ABSTRACT

THE EFFECT OF BAREFOOT VERSUS SHOD RUNNING ON JOINT KINEMATICS OVER A 30-MINUTE TRAINING SESSION

The purpose of this research was to examine the effects of a prolonged running session on the foot strike patterns of the shod versus barefoot condition. Four participants (n=4) completed the protocol, were filmed, and software was used to determine the angle of the ankle, knee, and hip, as well as the horizontal displacement of center of mass versus foot strike.

Kinematics of both conditions were compared using four one-way repeated-measures ANOVAs. The results revealed no significant difference for ankle angle ($p=0.944$), hip angle ($p=0.368$), and horizontal displacement of COM versus foot strike ($p=0.646$), and a significantly greater knee angle in the shod condition ($p=0.022$).

The effects of fatigue on kinematics of the two conditions were compared using four one-way repeated-measures ANOVAs. For the barefoot condition these ANOVAs revealed no significant fatigue effect for ankle angle ($p=0.462$), knee angle ($p=0.909$), hip angle ($p=0.203$), or displacement of COM ($p=0.219$). For the shod condition there was no significant fatigue effect for ankle angle ($p=0.391$), knee angle ($p=0.277$), and horizontal displacement of COM versus foot strike ($p=0.448$), and a significant effect on hip angle ($p=0.040$). More research is needed to properly assess the effect of fatigue on joint kinematics while running barefoot.

Jason Wara
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THE EFFECT OF BAREFOOT VERSUS SHOD RUNNING ON JOINT KINEMATICS OVER A 30-MINUTE TRAINING SESSION

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CHAPTER 1: INTRODUCTION

Barefoot running is not a new concept. It has been around for millions of years (Bramble & Leiberman, 2004). However, just recently a debate has arisen in the running and athletic community between whether it is more beneficial to run in shoes or to run barefoot. This topic has become one of the more hotly contested topics in running today, with both sides espousing reasons why you should run in shoes or why you should run barefoot, or at least in a very minimal running shoe. While both sides make plausible claims for their side and against the other, surprisingly little research has been done on the topic. The available research has focused on injury prevention, the impact forces at foot strike, running economy, biomechanical differences, and the effect on the associated musculature of the foot.

Research that has been performed on joint kinematics of barefoot running has revealed that barefoot runners will adapt a fore-foot or mid-foot strike, as opposed to a heel strike seen more often in shod runners (Jenkins & Cauthon, 2011). It is believed that this change in foot strike is facilitated by a subconscious effort of the body to avoid injury, and is often cited by advocates of barefoot running as to why it may be less injurious as shod running, although no research has made a distinct connection between barefoot running and lower injury rates. While it has been established that there is a change in biomechanics between barefoot and shod running, almost all of the studies examining this change asked runners to run in the barefoot condition for only a short duration of time. One drawback with this short duration is that people do not often go on training runs that are only 5 min long. Very little research has compared the effect of a prolonged training session of shod versus barefoot running biomechanics, which is what this study will examine.

Running economy is defined as the amount of oxygen used at a standard running speed (McLaughlin et al., 2010). A more economical runner will use less oxygen than a less economic runner at a given running speed, suggesting that the more economical runner may be better suited for that particular endurance event (McLaughlin et al., 2010). Numerous studies have shown that running in the barefoot condition increases running economy (Burkett, Kohrt, & Buchbinder, 1985, Squadrone & Gallozzi, 2009, Webb, Saris, Schoffelen, Van Ingen Schenau, & Ten Hoor, 1988), and that the weight of the shoe has an effect on running economy. Flaherty (1994) found that there was 4.7% higher oxygen consumption in shoes weighing 700g versus the barefoot condition. It has also been theorized that the deformation of the shoe at impact can lead to inefficiency in the usage of the stored elastic energy of the tendons (Divert, Mornieux, Freychat, Baly, & Mayer, 2008).

Running barefoot can also lead to a change in biomechanics. It has been observed that running barefoot promotes a mid to fore-foot strike as opposed to a heel strike, which is associated with wearing shoes (Lieberman et al., 2010). It has been shown that the tendency to land with mid to fore-foot strike is due to the body unconsciously trying to decrease the forces at impact of the foot and the surface (Lieberman et al., 2010). This change in biomechanics also leads to a greater stride frequency and smaller stride lengths in barefoot runners, which could affect running economy and, in turn, the ability of the runner to maintain an unfamiliar foot strike pattern. This could be especially apparent over a longer training session as fatigue increases. So, while runners may begin a run with a forefoot strike when barefoot, they may experience a change in biomechanics over time, leading to different foot strike patterns as they tire.

Running barefoot also has an effect on the associated musculature of the foot. Bruggemann, Potthast, Braunstein, and Niehoff (2005) found that there was an increase in the cross-sectional area of the flexor hallucis brevis, flexor digitorum brevis, abductor hallucis, and quadrates plantae muscles of study participants who wore a shoe that mimicked being barefoot during their track warm-up, while there was no change in muscular size of the control group. Other studies have also found that training barefoot led to an increase in the size and strength of the associated musculature of the foot when compared to going shod. This increase of foot strength could lead to a greater push-off in the stride of a runner, but as no studies currently exist on the effect that increased musculature of the foot from training barefoot has on performance or mechanics, one can only speculate on the effects.

One of the main focal areas in the debate between barefoot and shod running asks the question, how might running barefoot affect injury rates? There has been very little history of study in this area, but the majority of current research on barefoot running seeks to answer this question. One of the findings of the research is that running barefoot, or with a barefoot running style, defined as a forefoot or mid-foot strike, will produce smaller impact forces than a rear-foot strike (Bishop, Fiolkowski, Conrad, Brunt, & Horodyski, 2006). These reduced impact forces could lead to less injury, as the repetitive stress associated with heel strike can lead to injuries that are associated with repetitive, high impact forces (van Mechelen, 1992). Other factors that relate to injury that are poorly studied are the different torques applied around the joints during different foot strike patterns, the effects of shoe cushioning and proprioception, and the possible increased risks of injury to a transition to barefoot running or a barefoot running style (Lieberman et al., 2010).

As can be seen, there exist many gaps in the research when it comes to barefoot versus shod running. The present study hopes to add to the barefoot running literature by examining the effect a 30-min training session has on the foot strike patterns of runners in the shod and barefoot conditions.

Statement of the Problem

The purpose of this research was to examine the effects of a prolonged running session on the foot strike patterns of shod versus barefoot condition.

Hypothesis

When running in the barefoot condition, participants will begin the run with fore-foot or mid-foot strike but the fatigue experienced from the longer duration of the test will cause them to change their biomechanics to a stride that more closely resembles their shod running biomechanics.

Delimitations

The inclusion criteria for this study were males and females between the ages of 18 and 35 years of age. Subjects met the ACSM criteria for an "apparently healthy" adult. They also ran at least 15 miles per week for the past 4 months. Participants also ran 20 miles barefoot or more over the previous 4 months. Additionally participants had run at least 3 miles barefoot on a treadmill. There was a gender bias with three or the four participants being male. The participants only performed for 30 min to induce fatigue at one treadmill speed relative to their VO_{2max}, and they wore their own shoes, all with different specificities in their construction.

Limitations

It was presumed that all subjects put forth peak effort in all of the tests and trials. Due to the blistering that may have occurred from performing the trials on a treadmill, participants were wearing a sock during the barefoot trial. This may have had an effect on proprioception, but should not have affected foot strike patterns. The study was underpowered due to the small number of participants (n=4).

CHAPTER 2: LITERATURE REVIEW

This chapter reviews the current literature concerning barefoot running. The topics covered are biomechanics, impact forces, running economy, the effect on associated musculature, and injury.

Biomechanics

One of the areas of greater research in concern to barefoot running, or more specifically, the effect of barefoot versus shod running, is biomechanics. The main differences found in the gait between shod and barefoot runners has been in the position at which the foot strikes the ground, the stride rate, stride length, range of motion at the ankle, knee and hip, and the degree of plantarflexion at foot strike. This section will focus on the biomechanical differences in barefoot versus shod running alone, and following sections will examine in further detail how all of these biomechanical differences effect running economy, impact forces at foot strike, and the musculature of the foot. When all of these factors are examined, the evidence seems to point in the direction of greater running economy in barefoot running, a factor that contributes to overall performance.

The position of the foot when it strikes the ground has been found to be more plantarflexed when barefoot and barefoot runners tend to land with a more mid-foot to fore-foot strike, as opposed to a heel strike that is observed in the majority of shod runners (Lieberman et al., 2010). It has also been observed that runners will adjust their gait when going from shod to the barefoot condition. While runners may heel strike when shod, when barefoot they will exhibit a more mid- to fore-foot strike in what has been hypothesized as an unconscious way of protecting themselves from the impacts created at foot strike (Divert, Mornieux, Baur, Mayer, & Belli, 2005).

It has also been observed that stride length is affected. In a study comparing barefoot and two shod conditions in experienced barefoot runners, it was found that stride length was significantly shorter in the barefoot condition as opposed to the shod condition (Squadrone & Gallozzi, 2009). Lieberman et al. (2010), Divert, Mornieux, et al. (2005), and De Wit, De Clercq, and Aerts (2000) also found evidence of a shorter stride length in studies. In each case stride length was shorter in the barefoot condition.

Another difference in the biomechanics of running barefoot versus shod is seen in the stride frequency (Nigg, 2009). In the vast majority of studies that examined the biomechanics of barefoot running, participants exhibited a higher stride frequency when running in the barefoot condition. This makes sense, as a higher stride frequency would result from a decrease in stride length which, as stated above, has been observed when running in the barefoot condition (Squadrone & Gallozzi, 2009). These two factors—increased stride rate and decreased stride length—have an effect on running economy and the force of impact at foot strike, both of which will be addressed in further detail in following sections.

The next observable biomechanical difference in gait in barefoot versus shod runners is the range of motion at the ankle, knee, and hip joints. The most observable difference in range of motion of these three joints is seen at the ankle. A number of investigators have found that barefoot runners foot strike with a more plantarflexed ankle. In a study performed by Lieberman and colleagues (2010) it was observed that participants who had grown up habitually unshod were more likely to fore-foot strike versus heel strike (Lieberman et al., 2010). It has also been observed, as stated above, that even those who run habitually shod will exhibit a more plantarflexed ankle in an unconscious change in gait in order to reduce impact forces at foot strike (Divert, Mornieux, et al., 2005). These changes in gait have also been seen to decrease peak loads at the hips and knees (Shakoor & Block, 2006). Indeed, smaller knee and hip angles have been observed in the barefoot condition, leading to conclusions that the increased variations in these lower-extremity joints may be related to the ability of the mechanoreceptors to adjust to the joint, which may be a mechanism for reducing the magnitude of repetitive impact forces (Kurz, Stergiou, & Blanke, 2003).

One final observation that has been found in the biomechanics of barefoot versus shod running was a higher electromyographic activity in pre-activation of plantarflexory muscles: the gastrocnemius lateralis, gastrocnemius medialis, and soleus (Divert, Mornieux, et al., 2005). These observations make sense logically as a change in gait should result in a change in the activation of these muscles. The pre-activation of these muscles as well as the other biomechanical factors all contribute to modification of the peak forces experienced at foot strike, which will be covered in the next section.

Impact Forces

The changes in the biomechanics of running barefoot versus shod have been shown to have an overall effect on the impact forces the body experiences at foot strike. Studies by Lieberman et al. (2010), Divert, Baur, et al. (2005), and Squadrone and Gallozzi, (2009) have all found that the peak impact forces were reduced when running in the barefoot condition. These lower impact forces were associated with specific changes in the biomechanics of running barefoot versus shod. Typically those running barefoot land with a more plantarflexed ankle, causing them to land on their mid or fore-foot, as opposed to a heel strike, which is typically seen in the shod condition (Divert, Mornieux, et al., 2005). Lieberman et al. (2010) found that larger transient forces, sharp spikes in the force curve, were generated in participants who were shod as well as those who heel struck when barefoot, while those who landed with a mid- or fore-foot strike lacked those transient forces (Lieberman et al., 2010). Along these same lines, Robbins and Hanna (1987) found that through training in the barefoot condition, improved sensory evaluation resulted in gait changes which led to a mid-foot strike and thus, reduced forces at impact. Robbins and Hanna (1987) also found that there is an adaptation to the associated musculature of the foot, which resulted in greater strength and a medial longitudinal arch that is higher and better able to deform at impact.

It has also been observed that, along with the gait changes associated with barefoot running, there are higher braking and pushing impulses and higher pre-activation of the triceps surae (Divert, Baur, et al., 2005). It is proposed that this pre-activation of the triceps surae is related to the anticipated impact at foot strike and that this pre-activation also attributed to the decreased forces experienced at impact (Divert, Baur, et al., 2005). The variability of gait patterns associated with barefoot running has also been theorized to lead to the ability of the mechanoreceptors of the lower-extremity joints to adjust the joint pattern of impact absorption, and that this may also be a mechanism for overcoming the repetitive impact forces associated with running (Kurz, Stergiou, & Blanke, 2003). This leads to the idea that there will be greater proprioception in the barefoot condition as the body experiences greater feedback from the environment and that the greater propioception will result in appropriate gait adjustments. This increase in proprioception is a logical assumption to make, but there have been very few studies done in this area. Those that do exist have looked at the barefoot condition as it applies to proprioception in static conditions. Robbins, Waked, and Gouw

(1995) investigated the loss of proprioception in males through the measurement of the perception of slope of variously sloped platforms (Robbins et al., 1995). What was discovered was that there was a loss of proprioception with the wearing of shoes and with aging (Robbins et al., 1995). These findings led to the conclusion that a barrier between the mechanoreceptors of the foot and the ground would inhibit foot position awareness (Robbins et al., 1995). Two other studies on proprioception revealed that thicker and softer shoes led to a decrease in the balance of both younger and older men (Robbins, Gouw, & McClaran, 1992; Robbins, Waked, & Gouw, 1994).

Not all of the studies conducted on the impact forces at foot strike in barefoot versus shod running have found lower impact forces. Nigg (2009) found a difference between peak impact force and maximal arch deformation, leading to the conclusion that the increased musculature of the foot and its corresponding improvement in shock attenuation was not valid. It was also found by Komi, Gollhofer, Schmidtbleicher, and Frick (1987) that there was an increased passive peak vertical force, a force similar to the peak transient forces observed when running with shoes, in the barefoot versus the shod condition (Komi et al., 1987). This study also found that there was no significant difference in stride rate or stride frequency, which is in opposition to a number of other studies in the same area. The methodology of the Komi et al. study required the four participants to land with a heel strike (Komi et al., 1987). This heel strike when barefoot would result in higher peak impact forces. However, heel striking while barefoot is an unnatural barefoot gait, as participants have been shown to change their gaits when running barefoot.

Along these same lines of evidence against decreased impact forces at foot strike in barefoot runners, De Clercq and Aerts, (1994) found that at heel strike a barefoot runner will undergo a 61% deformation of the heel pad at impact versus only a 36% deformation of the heel pad when shod. This study concluded that at this level of deformation, the heel pad no longer acted as a shock attenuator but as a protective structure which had a much greater potential to be injured (De Clercq & Aerts, 1994). This evidence, again, is contrary to a number of studies which have shown that the changes in gait when barefoot work to avoid the incidences of high force impact. However, just as in the Komi et al. (1987) study, participants were required to heel strike which, evidence suggests, is contrary to the gait changes that are experienced when running barefoot.

One final opposition to the evidence of decreased shock attenuation in the barefoot running comes from a study done by Ogon, Aleksiev, Spratt, Pope, and Saltzman (2001). In this study it was found that there was an increased rate of shock transmission to the erector spinae muscles in the barefoot condition versus the shod condition (Ogon et al., 2001). Again, as in the two studies previously noted, this study had participants heel strike during all of the running conditions. As has been observed in a number of studies concerning gait changes in barefoot running, evidence appears to point away from a heel strike when barefoot and to gait changes that favor a more mid- to fore-foot strike, thus reducing the peak impact forces at impact.

Comparison of all the research appears to point to changes in gait between the barefoot and shod conditions, which lead to decreased peak impact forces at foot strike in the barefoot condition. These changes in gait and impact forces lead into the next area of inquiry, which is running economy.

Running Economy

Running economy is one of the areas that have been addressed in the literature concerning barefoot versus shod running. Running economy is defined as the amount of oxygen that is being used at a standard running speed (McLaughlin et al., 2010). A more economical runner will use less oxygen than a less economic runner at a given running speed, indicating that they may be more effective or more efficient and so, better suited for that particular endurance event (McLaughlin et al., 2010).

Early investigations into the differences in running economy found that there was reduced oxygen consumption when running barefoot versus running shod (Burkett et al., 1985). This reduced oxygen consumption was attributed to the mass of the shoe (Caitlin & Dressendorfer, 1979). Another study done along these same lines found a 4.7% higher oxygen consumption in shoes weighing 700g versus the barefoot condition (Flaherty, 1994). A more recent study comparing the running economy of barefoot, minimalist shoes, and cushioned running shoes found the same decrease in oxygen consumption as the weight of the shoe decreased, with running barefoot being the most economical condition (Hanson, Berg, Deka, Meendering, & Ryan, 2011).

Divert et al. (2008) conducted a study that added weight to unshod feet and found that the increased energy utilization was a product of the mass of the shoe as opposed to the change in gait mechanics (Divert et al., 2008). They also hypothesized that shock attenuation related to the shoe may dampen the stored energy of the Achilles tendon and add to the inefficiency associated with the shod condition (Divert et al., 2008). Further inefficiency in the use of stored elastic energy may also occur with the actual deformation of the shoe with each stride (Webb et al., 1988). This is energy that may be saved in the barefoot condition, leading to greater running economy (Webb et al., 1988). In a study of experienced barefoot runners a non-significant difference in improved running economy was found when comparing shod and barefoot running (Squadrone & Gallozzi, 2009). This study theorized that these experienced barefoot runners had changed their running style, making even the shod condition more economical because the participants ran with a barefoot running style even when wearing shoes (Squadrone & Gallozzi, 2009).

These studies on barefoot running versus shod running all point toward improved running economy in the barefoot condition. This difference in economy seems to be associated with the added weight of the shoe to the lower leg. There still remain questions on the storage and restitution of elastic energy and how this may contribute to the increased running economy of the barefoot condition. It also remains to be seen if training barefoot develops a gait similar to that when barefoot while shod, although the evidence points in that direction. If running barefoot does lead to greater running economy, as the research suggests, and this greater economy is, in part, related to the restitution of stored elastic energy in the tendons, then a fore-foot or mid-foot strike is needed for this energy to develop, as there will be none, or little, energy stored in the Achilles tendon with a heel strike. As has been seen in research related to the biomechanics of barefoot running, barefoot runners tend to land with more of a fore-foot to mid-foot strike. This will allow for the storage and restitution of elastic energy in the arch of the foot and the Achilles tendon.

A problem arises when examining the duration of a training bout and the biomechanics of barefoot running over an extended run. Almost every study that has been done included participants that are only asked to run in the barefoot condition for between 5 and 8 min. A longer training run in the barefoot condition could change biomechanics from the associated fatigue experienced from the training bout, causing participants to no longer be fore-foot or mid-foot strikers, but to become heel strikers. This change in biomechanics could offset the increase in running economy and could also lead to an increased risk of injury. The present study seeks to find out what happens to foot strike patterns over a longer duration run (30 min) in the shod versus barefoot condition, which could lead to better understanding of how fast or slow people should transition to barefoot running or a more barefoot running style.

Associated Musculature

Another topic of research that could have an effect on performance of barefoot running is the effect that barefoot running has on the musculature of the foot. A study done by Kadambande, Khurana, Debnath, Bansal, and Hariharan (2006) found that there was increased pliability of the foot in those that grew up going predominately barefoot versus those that grew up wearing shoes (Kadambande et al., 2006). However, the study did not find a significant difference in intrinsic foot muscle function (Kadambande et al., 2006).

A similar study examined 2,300 children for any effect of footwear on arch development and came to the conclusion that wearing shoes led to a detriment in the normal development of the medial longitudinal arch which in turn led to a decrease in the strength and development of the plantar intrinsic musculature (Rao & Joseph, 1992). A study was also conducted on a Nike shoe that was marketed to mimic the barefoot condition (the Nike Free 5.0). It was found in the participant group that performed their warm-up in a pair of Nike Frees that there was a significant increase in the cross-sectional area of the flexor hallucis brevis, flexor digitorum brevis, abductor hallucis, and quadrates plantae muscles, while there was no change in that of the control group (Bruggemann et al., 2005). It was also found that there was an increase in strength in the flexor hallucis longus and flexor digitorum longus muscles of the experimental group, while there was no change in the control group (Bruggemann et al., 2005). While this study did claim to show increased strength of various muscles of the foot the methodology used in the measurement of the strength of the said muscles was not included, nor did the study note whether the adaptation was chronic or acute. It would also have been interesting to see whether the increased in the strength and the cross-sectional area of the listed muscles of the foot led to increased performance. Logically it would seem that an increased strength of the musculature of the foot would assist in the push-off phase of a runners stride, but almost no studies have measured the effect that increased musculature of the foot from training in the barefoot condition has on performance during a prolonged barefoot run.

Injury

Of all of the issues and debates concerning barefoot versus shod running, the topic of injury is perhaps the most hotly debated, as well as the least understood. The research that has been done on the effect of shod versus barefoot running on injury has focused on differences in impact forces, the effect of shoe cushioning on proprioception, moment forces applied around the joints, the effect of transitioning to barefoot running and its relationship to injury, and finally the differences in biomechanics between shod and barefoot running.

When examining injury as it relates to barefoot versus shod running, one must first understand the factors that may lead to injury in endurance runners. Repetitive stress injuries are especially prevalent amongst endurance runners (Ryan, MacLean, & Taunton, 2006). The dynamic forces that are applied during every step in running can lead to these repetitive stress injuries. Therefore, high rates of forces and magnitude of loading may contribute to these repetitive stress injuries. Peak impact forces stand out as the highest and most rapid loads on the musculoskeletal system, and therefore have been studied as a potential cause for injury (Lieberman et al., 2010).

All of the factors discussed above relate to, and are affected by, barefoot running. The present study seeks to add to the literature and be a small piece of the larger puzzle as it relates to barefoot versus shod running. Through the examination of joint kinematics over a 30-min training session potential changes in stride and joint kinematics may be observed as the participant fatigues during the 30-min session. Data that are gathered from this experiment can help in the better understanding of how, and how fast, people should transition to barefoot running. It can also lead to other studies on how impact forces change in barefoot versus shod running over an extended training session. The purpose of this study is to begin to fill in some of the gaps that exist in the current research and springboard into other studies related to how an extended barefoot running session affects the other factors discussed above.

CHAPTER 3: METHODOLOGY

This chapter describes the methodology of the study. It is divided into sections, which describe the selection of the participants, the equipment and instrumentation, the procedures, and the data analysis.

Participants

Participants were males and females between the ages of 18 and 35 years of age. Inclusion criteria were as follows: participants met the ACSM criteria for an “apparently healthy” adult, they had run at least 15 miles per week 4 months, and they had run a minimum of 20 miles barefoot over the previous 4 months. Additionally, participants had run at least 3 miles barefoot on a treadmill or were accustomed to running barefoot on a treadmill. Exclusion criteria were contraindications to exercise, and participants who did not meet the specified inclusion criteria.

Equipment and Instrumentation

The participants ran on a motorized treadmill during the tests (Endurance Model T10, Forest Park, IL). For the shod session, participants wore the shoes in which they did the majority of their running. When running in the barefoot condition, participants wore a thin sock with minimal grip on the sole. The purpose of the sock was to prevent the formation of blisters on the feet of the participants. The belt of the treadmill, along with the heat and friction that it creates, can lead to blistering of the feet in runners, causing them to prematurely end the training session. The sock reduced this chance of blistering and facilitated completion of the test. Surface anatomical landmarks were marked to improve reliability of digitizing. The tip of the participant’s toe and the back of their heel were marked in order to better digitize the collected video. The point marked that represented the toe was placed over the first metatarsal and the point that signified the ankle was placed on the malleolous The marker on the hip was placed 0.02m proximal to the greater trochanter, the marker at the knee joint was in the center 0.02m above the tibial plateau, and the shoulder marker was put at the height of the acromion (Bobbert , Yeadon, & Nigg, 1992). The markings were made with athletic tape and black marker. These markings were done in both the shod and barefoot condition. A one-camera set-up was used to capture the movement of the participants in the sagittal plane. The camera was set up on both the left side of the runners in order to capture motion of the left leg. Vicon-Motus software was used to digitize the toe, heel, ankle, knee, hip, shoulder, wrist, and end of hand points during the tests. This software was also used to determine the angle of the ankle, the angle of the knee, and the angle of the hip. The software was also used to find the center of gravity of the participant and determine the horizontal location of the participant's foot strikes in relation to the horizontal location of their center of gravity.

The running speed in the trials was that which evokes 75% of their age predicted maximum heart rate. Prior to the digitized trial, during the familiarization session, the participants wore a heart rate monitor and were asked to run on the treadmill. The speed of the treadmill was increased incrementally until the participant reached 75% of their age predicted maximum heart rate. This corresponding speed was used as the speed to which the treadmill was set during the two trials.

Procedures

During the first session participants filled out an informed consent form (see Appendix), were familiarized with the treadmill, running with the sock, the markings that were placed upon surface anatomical landmarks, and the filming system. The procedures were explained and meeting times for the subsequent sessions were determined. The height, age, and body mass of the participants was also recorded, after which the participant was outfitted with a heart rate monitor. Electrolytic gel was used on the heart rate monitor to improve electrical contact. Once the heart rate monitor had been fitted, an incremental exercise test was performed in the shod condition on the treadmill that was used for all of the trials. The treadmill was set at a 1% incline to better simulate overground running conditions (Jones & Doust, 1996). The incremental exercise test continued until the participant reached 75% of their age predicted maximum heart rate; afterwards the participant was asked to cool down until their heart rate returned to 120 beats per minute. The participant was then fitted with the running sock that they were wearing to simulate the barefoot condition. Once the participant had been fitted with the sock, they performed a warm-up on the treadmill and a 10 min run at the speed in which the participant ran shod until they reached 75% of their maximum age predicted heart rate. This procedure allowed the participants to become familiar with the feeling of running in the sock and a foot strike that may be different than that in the shod condition. It also allowed the participants to become familiar with the speed at which they would be running when performing the 30-min trial. After the 10 min, run the participant performed a cool-down. Prior to the next test session the participants were allowed to take the socks home and run in them for a 10 day period for greater familiarity. It has been observed that running and walking patterns may be altered and unnatural when first performing in new shoes (Nyska, McCabe, Linge, & Klenerman, 1996). This extra practice time with the sock was intended to minimize this observed effect. Finally, the time of the next meeting, as well as what condition in which they would be performing the test was arranged.

The second and third sessions consisted of testing in the barefoot and shod conditions. The sequencing of the two conditions was randomly selected. The participants were asked to avoid a strenuous exercise bout in the 2 days leading up to the test to minimize potential fatigue, as explained to them in the familiarization session. During each session the participants completed a 5 min warm-up on the same treadmill used during the familiarization session and the trial. The treadmill was set to the speed that corresponded to 75% of the subject's heart rate that was established during the familiarization session. The entire duration of the trial was videotaped.

Filming of the running occurred in the sagittal plane. The camera was set-up to the left of the runner and was positioned so that it captured the entire body of the runner. The room was well lit for the sake of video clarity.

After the first session the subject determined a time to meet the following week in order to perform the same protocol, but in the opposing condition of the first trial. All testing, along with the familiarization session, was performed in the Human Performance Laboratory, located on the campus of California State University, Fresno.

Data Analysis

Joint kinematics of the ankle, knee, and hip were examined using Vicon-Motus software. Digitization of the participant's toe, heel, ankle, knee, and hip was done in order to measure the angle of the ankle, knee, hip, and horizontal displacement of the center of mass relative to foot strike. The shoulder, elbow, wrist, and end of the hand were digitized in order to find the center of gravity of the participant. Digitization was done for the left side of the participant. For every 5 min interval during the trial a segment of three full strides was digitized. A full stride was from foot strike to toe-off, better known as the support phase of one step. Foot strike was defined as the time when the foot first contacted the treadmill, toe-off was the point in which the foot ceased to contact the treadmill, and mid-stance was the point in which the malleolous was directly beneath the participant's center of gravity. The first interval began at t=0 with the corresponding digitizations being done at the time intervals of 5 min, 10 min, 15 min, 20 min, 25 min, and then at the final three full strides of the trial.

The average of the angle of the ankle, knee, hip, and horizontal displacement of the center of mass relative to foot strike of the three strides was taken when the participant reached the contact point between the foot and the treadmill. The averages of these angles was compared between the shod and barefoot condition for each time segment. The distance between foot strike and the participant's center of mass was measured for each of the three strides during each time interval using the Vicon-Motus software in both the shod and barefoot condition. Descriptive statistics, including the grand means, for all dependent variables in both conditions (shod and barefoot) and all times (0-30 min) were done. Figures of each dependent variable versus time for both conditions were also created.

The kinematics of the two conditions were compared for each dependent variable by collapsing data from all times (0-30 min) into grand means, and four one-way repeated-measures ANOVAs were conducted to compare means of each dependent variable.

The effect of fatigue on kinematics was done using a series of four one-way repeated-measures ANOVAs for each dependent variable, comparing the variable at time 0, the non-fatigued state, with that of time 30, the fatigued state.

CHAPTER 4: RESULTS

Descriptive Statistics for the Barefoot Condition

Following the digitization of the participants for times (t) 0, 5, 10, 15, 20, 25, and 30 min, the average ankle, knee, and hip angle at foot strike for each time was determined. The average horizontal displacement of the center of mass (COM) versus foot strike was also determined. The Tables 1-7 show the descriptive statistics for each time in the barefoot condition.

Table 1

Descriptive Statistics of Kinematic Variables for the Barefoot Condition, time=0

Variable	Mean	Standard Deviation
Ankle Angle	83.7	6.17
Knee Angle	158.1	2.15
Hip Angle	159.6	2.08
Horizontal Displacement of COM v. Foot Strike	0.165	0.027

Table 2

Descriptive Statistics of Kinematic Variables for the Barefoot Condition, time=5

Variable	Mean	Standard Deviation
Ankle Angle	85.32	4.42
Knee Angle	159.37	2.14
Hip Angle	162.35	4.69
Horizontal Displacement of COM v. Foot Strike	0.1675	0.0143

Table 3

Descriptive Statistics of Kinematic Variables for the Barefoot Condition, time=10

Variable	Mean	Standard Deviation
Ankle Angle	82.91	5.09
Knee Angle	158.80	3.84
Hip Angle	161.10	3.00
Horizontal Displacement of COM v. Foot Strike	0.1735	0.0136

Table 4

Descriptive Statistics of Kinematic Variables for the Barefoot Condition, time=15

Variable	Mean	Standard Deviation
Ankle Angle	85.03	3.67
Knee Angle	158.92	3.65
Hip Angle	161.76	2.38
Horizontal Displacement of COM v. Foot Strike	0.1730	0.00963

Table 5

Descriptive Statistics of Kinematic Variables for the Barefoot Condition, time=20

Variable	Mean	Standard Deviation
Ankle Angle	84.17	3.68
Knee Angle	157.35	1.41
Hip Angle	160.73	3.10
Horizontal Displacement of COM v. Foot Strike	0.1708	0.00714

Table 6

Descriptive Statistics of Kinematic Variables for the Barefoot Condition, time=25

Variable	Mean	Standard Deviation
Ankle Angle	84.93	4.86
Knee Angle	157.90	2.24
Hip Angle	160.45	4.76
Horizontal Displacement of COM v. Foot Strike	0.1700	0.0063

Table 7

Descriptive Statistics of Kinematic Variables for the Barefoot Condition, time=30

Variable	Mean	Standard Deviation
Ankle Angle	82.31	5.83
Knee Angle	158.18	3.13
Hip Angle	158.79	2.81
Horizontal Displacement of COM v. Foot Strike	0.1878	0.0053

Descriptive Statistics for the Shod Condition

The Tables 8-14 show the descriptive statistics for the shod condition for times 0, 5, 10, 15, 20, and 30 min.

Table 8

Descriptive Statistics of Kinematic Variables for the Shod Condition, time=0

Variable	Mean	Standard Deviation
Ankle Angle	84.84	7.78
Knee Angle	163.21	1.30
Hip Angle	162.31	3.01
Horizontal Displacement of COM v. Foot Strike	0.1935	0.051

Table 9

Descriptive Statistics of Kinematic Variables for the Shod Condition, time=5

Variable	Mean	Standard Deviation
Ankle Angle	84.49	7.22
Knee Angle	162.09	1.91
Hip Angle	160.34	3.14
Horizontal Displacement of COM v. Foot Strike	0.1878	0.035

Table 10

Descriptive Statistics of Kinematic Variables for the Shod Condition, time=10

Variable	Mean	Standard Deviation
Ankle Angle	84.72	6.71
Knee Angle	161.64	2.38
Hip Angle	160.13	3.52
Horizontal Displacement of COM v. Foot Strike	0.1853	0.044

Table 11

Descriptive Statistics of Kinematic Variables for the Shod Condition, time=15

Variable	Mean	Standard Deviation
Ankle Angle	84.47	6.05
Knee Angle	160.88	2.66
Hip Angle	158.29	2.67
Horizontal Displacement of COM v. Foot Strike	0.1848	0.045

Table 12

Descriptive Statistics of Kinematic Variables for the Shod Condition, time=20

Variable	Mean	Standard Deviation
Ankle Angle	83.08	7.58
Knee Angle	160.49	3.10
Hip Angle	159.22	4.37
Horizontal Displacement of COM v. Foot Strike	0.1795	0.044

Table 13

Descriptive Statistics of Kinematic Variables for the Shod Condition, time=25

Variable	Mean	Standard Deviation
Ankle Angle	83.67	7.30
Knee Angle	161.03	1.73
Hip Angle	159.00	2.78
Horizontal Displacement of COM v. Foot Strike	0.1955	0.055

Table 14

Descriptive Statistics of Kinematic Variables for the Shod Condition, time=30

Variable	Mean	Standard Deviation
Ankle Angle	83.93	6.51
Knee Angle	160.81	3.20
Hip Angle	158.64	3.89
Horizontal Displacement of COM v. Foot Strike	0.1835	0.054

Grand Means Comparing Shod and Barefoot Conditions

Table 15 shows the grand means of the ankle, knee, hip, and horizontal displacement of center of mass versus foot strike in both the barefoot and shod conditions.

Table 15

Grand Means Comparing Barefoot and Shod Kinematics

Variable	Shod	Barefoot
Ankle Angle	84.17	84.05
Knee Angle	161.45	158.37
Hip Angle	159.71	160.68
Horizontal Displacement of COM v. Foot Strike	0.1871	0.1725

Changes in Means Versus Time

The following section contains figures comparing the mean of the ankle angle, knee, angle, hip angle, and horizontal displacement of the COM versus foot strike over the times that data were examined during the trials. Figures 1-4 examine the barefoot condition and Figures 5-8 examine the shod condition.

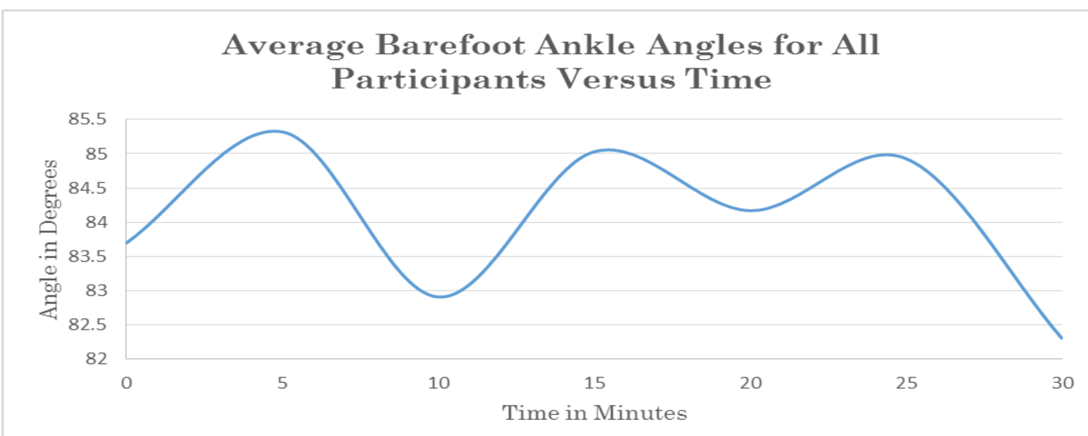

Figure 1. Average barefoot ankle angles for all participants versus time.

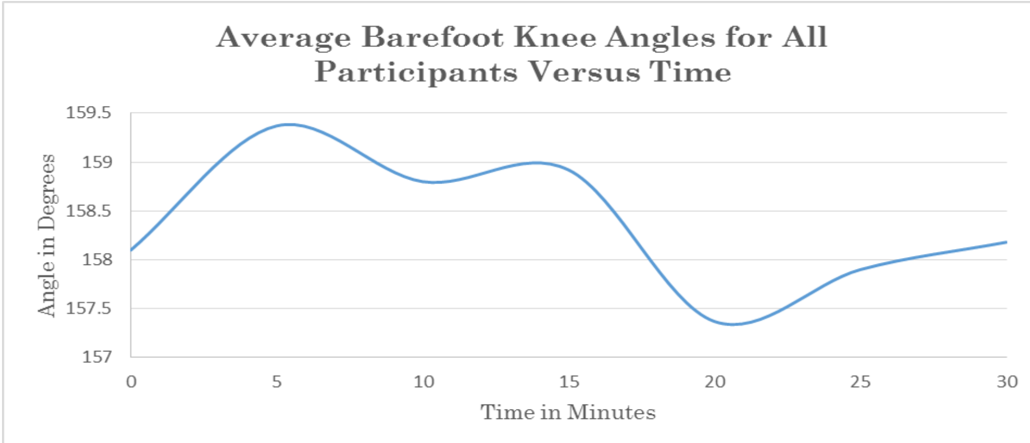

Figure 2. Average barefoot knee angles for all participants versus time.

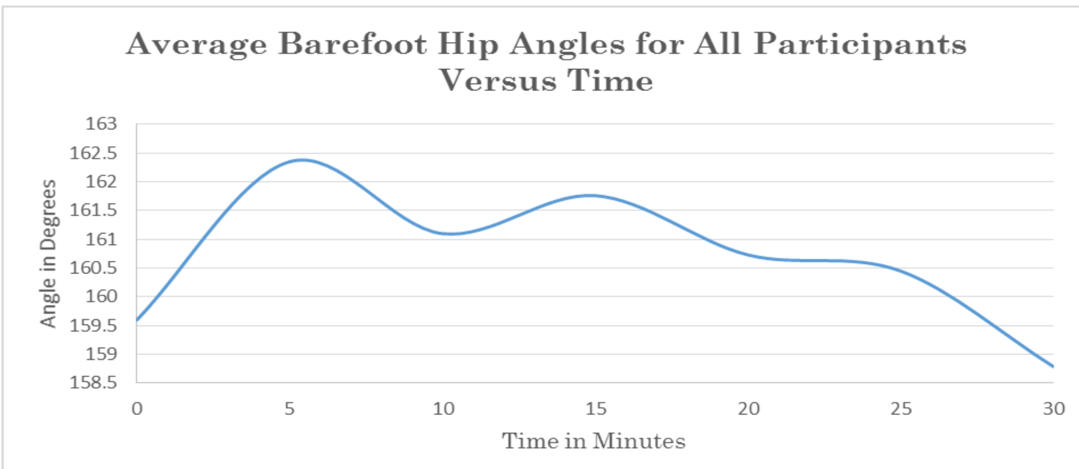

Figure 3. Average barefoot hip angles for all participants versus time.

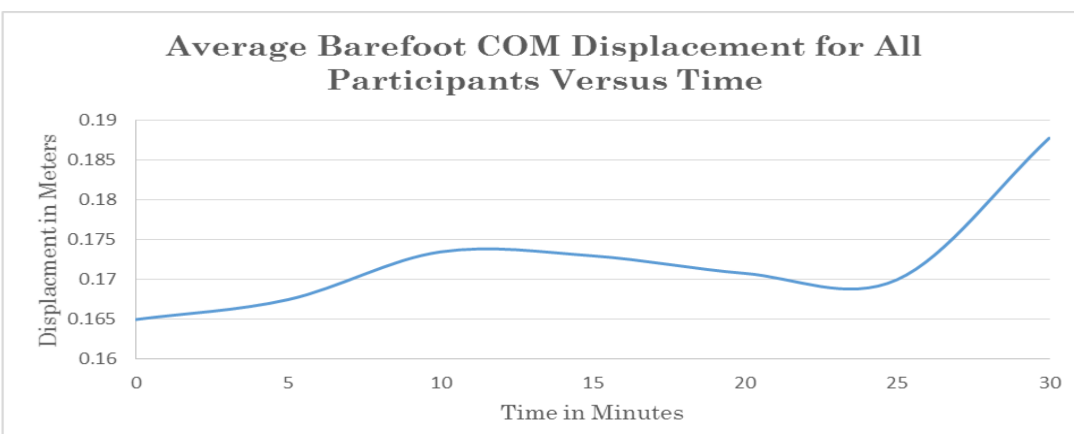

Figure 4. Average barefoot COM displacement for all participants versus time.

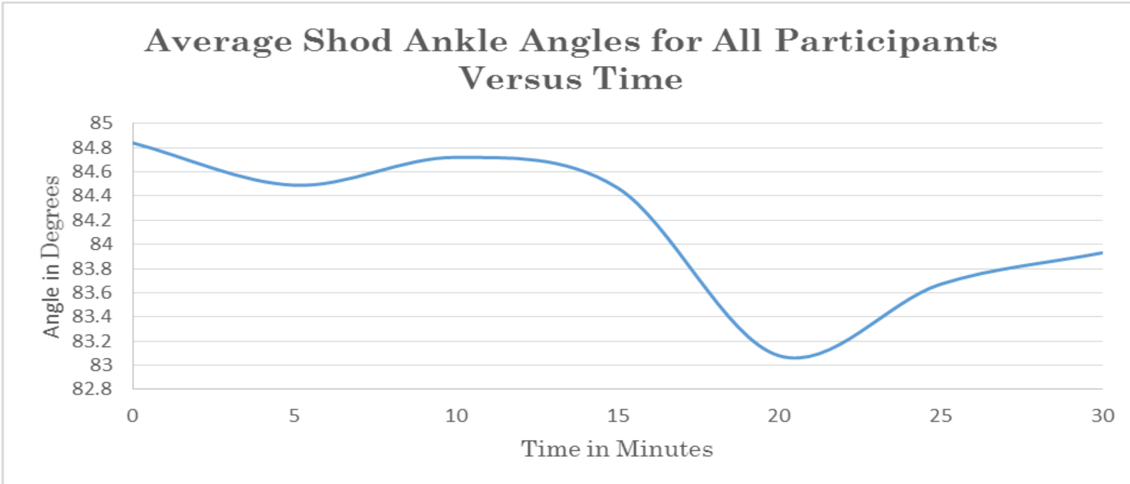

Figure 5. Average shod ankle angles for all participants versus time.

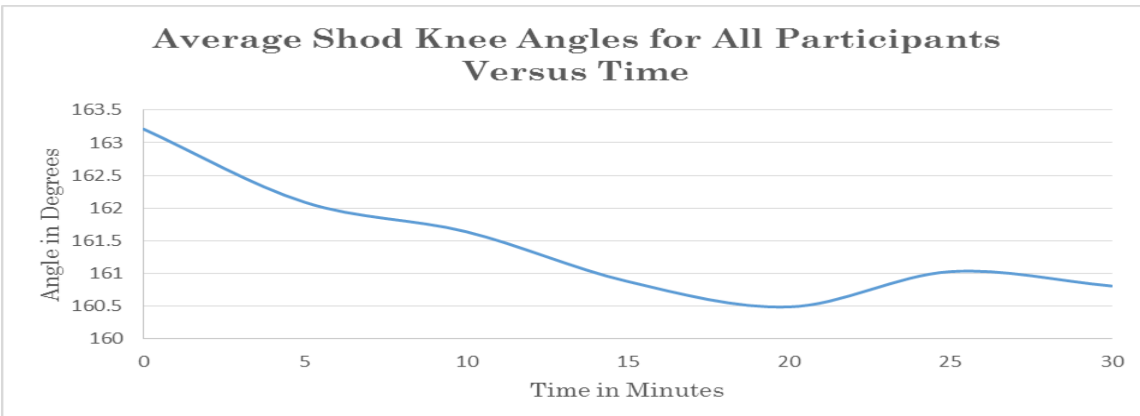

Figure 6. Average shod knee angles for all participants versus time.

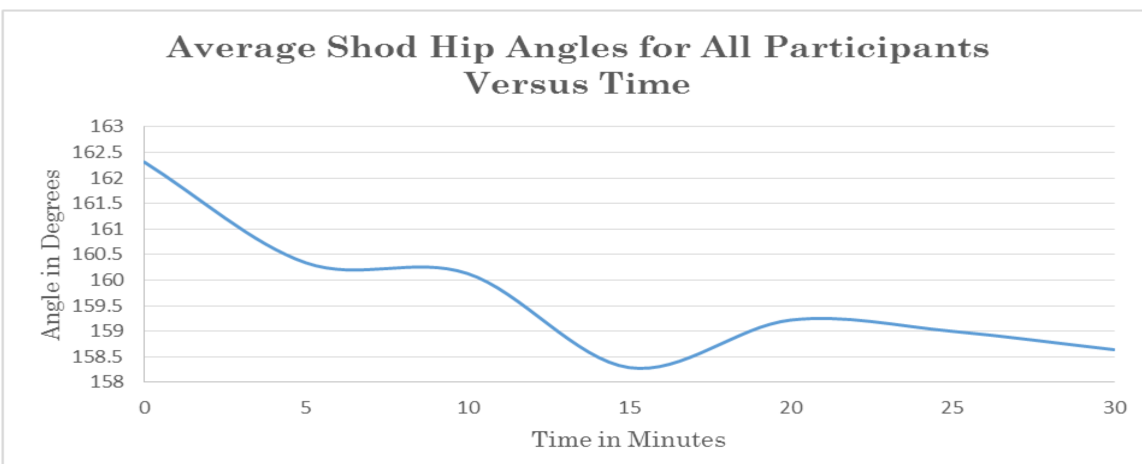

Figure 7. Average shod hip angles for all participants versus time.

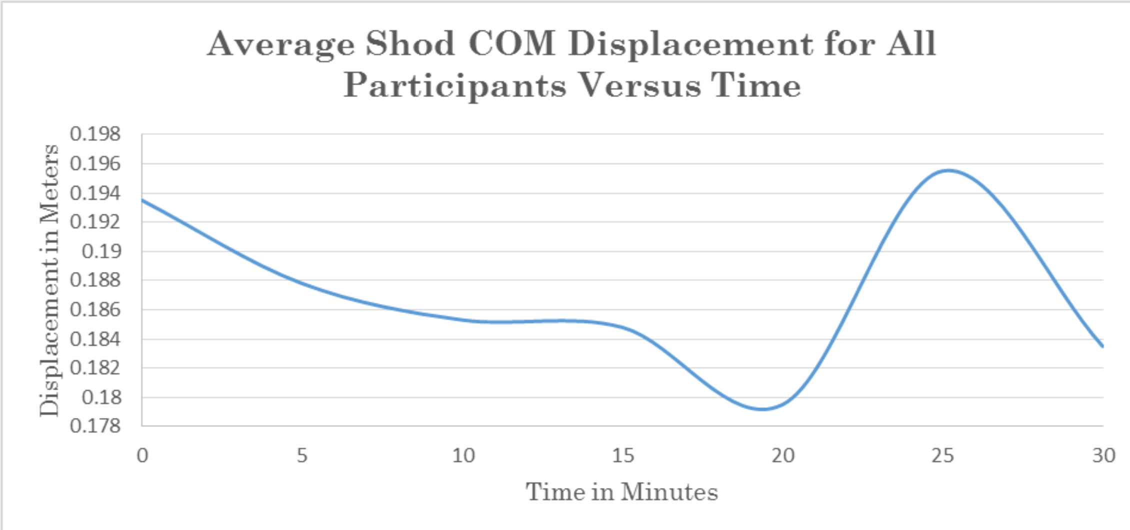

Figure 8. Average shod COM displacement for all participants versus time.

<u>Comparison of Kinematics in the Barefoot and Shod Conditions</u>

To compare kinematics in the barefoot condition versus the shod condition, a series of four one-way repeated-measures ANOVAs was conducted for each dependent variable; ankle angle at foot strike, knee angle at foot strike, hip angle at foot strike, and horizontal displacement of the heel and center of mass at foot strike. Results of these ANOVAs revealed no significant difference for ankle angle ($p=0.944$), significantly greater knee angle in the shod condition compared to the barefoot condition ($p=0.022$), no significant difference for hip angle ($p=0.368$), and no significant difference for the horizontal displacement of center of mass from foot strike ($p=0.646$).

<u>Effect of Fatigue on Joint Kinematics in the Barefoot Condition</u>

To compare the non-fatigued condition (time=0 min) to that of the fatigued condition (time=30 min) while running barefoot, a series of four one-way repeated-measures ANOVAs was conducted (one for each dependent variable; ankle angle at foot strike, knee angle at foot strike, hip angle at foot strike, and the horizontal displacement of the heel and the center of mass at foot strike. The results of these ANOVAs revealed no significant fatigue effect for ankle angle (p=0.462), no significant fatigue effect for knee angle (p=0.909), no significant fatigue effect for hip angle (p=0.203), and no significant fatigue effect for horizontal displacement of the center of mass versus foot strike.

Effect of Fatigue on Joint Kinematics in the Shod Condition

To compare the non-fatigued condition (time=0 min) to that of the fatigued (time=30 min) while running shod, a series of for one-way repeated-measures ANOVAs was conducted, one for each dependent variable). The results of these ANOVAs revealed: no significant fatigue effect for ankle angle (p=0.391), no significant fatigue effect for knee angle (p=0.277), a significant fatigue effect for hip angle (p=0.040), and no significant fatigue effect for horizontal displacement of the center of mass versus foot strike (p=0.448).

CHAPTER 5: DISCUSSION

Effect of Running Barefoot Versus Shod on Kinematics

Of the dependent variables examined, the only joint angle the differing conditions (barefoot and shod) had a significant effect on was that of the knee. There was a significantly greater knee angle in the shod versus the barefoot condition. This is consistent with previous research, which has found that runners in the barefoot condition tend to land with a smaller knee angle and it has been theorized that these variations in lower-extremity joints may be related to the ability of the mechanoreceptors to adjust to the joint, which may be a mechanism for reducing the magnitude of impact forces (Kurz et al., 2003) This decreased knee angle allows the body to be a more efficient shock absorber. This may have been the reason for the significantly smaller knee angle in the barefoot condition.

While other studies have shown that running barefoot has an effect on the kinematics of the ankle, knee, hip, and stride length, this study, as stated, only found a difference between the two conditions when looking at the knee angle (Divert, Mornieux, et al., 2005; Lieberman et al., 2010; Squadrone & Gallozzi, 2009). This may have been due to the small sample size (n=4) of the study.

Effect of Fatigue on Barefoot Running Kinematics

The study found no significant fatigue effect between the dependent variables: ankle angle at foot strike, knee angle at foot strike, hip angle at foot strike, and displacement of center of mass versus foot strike. Research has shown that running barefoot can lead to improved running economy, with most of the difference being attributed to the lack of mass of the shoe (Divert et al., 2008). Perhaps this was a reason that there was no fatigue effect on joint kinematics in the barefoot condition. It would be interesting to see more studies on the effects of fatigue and running barefoot, specifically on its effect on oxygen consumption. The effect of fatigue on barefoot running kinematics has not been well studied and is an area for much more potential research.

Effect of Fatigue on Shod Running Kinematics

While the study found no significant fatigue effect on ankle angle, knee angle, or the horizontal displacement of the center of mass versus foot strike, it did find a significant fatigue effect on the angle of the hip. This is consistent with research that has found as participants fatigue they experience greater hip angles (Kellis & Liassou, 2009). They also found that fatigue can lead to greater ankle angles, knee, angles, and longer stride lengths, but this study did not find that. This may have been due to the small sample size (n=4) or the subjects not reaching a proper state of fatigue to elicit a response.

One study has examined the effect of fatigue on joint kinematics that found no significant difference in kinematics as a group, but large differences within individuals (Williams & Snow, 1991). Again, the small sample size of this study may have had an effect on the results, as one person with a greater hip angle at fatigue would skew the results in that direction.

Recommendations for Future Research

Future research can continue to focus on the effect that fatigue has on the joint kinematics of barefoot runners. Studies can examine if there is a similar effect on kinematics that have been observed in studies on fatigue of shod runners. In these studies, it was observed that as shod runners fatigued, they demonstrated changes in the kinematics of the ankle, knee and hip (Kellis & Liassou, 2009). It was also observed, in the fatigue state, that shod runners produced a greater stride length when compared to that of the non-fatigued state (Kellis & Liassou, 2009). While it was not seen in this study, previous research has shown that running barefoot produces a shorter stride length (Squadrone & Gallozzi, 2009). Future research can examine whether there is a fatigue effect on the stride length of barefoot runners.

It would also be interesting to see the effect that fatigue has on oxygen consumption while performing in the barefoot condition. It has been observed that running barefoot produces a greater running economy, mostly due the loss of the weight attributed to the shoe (Hanson et al., 2011). Future studies can focus on the effect of fatigue on oxygen consumption when running barefoot and examine whether the improved running economy remains present over longer durations. This study may also be repeated using more participants.

Although many studies currently exist, the research on barefoot running and its effects is relatively new. There are many avenues for future research that can help understand the effects that barefoot running has on biomechanics, running economy, impact forces, associated musculature, and injury prevention.

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APPENDIX: INFORMED CONSENT FORM

Informed Consent

You are invited to participate in a study conducted by Jason Wara and the CSU Fresno Department of Kinesiology. We hope to learn the effect of barefoot versus shod running on foot strike over a 30 minute training session. You were selected as a possible participant in this study because you are a male or female between the ages of 18 and 35 years of age, you meet the ACSM criteria for an “apparently healthy” adult, you currently run at least 15 miles per week and have for the past four months. You also have run 20 miles barefoot over the previous four months. Additionally, you have run at least three miles barefoot on a treadmill or are accustomed to running barefoot on a treadmill.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law.

If you decide to participate, we will ask you, during the familiarization session, to have a heart rate monitor put on you and then you will be asked to run on a treadmill until you reach 75% of your age predicted maximum heart rate. You will then be fitted with a thin running sock and asked to run for 10 minutes on the same treadmill in order to become accustomed to running on the treadmill while wearing the sock. After this run, a time for the next meeting will be set. During the second meeting you will be asked to run and be filmed either shod or in the sock (this condition will be chosen randomly at the end of the first session) for 30-minutes on the same treadmill that was used during the familiarization period, at the speed that was determined to elicit 75% of your age predicted heart rate max during the familiarization session. The final session will consist of you performing the same procedure but in the opposite condition of the second test. Potential risks include possible muscle soreness related to running and potential blistering associated with the friction and heat created by the treadmill. The potential risk of blistering will be decreased through the wearing of the thin sock. Potential benefits of the study include an insight into the biomechanics of your stride while shod and barefoot. We cannot guarantee, however that you will receive any benefits from this study.

Potential risks of the study include the following: The efforts are sub maximal in nature but there may be some muscle soreness associated with running prior to completing the trials. Blistering the feet may occur due to the friction and heat created by the treadmill. You will be provided with and asked to wear a thin sock to decrease this chance of blistering.

Your decision whether or not to participate will not prejudice your future relations with California State University, Fresno and the Department of Kinesiology. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without penalty. The Committee on the Protection of Human Subjects at California State University, Fresno has reviewed and approved the present research.

If you have any questions, please ask us. If you have any additional questions later, Dr. Tim Anderson at 559.278.2016 will be happy to answer them. Questions regarding the rights of research subjects may be directed to Constance Jones, Chair, CSUF Committee on the Protection of Human Subjects, (559) 278-4468.

You will be given a copy of this form to keep.

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. YOUR SIGNATURE INDICATES THAT YOU HAVE DECIDED TO PARTICIPATE, HAVING READ THE INFORMATION PROVIDED ABOVE.

Date

Signature

Signature of Witness (if any)

Signature of Investigator