, MD) was used to calculate joint moments (normalized to height and weight) and a customized LabView (National Instruments Corporation, Austin, TX) program was developed to determine the magnitude of joint moments occurring during the active peak vertical ground reaction force (PVGRF).

Force and position data were recorded and processed with Vicon Nexus (Vicon, Centennial, CO). Subjects were marked with reflective markers according to a modified Helen Hayes model. Thirty-two markers were placed on the subject by test administrators - three markers were placed on the front of the foot and three on the heel, one marker was placed on left and right sides at each of the following landmarks: lateral malleolous, shank, lateral knee joint, thigh, ASIS, PSIS, lateral wrist, forearm, lateral elbow, upper arm, acromion process, and head just anterior to each ear. Modifications were necessary as a result of the three different footwear conditions contained in the experiment. In order to improve consistency of results in the three conditions, a coordinate system for the feet, separate from the coordinate system for the lab, was created using a static trial at the beginning of each condition. Six MX 13+, two F20 and two T20 cameras recorded marker positions. A calibrated volume 2 m long, 2 m wide and 2.5 m high was

created around the force plate. The marker position data was filtered using a 6 Hz Butterworth filter.

Shoes

All subjects wore the same type of shoes for testing. The shoes in this study were the Nike Air Pegasus and the Vibram Fivefingers[®] Classic or Bikila styles. The Air Pegasus is designed with sufficient cushioning and is neutral in terms of motion control. The VF[®] have a stretch nylon fabric on the upper part of the shoe with a 3.5mm rubber sole razor zipped for flexibility and slip resistance.

Statistical Analysis

A mixed model analysis of variance, blocking on individuals, was used to analyze difference between the joint moments at the hip, knee and ankle in the sagittal plane. Alpha was set at 0.05 to test for significance and beta was set at .2 signifying an accepted significance 80% of the time when a difference was found.

Results

Joint moments for the lower extremity were calculated in the sagittal plane and correspond to the ankle plantar flexion moment, knee extension moment and hip extension moment. The moments were normalized for each subject according to weight in kilograms and height in meters (Nm/kgm).

At the ankle, the shoe condition had a lower plantar flexion moment when compared with the barefoot and VF[®] running conditions (see Table 1). The difference between shoe and barefoot was .277 Nm/kgm ($p < .001$). The difference between shoe and VF[®] was .211 Nm/kgm ($p < .001$) and the difference between the barefoot and VF[®] was not significant for the ankle plantar flexion moment ($p = .110$).

At the knee, the shoe condition had a higher extension moment when compared with the barefoot and VF[®] running conditions (see Table 1). The difference between shoe and barefoot was .395 Nm/kgm ($p < .001$) and the difference between shoe and VF[®] was .296 Nm/kgm ($p < .001$). There were no differences detected for the knee extension moment when comparing the barefoot and VF[®] conditions ($p = .064$).

At the hip, the shoe condition had a lower extension moment when compared to the barefoot running condition (see Table 1). The difference between shoe and barefoot was .134 Nm/kgm ($p = .002$). There were no differences detected for the hip extension moment when comparing the VF[®] condition to the shoe ($p = .142$) or the barefoot condition ($p = .227$).

In order to fully understand and discuss joint moments of the lower extremity it is important to consider the corresponding joint angles at the active peak vertical ground reaction force. Ankle angles during the shod and VF[®] condition were similar ($p = .995$), while the ankle angles in the barefoot condition were three degrees smaller than the other two conditions ($p < .005$). The knee flexion angle was greatest in the shoe and was significantly different from knee angles in the VF[®] and barefoot conditions ($p < .001$). The hip flexion angle was only different when comparing the shoe and barefoot running conditions ($p < .001$). The distance from the VGRF to the ankle joint center was calculated and reported as the center of pressure (COP) distance. This measurement was used to further explain the moments occurring at the ankle joint.

Discussion

The purpose of this study was to compare joint moments of the lower extremity in three different running conditions. We expected that joint moments of the ankle, knee and hip would be lower while wearing the VF[®] running shoe when compared with standard running shoe and that the VF[®] running shoe would closely resemble the joint moments for the barefoot running

condition. Our results sometimes supported our hypotheses while at other times refuted our hypotheses depending upon the joint under consideration.

Forces

We expected to see differences in foot strike patterns for the various running conditions similar to results found in previous research (Lieberman et al., 2010; Squadrone & Gallozzi, 2009). Due to these expected differences we chose to compare joint moments during the active peak vertical ground reaction force instead of initial foot contact or average joint moment across the stance phase of gait. The subjects in our study showed no difference in the magnitude of the PVGRF for the three different running conditions and thus we were able to dismiss force differences as a possible explanation for differing lower extremity joint moments in the three running conditions.

When considering forces it is important to remember how adaptations that occur as a result of varying forces or loads can impact the strength of a bone or joint. According to Wolff's law, a bone or soft tissue will adapt to the stresses it is placed under. If they are placed under higher levels of stress, healthy bones and joints should adapt to these stresses and become stronger. In contrast, a bone or joint that experiences reduced stresses may become weaker in the long run and may experience a higher incidence of injury. Any research examining a reduction of forces must also consider how reduced forces can potential lead to weaker joints and increased incidence of injury.

Ankle

The sagittal plane ankle joint moment in the VF[®] running shoes was the same when compared with the barefoot condition, but the values of both of these conditions were greater than those calculated during shod running. Even though PVGRF and ankle angles were similar

between the shoe and VF[®] conditions, joint moment differences were observed. The differences in ankle moments between the shod and VF[®] conditions, for our subjects, were attributed to the smaller distance from the center of pressure of the force to the ankle joint center during the shod running condition. This occurs as a result of the runner being able to generate force at a distance closer to the ankle joint center. This reduction in distance decreases the ankle joint moment, while still generating comparable VGRF to propel the runner forward, and may lead to a decrease in running related injuries at the ankle joint. The difference between barefoot and shod conditions could be attributed to the difference in joint angle as well as COP distance. The ankle is not the primary location of lower extremity running injury and may not be the most important variable to consider when comparing varying running conditions.

Hip

Previous research has shown that hip moments in the frontal and transverse planes were significantly lower for barefoot running when compared with shod running (Kerrigan et al., 2009). Our subjects experienced sagittal plane joint moments that were lower at the hip for the shod condition when compared with the barefoot condition. This could be due to the fact that we only calculated moments in the sagittal plane at PVGRF and did not do an average joint moment across the entire stance phase. The VF[®] shoe did not significantly reduce joint moments, for our subjects, at the hip when compared with the shod condition. The hip moments for the VF[®] condition were closer to the barefoot, the highest of the three, than the shod condition and thus may not reduce injury rates at the hip as a result of reduced joint moments.

Knee

The knee extension joint moment in the VF[®] running shoes was the same when compared with the barefoot condition and these values were significantly less than the moments calculated

during shod running. This result was what we expected and previous research has shown that sagittal plane joint moments were lower during barefoot running when compared with shod running (Kerrigan et al., 2009). Our subjects had the largest amount of knee flexion when running in shoes and exhibited less knee flexion when running in the barefoot and Vibram® conditions. This increased amount of flexion at the knee led to the increased knee extension moment in the shod condition.

The study has some limitations that should be further considered in order to understand the relationship between running conditions and joint moments of the lower extremity. Due to the lab conditions, data was only collected for one gait cycle and as such may not be a direct representation of repeated running strides. Subjects all ran at seven-minute-mile (3.84 m/s) pace, which was not always the preferred running speed for the subjects. The three different running conditions required the movement of markers on the foot which placed an importance on precision when placing the subjects in the separate coordinate system for the feet when calculating ankle angles and moments. In addition some subjects ran in the Vibram® Classics, while others ran in the Bikilas adding some variability into the study. Further research should include repeated gait cycles, varying running speeds, increased precision between varying conditions, control of type of VF® running shoe and long term injury tracking to confirm whether rates change and how they change with additional strengthening of the associated joints.

Conclusion

The VF® running shoe was developed to mimic barefoot running, increase stability and reduce impact. ("Barefoot Running," 2012). Our study showed that the VF® shoes were effective at mimicking barefoot running when considering lower extremity joint moments and angles (excluding ankle angle), supporting the proposal by Vibram® that their shoe design allows the

anatomy of the individual to work more naturally and freely, as if the individual was running barefoot, in addition to reducing the impact forces ("Barefoot Running," 2012). However, our subjects had elevated joint moments at the ankle and hip during VF[®] and barefoot running when compared with shod running.

It is important to remember that decreased joint moments do not necessarily lead to a reduction in injury. As discussed previously, Wolff's law must be taken into consideration by any athlete or coach looking for a way to improve performance while decreasing injury incidence. When taking this law into consideration, they could add variety to a program in order to strengthen the associated bones, joints and muscles. This could be done through cross training, running in a variety of shoes and exercises specifically aimed at strengthening the associated structures through elevated stresses. Individual differences should be taken into consideration when planning any type of training program aimed to increase performance and decrease injury.

Previous research has revealed high levels of running related injuries and that the knee is the predominant location of these injuries (van Gent et al., 2007). Joint moments of the lower extremity have been shown to potentially lead to lower extremity running injuries (Ferber et al., 2002; McClay & Manal, 1999; Messier et al., 2008; Scott & Winter, 1990) which is why current running shoes have been developed to reduce impact forces at the knee. The VF[®] has claimed to reduce impact forces, a claim supported by our research study (at the knee in the sagittal plane) for runners who have no prior experience with barefoot running. As most runners who will attempt running in VF[®] will have no prior VF[®] (or barefoot) running experience, it is noteworthy that our subjects experienced some of the potential benefits of VF[®] within the first few moments of running in the shoe. If these same results can be found among highly trained runners, individuals with no prior running experience and runners with chronic knee pain, they

would offer significant benefits to a variety of individuals. Though the VF[®] did not reduce joint moments in the sagittal plane at the ankle and hip, the shoe did reduce impact forces at the knee, the site of the highest incidence of running related injuries. Prospective studies aimed at combining a reduction in joint moments with strengthening of associated structures should be carried out to truly understand how the alterations associated with VF[®] and other minimalist running changes long term incidence of injury.

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***Table 1** Joint moments at the active peak vertical ground reaction force
 B=Significant difference from barefoot
 V=Significant difference from Vibram[®]

Joint	Barefoot	Vibram	Shoe
Ankle Plantarflexion Moment (Nm/kgm)	1.49	1.43	1.21 ^{BV}
Knee Extension Moment (Nm/kgm)	1.86	1.96	2.26 ^{BV}
Hip Extension Moment (Nm/kgm)	1.49	1.43	1.35 ^B

***Table 2** Average lower extremity joint angles for the three different conditions as well as the COP distance from the vertical ground reaction force to the ankle joint.
 B=significant difference from barefoot, V=significant difference from Vibram[®]

	Barefoot	Vibram	Shoe
Ankle Plantarflexion Angle (degrees)	26.0	29.1 ^B	29.2 ^B
Knee Flexion Angle (degrees)	42.5	44.2	47.7 ^{BV}
Hip Flexion Angle (degrees)	27.5	29.5	33.1 ^B
COP Distance (m)	.107	.103	.089 ^{BV}

Chapter 1

Introduction

Running, once primarily used for transportation, has now become one of the primary forms of exercise. The benefits of cardiovascular exercise, such as running, are numerous and include: decreased depression and increased emotional well-being (Galper et al., 2006), reduced risk for heart attack and stroke (Fentem, 1994) reduction in blood pressure (Fentem, 1994; King et al., 2009; Myers, 2003), improved treatment and reduced risk for diabetes (Fentem, 1994; Gulve, 2008; Manders et al., 2010) and reduction in coronary heart disease (Hatziandreu et al., 1988; Thompson et al., 2007). These studies, along with many others show numerous health benefits associated with habitual exercise.

Over 36 million Americans ran at least once in 2003 and over 10.5 million ran at least 100 days (Paluska, 2005). As the number of runners increase, the incidence of running injuries goes up as well. Many runners sustain lower extremity running injuries (van Gent et al., 2007), with some reported incidence rates as high as 79% in recreational runners (Lun et al., 2004).

Barefoot running is one of the areas of running research that has gained popularity in recent years. During running a runner will need to withstand forces up to 3 times their body weight in the first 50 ms of the stance phase. These forces quickly travel up the body and can contribute to the high incidence of injury in runners, including plantar fasciitis and tibial stress fractures (Lieberman et al., 2010; Milner et al., 2006; Pohl et al., 2009; van Gent et al., 2007). Barefoot running has been found to reduce these impact forces as a result of a flatter foot placement and no rear foot strike (Lieberman et al., 2010; Squadrone & Gallozzi, 2009).

Barefoot runners have a lower peak impact force than their shod counterparts (1.62 times BW and 1.72 times BW respectively) at 3.33 m/s (Squadrone & Gallozzi, 2009).

Peak impact forces are not the only area that differences are seen during barefoot running. Joint moments of the lower extremity were found to be significantly lower at the hip for adduction and internal rotation torques, at the knee for flexion, varus and internal rotation torques and at the ankle for internal rotation torques (Kerrigan et al., 2009). These joint torques, or moments, are an important aspect of running that must be considered in relation to running injury. Joint moments can be an effective indicator of the stresses placed on the neuromuscular system (Winter, 1983b) and elevated joint moments at the knee can lead to injury (McClay & Manal, 1999; Scott & Winter, 1990). Research has also suggested joint moments can contribute to lower extremity injuries (Ferber RI, 2002; Messier et al., 2008). In addition increased frontal (ab-adduction) and transverse (external-internal rotation) moments at the knee might be related to the development of patellofemoral pain syndrome in runners (Stefanyshyn, 1999).

Barefoot running does have some limitations. Someone who chooses to participate in a barefoot running program may need to find areas that have soft surfaces free of sharp objects to perform their running. Though the skin on the sole of the foot is stronger and thicker than other areas, injuries, such as puncture wounds, can still come to the foot. This problem has led to the development of the FiveFingers running shoe from Vibram. This shoe is designed to mimic barefoot running while giving the runner protection from objects encountered while running. Research on the Vibram FiveFingers (VF) running shoe is minimal, but does include a study performed in 2009 that concluded that the VF was effective at mimicking the barefoot running condition while offering protection to the feet of the runner (Squadrone & Gallozzi, 2009). Additionally the study showed that the VF did significantly reduce peak impact forces in

comparison with running shoes (1.59 times BW and 1.72 times BW respectively) and that the impact forces of the VF was less than the 1.62 times BW reported during barefoot running

After an extensive search of the literature no study has been found that investigated the joint moments associated with the Vibram FiveFingers running shoe. The purpose of this study is to determine the effects of Vibram FiveFingers running shoes on ankle, knee and hip joint moments during the active peak vertical ground reaction force in recreational runners and how these joint moments compare both to barefoot and shod running.

Statement of Purpose

The purpose of this study is to compare joint moments during the active peak vertical ground reaction force when running in three different conditions: barefoot, Vibram FiveFingers and shod.

Hypothesis

Hip, knee and ankle joint moments in the sagittal plane will be lower during the active peak vertical ground reaction force when running in the Vibram Fivefingers and barefoot conditions when compared with the standard shod condition.

Null-hypothesis

Hip, knee and ankle joint moments in the sagittal plane during the active peak vertical ground reaction force will not be lower during the Vibram Fivefingers and barefoot condition when compared with the standard shod condition.

Independent variables

Type of running: barefoot, Vibram FiveFingers or shod

Dependent variables

Lower extremity joint moments during the active peak vertical ground reaction force of the gait cycle

Assumptions

Subjects will be truthful when reporting no lower extremity injuries preventing them from running in the last 12 weeks and that they have been running consistently for six months.

Operational definitions

Active Peak: Peak vertical ground reaction force (after impact peak, when present).

Joint torque/moment: Torque produced by the muscle force about the joint center

Limitations

Only one gait cycle and foot strike will be calculated per trial for joint moments

Speeds will be limited to 7-minute-miles (3.84 m/s)

Delimitations

Testing will be done in the biomechanics lab.

Subjects will be between the ages of 18 and 30.

Participants must be recreational runners, defined by weekly mileage of 15-30 miles consistently for the last six months.

Only one speed will be analyzed during the study.

Chapter 2

Review of the Literature

Running has become one of the primary forms of exercise for many adults. Over 36 million adults ran at least once in 2003 and over 10.5 million of these runners ran at least 100 days (Paluska, 2005). As running becomes increasingly popular, injury prevention becomes one of the key areas of research moving forward. In an overview of running injuries, Van Gent et al. reported the incidence of lower extremity injuries in running to be in the range from 19.4% to 79.3% (van Gent et al., 2007). This range, though large as a result of reviewing many research studies, shows that injury from running is common. One specific study of recreational runners reported that upwards of 79% of recreational runners will experience a running related injury (Lun et al., 2004). The high incidence of lower extremity injury has prompted quantifiable amounts of research to be directed towards remedying this problem. This review will look at three current aspects of running research; the difference between barefoot and shod running, joint moments relating to running injury and finally the similarities and differences between running in the Vibram Fivefingers (VF) running shoe compared with barefoot running.

Barefoot v. Shod Running

Foot strike Pattern

Differences in foot strike patterns are one of the research areas in barefoot and shod running. There are three main types of foot strike patterns in runners. The first is the rear foot strike (RFS). This pattern consists of the runner landing first on the heel of their foot and the rest of the foot coming in contact at a later time. The fore foot strike (FFS) pattern consists of the runner landing first on the front (or ball) of the foot with the rest of the foot contacting the ground after this initial contact. The final pattern is the mid-foot strike (MFS), consisting of the

runner coming down on the ball and heel of the foot concurrently. A large number of shod endurance runners make contact with the heel of the foot first (RFS) (Hasegawa, Yamauchi, & Kraemer, 2007; Jungers, 2010; Lieberman et al., 2010). Barefoot runners, in contrast to shod runners, have a tendency to adapt to more of a MFS or FFS pattern during running. This altered foot strike pattern may be a result of increased plantar flexion at the ankle prior to impact creating a flatter foot placement (De Wit, De Clercq, & Aerts, 2000; Divert, 2005; Jungers, 2010; Lieberman et al., 2010; Squadrone & Gallozzi, 2009).

In addition to altered foot strike pattern, research has also investigated the pros and cons of these foot strike patterns. Lieberman and colleagues state that a rear foot-striking runner must repeatedly survive a force of 1.5-3 times their body weight (Lieberman et al., 2010). These forces can quickly travel up the body and can contribute to the high incidence of injury in runners, including plantar fasciitis and tibial stress fractures (Lieberman et al., 2010; Milner et al., 2006; Pohl et al., 2009; van Gent et al., 2007). The researchers who cited flatter foot placement as an adaptation to barefoot running argued that this foot placement reduces the pressure placed on the heel during regular shod running (De Wit et al., 2000; Divert, 2005; Squadrone & Gallozzi, 2009). These reductions in force at the heel stem from the altered foot strike pattern that often accompanies barefoot running.

Joint Torques

Research in barefoot running focuses primarily on the kinematic differences between barefoot and shod running, thus they focus solely on the aspects of motion without regard for the mass or forces associated with barefoot running. Kerrigan et al. (2009) is one of the few research publications that take into account the kinetics of barefoot running. Their research looked at the effects of barefoot and shod running on lower extremity joint torques. Kerrigan and colleagues

studied a group of 68 healthy young adult runners running in a laboratory setting. Each participant completed two 15-second trials on an instrumented treadmill following a 3 to 5 minute warm-up. Joint torques in the sagittal, coronal and transverse planes were calculated bilaterally during the stance phase of gait over the course of 10 consecutive strides. Shod running presented increased peak joint torques at the ankle, knee and hip with marked increase at the knee and hip (Kerrigan et al., 2009). The increased joint torques at the ankle, knee and hip during shod running is important in relation to injury prevention.

Lower Extremity Running Injuries

Running is a lucrative business with large amounts of money invested in the development of new equipment to improve performance and reduce injury. Running related injuries in recreational runners has been reported to be as high as 79% (Lun et al., 2004). As a result of this level of running injuries, the etiology of running injuries is a frequent research topic today. Though there are a variety of components leading to running injuries, joint moments of the lower extremity will be the primary component addressed in this review.

Much research has been conducted on the prevalence, magnitude, and causes of joint moments at the ankle, knee and hip during running. In the 1980s, Winter became one of the first researchers to examine the kinetic variables associated with walking and jogging (Winter, 1983a). He found that as a runner switched from a walking pattern to a jogging pattern, they experienced increased forces and joint moments in the sagittal (flexion/extension) plane especially at the knee and hip (Winter, 1983b). In addition, Winter extensively outlined the moment pattern associated with light jogging.

Researchers have additionally studied the effects of joint moments in the lower extremity and how these moments can relate to injury. In 1983 Winter proposed that flexion and extension

joint moments could be an effective indicator of the stressed placed on the neuromuscular system. Messier (2008) and Ferber (2002) agreed with Winter and suggested that kinetic variables such as joint moments can contribute to lower extremity running injury. Stefanyshyn et al. found that increased frontal (ab-adduction) and transverse (external-internal rotation moments at the knee may be related to the development of patellofemoral pain syndrome in runners. Others have also found similar results suggesting that elevated joint moments at the knee can lead to injury (McClay & Manal, 1999; Morrey, 1989; Scott & Winter, 1990). With the apparent injury risks associated with increased joint moments, reducing these and the resultant internal forces should have a positive effect on reducing the prevalence of injuries (Nigg et al., 2003)

Vibram Fivefingers vs. Barefoot

Research is beginning to show that there are possible benefits to barefoot running. Some of those benefits have been discussed earlier and includes; flatter foot placement at contact leading to less stress on the heel (Divert, Mornieux et al. 2008; Rome, Hancock et al. 2008; Lieberman, Venkadesan et al. 2010), reduced prevalence of lower extremity injuries as a result of these reduced stresses (Robbins and Hanna 1987; Jungers 2010; Stefanyshyn, Stergiou et al.), and decreased torques of the lower extremity joints (Kerrigan, Franz et al. 2009).

Some benefits of barefoot running are beginning to become apparent, but there are still aspects of barefoot running that need to be addressed. For the recreational runner decreased injury may be enough to warrant a change to barefoot running, but elite level runners may want to consider how barefoot running alters performance. Barefoot effects on performance warrant a sizeable amount of research before an answer can be determined. Additionally, safety for the foot of the barefoot runner is a consideration of research. Liebermann pointed out that for the majority of human history, running has been done in either bare feet or minimal footwear such as

moccasins(Lieberman et al., 2010). Though true, surfaces today may be more detrimental to the sole of the foot. Many runners, who want to experience some of the supposed benefits of barefoot running, do not have the option of running on artificial or soft surfaces that provide safety for the feet. As a result of this concern Vibram has developed a very lightweight shoe, called the Fivefingers, which is supposed to mimic the effect of barefoot running.

Squadrone and Gallozzi (2009) published research looking at the physiological and biomechanical comparisons of barefoot and two shod conditions, one of those being the Vibram Fivefingers (VF). Their study looked at 8 healthy male subjects who had experience with barefoot running. Each came to the lab and participated in three six-minute bouts of treadmill running, - one bout barefoot, another in the VF and a shod condition. The order of the three bouts of running was randomized for each runner. During the various bouts of exercise foot or shoe-ground interface pressure distribution, lower limb kinematics, oxygen consumption (VO_2) and heart rate (HR) were collected simultaneously.

The data showed that in some cases the VF condition closely resembled the barefoot condition. The area that it most closely resembled barefoot running was in the lower limb kinematics especially when referring to ankle joint motion. As discussed earlier, flatter foot placement and reduced stresses on the heel are some of the benefits of barefoot running. This comes from a foot placement that is more plantar flexed prior to impact, which Squadrone and Gallozzi (2009) found to be one of the main areas that the VF resembled the barefoot running condition. More specifically they found that the ankle ROM at during the support phase during VF nearly mimicked those found in barefoot running (28 and 29 degrees respectively) and that this ROM was significantly greater than those during shod running (21 degrees). Another area that the VF condition mimicked the barefoot condition was the peak vertical force seen at

impact. The VF condition had a peak vertical force of 1.59 times BW in comparison to the barefoot condition, which was 1.62 times BW (Squadrone & Gallozzi, 2009). Both of these vertical forces were significantly lower than the shod condition, which was 1.72 times BW (Squadrone & Gallozzi, 2009).

The VF shoe did not always resemble the barefoot condition during the course of the research. One area that the VF was different was the increase in peak thrust vertical velocity. The peak thrust, or push in a particular direction, follows the impact peak and has been suggested as the maximum thrust in the force record (Munro, Miller, & Fuglevand, 1987). This peak thrust, or propulsion force, allows the runner to push off with high amounts of force, propelling the runner forward. The author suggest that the thin rubber sole of the VF allow the runner to push off more vigorously than during the barefoot condition. This difference, though not significant, might be seen as a more robust difference in a larger sampling size.

Squadrone and colleagues concluded that the Vibram Fivefinger running shoes, according to their kinematic analysis, seems to be effective at imitating the barefoot condition while offering a little bit of protection (Squadrone & Gallozzi, 2009).

Overview

It can be seen from the previous pages that not only has running become an increasingly popular form of exercise, but also that the injuries associated with running are widespread and detrimental for those who experience those injuries. One aspect of running injuries can be associated with the joint moments of the lower extremity. As a result it becomes important to research ways to limit those joint forces associated with the lower extremity. Researchers have shown that barefoot running can be an effective way to reduced lower extremity joint torques and hopefully in turn reduce the incidence of running related injuries. In order to stay caught up

with this type of thinking, running shoes are being manufactured to mimic barefoot running conditions while offering the runner with some protection from dangerous running surfaces. The Vibram Fivefingers is one of those shoes that have been developed to mimic the effects of barefoot running. Kinematically the VF does indeed closely resemble the barefoot condition. As a result we would suspect that the VF does significantly reduce the joint moments during the active peak vertical ground reaction force, at the ankle, knee and hip.

Chapter 3

Methods

Subjects

Twenty-five recreational runners will participate in this study. Runners will be recruited via word of mouth, fliers at BYU and local running stores and at BYU. The subjects will be between the ages of 18 and 30, will have had no lower extremity injuries that have prevented them from running at least 3 days/week in the prior 12 weeks and will have been running consistently between 15 and 30 miles/week for the last six months. Each subject will sign a consent form, which has been approved by the Brigham Young University institutional review board.

Testing Procedures

Following a brief warm up each subject will run barefoot, in Vibram FiveFingers and in running shoes (Nike Air Pegasus). Subjects will run at seven-minute-mile pace (3.84m/s) across a force plate (AMTI OR6-5, Advanced Mechanical Technology Inc., Newton, MA), collecting at 960 Hz. A motion analysis system (Vicon, Centennial, CO) will record position of reflective

markers on the runner at 240 Hz. Shoe order will be randomized for each subject. Timing lights (Brower, Draper, UT) positioned at head height will be used to verify that seven-minute-mile pace $\pm 5.0\%$ is achieved, and maintained, through a 2 m section around the location of the force plate. Each subject will have a 10-meter approach in order to reach seven-minute-mile pace.

Trials will only be analyzed when it can be determined that the right foot lands completely on the force plate. In order to minimize error subjects will not be informed of the importance of landing completely on the force plate. The researcher will move the subjects back or forward to facilitate a complete foot contact on the force plate without a change in normal running stride. Trials will be completed until the criterion has been met three times for right foot. Visual 3d (C-Motion Inc., Germantown, MD) will be used to calculate joint moments and a customized LabView (National Instruments Corporation, Austin, TX) program will be used to determine the magnitude of joint moments occurring during the active peak vertical ground reaction force.

Vicon

Force and position data will be recorded and processed with Vicon Nexus (Vicon, Centennial, CO). Subjects will be marked with reflective markers according to a modified Helen Hayes model. Modifications will be necessary as a result of the three different footwear conditions contained in the experiment. In order to improve consistency of results in the three conditions, a coordinate system, separate from the lab coordinate system, will be created using a static trial at the beginning of each condition. Six MX 13+, two F20 and two T20 cameras will record marker position. A calibrated volume 2 m long, 2 m wide and 2.5 m high will be created around the force plate. The marker position data will be filtered using a 6 Hz Butterworth filter.

Force Plate

Two AMTI model OR6-5 force plates (Advanced Mechanical Technology Inc., Newton, MA) embedded in the floor of the biomechanics lab at Brigham Young University will be used. The cement floor of the lab is covered by a thin layer of carpet except for the two force plates, which are uncovered in the center of the room.

Shoes

All subjects will wear the same type of shoes for testing. The shoes in this study are the Nike Air Pegasus and the Vibram Fivefingers. The Air Pegasus is designed with sufficient cushioning and is neutral in terms of motion control. The Vibram Fivefingers shoe is the classic version produced by Vibram. It has a stretch nylon fabric on the upper part of the shoe with a 3.5mm rubber sole razor sipped for flexibility and slip resistance. The third condition is barefoot.

Statistical Analysis

Using means and standard deviations from a previous study (Kerrigan et al., 2009) subject number, alpha and beta were determined. A mixed model analysis of variance, blocking on individuals, will be used to analyze moment differences at the hip, knee and ankle in the sagittal plane. Alpha will be set at 0.05 to test for significance and beta will be set at .2 signifying an accepted significance 80% of the time when a difference is found.

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