1-1-2006

Kinematic comparison of running barefoot and in the Nike Free 50

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KINEMATIC COMPARISON OF RUNNING BAREFOOT AND IN THE NIKE FREE 5.0

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Bachelor of Science
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2000

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1999

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree in Kinesiology
Department of Kinesiology
School of Allied Health Sciences
Division of Health Sciences

Graduate College
University of Nevada, Las Vegas
December 2006

UNLV

Thesis Approval

The Graduate College
University of Nevada, Las Vegas

November 6, 2006

The Thesis prepared by

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Entitled

Kinematic Comparison of Running Barefoot and in the Nike FREE 5.0

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Kinesiology

Examination Committee Chair

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1017-53

ABSTRACT

Kinematic Comparison of Running Barefoot and in the Nike Free 5.0

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The purpose of this study was to determine if knee and ankle kinematics during running were similar when running with bare feet and while running in a shoe designed to mimic barefoot running. Ten footfalls per subject-condition were evaluated kinematically using a 12-camera Vicon motion capture system (120 Hz) for 9 female runners (26.9 ± 4.0 yrs, 63.7 ± 5.9 kg, 168.0 ± 7.5 cm) at 4 times within two 8 minute conditions (barefoot and test shoes) on a treadmill. Seven knee and ankle variables representing impact (knee angle, ankle angle, and knee angular velocity) and stance (peak knee angle, timing of peak knee angle, peak knee angular velocity, and timing of peak knee angular velocity) kinematics and three spatio-temporal variables (contact time, stride length, and stride rate) were evaluated across conditions and times. For each stance phase of a stride, knee and ankle flexion angle data were normalized to time of stance phase. A spanning set analysis was conducted using these data sets to determine the joint variability for each time-condition. These results suggest that the kinematics were similar between the test shoe and barefoot conditions. It is hypothesized that the running

pattern observed while wearing the test shoe was a hybrid of barefoot and shod running styles with the difference at ground contact due to the heel cushioning of the shoe. Therefore, from this analysis of the knee and ankle kinematics, it is concluded that the Nike Free 5.0 shoes may indeed aid in any kinematic benefits that are found from barefoot running while helping protect the feet.

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AKNOWLEDGEMENTS

There are some key people I would like to thank for their help, love, and guidance throughout my educational career and especially in my pursuit of my master's degree. First, I would like to thank my faculty, most recently at the University of Nevada, Las Vegas, but also those who helped push me toward my dreams at Linfield College and the University of Washington. Dr. John A. Mercer, your unfettered guidance allowed me to pursue my goal of footwear testing and investigating a new method of testing variability. You trusted me to find my way, but were there when I really needed help. To Dr. Janet S. Dufek, I always appreciated the openness you offered. I could approach you with any questions or ideas and you always were there to respond to me with another question, always challenging me, thank you. I also want to thank Dr. Brent C. Mangus for being there to listen to the thumping of the repetitive loader, as well as me when I just needed an ear. Dr. Edward S. Neumann was always a clear headed engineer when I needed to speak to someone who knew my language, and really helped me understand just how much engineering and biomechanics can be related. To all the members of my committee, thank you for being so very understanding and helping me through the most difficult challenge of my life by completing this program and fighting breast cancer at the same time. I would also like to thank Dr. Paul Davis, my undergraduate advisor and Physics professor; your guidance helped me do what so few have done in the program. My good friends and teachers Brandon and Teodora Shumann, you made my time in

Seattle educational, fun, and exciting. I hope your family is doing well, thank you for being there for me when I needed it.

I would like to thank my colleagues in the Kinesiology program: Kristina Lindquist who was always there when I need a workout partner and has become a lifelong friend, Tiffany Zachry one of the smartest people I know and who I could always have very intriguing conversations with about anything and got very silly around 4 p.m. so we could laugh for hours, Julia Freedman who has just as much interest in barefoot running as I do and made me proud that this line of research has at least one more champion, and Kaori Teramoto who brought her calming Japanese influence into the lab. It has been good working with all the members of the lab: Amanda Tritch, Katie Orzechowski, Dave DeLion, and Anthony House. Thank you all for your help, your prayers, and your laughter. You all made it fun to work in the lab.

Above all else, I would like to thank my family for supporting me through everything in the past two and a half years. First and foremost, to my husband who was able to stand by my side and give up his own dreams to help me follow my own. His support has meant the world to me. Next, to my parents, Craig and Sidne Steindorf, and my sister, Diane, I could not have even thought I could do something like quit a great job to pursue my dreams unless you instilled in me that I could accomplish anything I set my mind to.

This has been a long journey; made longer by my fight over the last year with breast cancer, but you all have been a wonderful support system and made this an adventure I will never forget.

CHAPTER 1

INTRODUCTION

Each day millions of runners hit the road, trails, track, and treadmill. Running is one of the most frequently used forms of vigorous exercise; due to the high impact and repetitive loading associated with this activity, runners experience many different types of injuries than walkers or swimmers. Training errors and equipment problems have been reported to be the key contributors to injury in running (Hreljac, 2004; James *et al.*, 1978). The most important piece of equipment a runner has is the running shoe. Many changes have been made to the cushioning and support properties of shoes over the past 40 years, but the occurrence of overuse injuries has not been greatly reduced. For example, the most common overuse running injury 20 years ago was patellofemoral pain; this is still the case today (Taunton *et al.*, 2002). Chronic injuries such as plantar fasciitis are common among long distance runners (Taunton *et al.*, 2002). The plantar fascia supports the arch of the foot and repetitive strain on this ligament can cause inflammation. Such injuries take time to present themselves in runners and are not easily curable without rest.

One possible method for injury prevention is to add variability to workouts such as cross-training; barefoot running as a form of cross-training may be a plausible training tool for injury prevention. It has been hypothesized that running barefoot can increase the strength of the musculature of the foot and lower leg, therefore decreasing the stress put on the ligaments such as the plantar fascia (Robbins & Hanna, 1987). Using barefoot running to increase workout variability is similar to the idea of varying the training routine and thereby may decrease the likelihood of injury by increasing the joint motion variability. To address the growing popularity of this training method, Nike, Inc. has recently introduced a shoe that is advertised to mimic barefoot running. Given that the shoe industry is now designing shoes based on the model of the bare foot, the scientific community needs to investigate the benefits and drawbacks of barefoot activities.

Anecdotally, people do not choose to run barefoot due to the high impact that running creates on the heels and knees. In general, most barefoot populations are found in areas of the world where medical assistance is not prevalent therefore it is difficult to track the number of chronic running injuries in these populations. Nevertheless, chronic injuries have been reported to be less frequent by runners in barefoot populations than with shod populations (Robbins & Hanna, 1987).

There is limited research on the kinematics (Aguinaldo & Mahar, 2003; Bergmann *et al.*, 1995; Burkett *et al.*, 1985; de Wit *et al.*, 2000; Eils *et al.*, 2002; Kurz & Stergiou, 2003; Stacoff *et al.*, 2000) of barefoot running compared to running in standard shoes. Key variables being knee angle, ankle angle and knee angular velocity at ground contact, as well as peak knee angle and peak knee angular velocity in mid-stance (Burkett *et al.*, 1985; de Wit *et al.*, 2000; Eils *et al.*, 2002; McNair & Marshall, 1994), and kinematic variability (Kurz & Stergiou, 2003; Kurz *et al.*, 2003) of the knee and ankle flexion angles during stance phase. However, there is none investigating a highly flexible shoe such as the Nike Free 5.0 and its effect on running mechanics.

Therefore, the purpose of this study was to determine if knee and ankle kinematics during running were similar while running in the (Nike) test shoe and running barefoot, additionally to discern if accommodation of knee or ankle kinematics occurs over time. Based on the observations reported from previous literature, it was hypothesized that the cushioning of the test shoe would aid in decreasing impact at heel contact and therefore a difference in ankle and knee angle as well as the knee angular velocity at ground contact compared to barefoot running would be observed. With the freedom of movement of the test shoe, it was further hypothesized that there would be no difference between peak knee angle or angular velocity between the test shoe and barefoot conditions and the joint angle variability over stance phase would be similar between the two conditions. Finally, it was hypothesized that any differences noted would not be immediate, but that the runners would slowly make the necessary accommodation to their running mechanics based on the running condition.

CHAPTER 2

LITERATURE REVIEW

History of running shoe development

Distance running shoes were first developed from the dress shoes that were worn in the late 1800's and early 1900's (Cavanagh, 1980). These shoes were high-topped leather with a stiff sole and a heel designed for the marathoner by Spalding. Runners would put hundreds of miles on these shoes. Since that time there have been many modifications to the distance running shoe, many by coaches and other shoe designers. Some of the most well known footwear designers started in the 1930's such as Adi Dassler (adidas©) who began with track shoes and moved into the distance running shoe. In the 1970's many other key players in the training shoe industry came of age and have survived such as New Balance, Brooks, and Nike (1972) where Bill Bowerman helped developed the first training shoes with nylon uppers and more cushioning in the soles.

Heel cushioning and midsole comfort have been the primary focus for many athletic footwear developers. Modern shoes have evolved through a variety of cushioning materials to protect the heel and dissipate the force of impact before it reaches the body. Running shoe cushioning began as hard rubber soles attached to leather uppers. In 1974 a lighter foam EVA mid-sole was created by Schwaber (Cavanagh, 1980), and later the dual density mid-sole was introduced by Bates (1982). Next thermodynamic fluid systems were created such as the Nike Air®, Asics Gel®, and the Brooks Hydroflow®. More recently mechanical systems have been introduced. These include arches and springs. All of these innovations have been created to decrease the shock of impact at the heel of the runner. However, if the majority (>75%; Kerr *et al.*, 1983) of runners didn't run with a heel-strike pattern, the focus of the design of running shoes may be very different.

Aguinaldo and Mahar (2003) put mechanical springs to the test by investigating impact force patterns of running in shoes with two different styles of cushioning columns. One of the two types of cushioning columns was from a popular manufacturer made out of highly resistant urethane foam (Shoe 1) while the other was from a less expensive, less known manufacturer using a thermoplastic polyester polymer (Shoe 2). Impact characteristics while running in each of these shoes were compared to a top model running shoe with a standard EVA midsole (Shoe 3). Impact characteristics were investigated since high impact forces as well as high loading rates have been shown to be key contributors to overuse injury in distance runners (Hreljac *et al.*, 2000). Aguinaldo and Mahar (2003) observed that the impact force and loading rate during running in Shoe 2 was less than during running in Shoe 1 (material property effect). The runners experienced less impact based on a considerably slower loading rate than previously found with other shoes (cushioning structure effect) (Clarke *et al.*, 1983; Hennig *et al.*, 1996). This result suggests that the column characteristic, not the material properties, decreases the loading rate at impact (Aguinaldo & Mahar, 2003). The cushioning column system may therefore be a positive influence on the running shoe market. For people who exhibit a high loading rate (i.e., heel strikers or pes planus arch types), this type of shoe may be beneficial.

Two of the leading running shoe manufacturers have recently taken very different paths for their latest product releases, and both companies appear to be targeting the serious runner. Adidas© has released a smart shoe, the adidas_1, which has a sensor in the heel that measures deflection of the mid-sole and will automatically adjust the insole stiffness using a gearbox located in the middle of the insole. The last 4 steps are recorded and processed so that an optimal level of insole stiffness will be achieved without regard to the external running surface. This product takes surface variation out of the equation and has the ultimate adaptability for any runner.

Meanwhile, Nike, Inc. has proceeded in another direction. Rather than creating a shoe with artificial intelligence, they have gone back to a basic concept and have created a shoe with increased flexibility to mimic the movement of the human foot. This shoe has no outsole and deep grooves in the midsole to add flexibility and motion to the shoe. The manufacturer states that the shoe will allow the benefits of barefoot running, such as increased strength of the foot and lower leg musculature, while protecting the body from the impact of barefoot running and protecting the soles of the feet (Nike, 2005). The validation that the company gives is based on running pressure maps and visual interpretation of the bare foot action while running on grass. The pressure map of the foot found when running in the shoe more closely resembles the map of barefoot running than that of running in a standard shoe. Also, based on visual inspection, the toes extend and flex more and greater muscle use is seen while running barefoot than in shoes (Nike, 2005).

These two competing hypotheses currently exist: either let the shoe work for the runner to decrease loading (adidas), or increase the foot strength by decreasing the structure of the shoe (Nike). That which is more applicable to the runner is presently unknown.

Arch height and injury

The relationship of wearing shoes and pes planus (flat feet, or fallen arches) has been studied in children. When a person has flat feet the bones of the arch do not support the weight of the body and fall causing tension on the fascia of the feet.

It is well known that children are born with flat feet and the arch develops as the children reach physical maturity. Echarri and Forriol (2003) studied Congolese children between 3 and 12 years of age including city children who predominantly wore shoes and rural children who had mainly been barefoot. Boys were found to have a greater tendency for flat feet than girls with the proportion of flat feet decreasing as children of both sexes got older (Echarri & Forriol, 2003). The importance of this may be that as children age, their activity levels increase. If they remain barefoot as they age, as seen by Echarri and Forriol (2003) then as children increase their activity as they age, they may be maintaining their arch height because they are barefoot. Joseph and Bhaskara Rao (1992) studied Indian children between the ages of 4 and 13 years on the prevalence of flat feet. The flat foot was most common in those who wore close toed shoes, less common in those who wore sandals or slippers and least common among children who were unshod. This again demonstrates how wearing shoes as a child can cause arches to fall as the child ages. Staheli (1991) determined that for children, optimum foot development occurs in the barefoot environment thus, the best model for footwear (for children) is probably the unshod state (Staheli, 1991). Finally, in a study of skeletally mature persons, the influence of the age at which shoe-wearing began was compared against the prevalence of the flat foot. Sachithandam and Joseph (1995) found the incidence of flat feet in adults was higher when shoe wearing started by the age of 6 compared to starting after the age of 15. All of these studies illustrate that during the development of the foot, to preserve arch height, barefoot is a preferred condition.

Pes planus has been shown to increase the likelihood of running injury (Hreljac *et al.*, 2000), specifically general knee pain, patellar tendonitis, and plantar fasciitis as the most frequent injuries (Williams III *et al.*, 2001), and more knee injuries are reported than for runners with high arches. The studies of children and arch structure (Bhaskara Rao & Joseph, 1992; Echarri & Forriol, 2003) discussed in this review suggest that wearing shoes at a young age may then lead to pes planus as an adult and therefore translate to an increase in the likelihood of running injury as an adult.

The benefits of barefoot locomotion were studied multiple times by Robbins and colleagues in a laboratory setting. In one study, Robbins and Hanna (1987) attempted to rehabilitate the internal foot structures by increasing the intrinsic musculature of the foot. Changes of the dynamic structure of the medial longitudinal arch created by increasing weight bearing activity were evaluated. Each subject was instructed to increase weight bearing activity by 1 hour daily while keeping a training log to track the duration and type of barefoot activity over 4 months. If the arch span decreases between pre- and post-training that means the height increased and as weight was applied to the arch it was more able to accept that weight without deforming or flattening out. Conversely, if it increases, then the arch is not accepting the weight and likely putting stress on the other internal tendons and ligaments of the foot. The mean arch span shortened for the test group and lengthened for the controls (Robbins & Hanna, 1987). This decrease of arch span indicated an increase of arch height and suggested that the arch can be rebuilt through increasing barefoot activity. Therefore, less stress may be placed on the ligaments and tendons of the foot. For runners who are prone to injury due to flat feet, the observations of Robbins and Hanna (1987) suggest that increasing barefoot activities may increase the strength of the foot musculature and possibly decrease the incidence of injury to the internal structures of the foot by increasing the height of the arch and consequently assisting with the shock absorbing function of the foot and removing the stress on the soft tissues.

Sensory influences of the bare foot

The arch of the foot is designed to support the body as a very complex strut system conversely the heel is not anatomically designed to accept impact loads. The arch is where foot flexibility can be used for load acceptance and shock reduction during impact activities such as locomotion. By wearing shoes, runners are physically altering the way that the foot behaves and are possibly attenuating the sensory capacity of the foot and therefore not using the structure of the foot to its full advantage. In modern training shoes, fairly thick mid- and outsoles are prevalent. These thick soles may be attenuating the sensory response of the foot to varying surface influence (Robbins & Gouw, 1991). When training shoes were first developed the soles were fairly stiff, but thin. These thin soles probably transmitted the impact of contact and the variations of surface characteristics to the runner more easily than modern running footwear. Following this logic, it may be that historically runners ran with less heel contact than do modern runners while modern runners have developed "lazy feet" in this regard. Therefore the modern feet have become dependent on the shoe to provide a mechanism to push them through stance phase. Running shoes have a wide outsole. The stability that the heel counter and supportive mid- and outsoles provide may be assisting modern runners such that they can balance easily and therefore reduce the need of the small muscles of the lower leg to work as hard. Robbins and Gouw (1991) hypothesized that footwear attenuates the high impact of running and therefore decreases the magnitude of the impact signal sent to the brain. This causes decreased impact modulating behavior in the preparation for the next step as well as decreased knee flexion at contact of the next step and a decrease in the use of the foot as an intrinsic shock absorber and instead relying on the shoe (Robbins & Gouw, 1991). Robbins et al. (1988) anticipated a future shoe that when worn while traversing over an uneven surface would create the impact moderating behavior that is found in a bare foot when walking over the same surface. This shoe would need to utilize the intrinsic shock absorbing qualities of the foot as well as activate other smaller muscle groups used for balance. Perhaps this concept is similar to the flexible shoe that Nike released in 2004.

Eils et al. (2002) tested the idea of reduced plantar sensation by immersing one of their subjects' feet in an ice bath and then tracking the barefoot walking ground reaction force. They observed that when sensation was reduced, a more cautious walking pattern was produced (Eils *et al.*, 2002). This post immersion walking pattern was similar to that of walking in shoes. The loading rate was decreased compared to barefoot walking with a similar magnitude of peak impact force. When comparing barefoot to shod walking, the loading rate is higher for the barefoot condition with the magnitude of the passive and active peaks remaining relatively constant between the two conditions. This resemblance is possible evidence that shod locomotion may cause a decrease in sensory capabilities of the foot and therefore reduce plantar sensation in accordance with Robbins and Guow (1991).

A reason that runners do not run in bare feet is that it is perceived as being dangerous. The possibility for injury due to cuts, blisters, and other acute injuries is increased by not having the protective surface of a shoe. However, the plantar surface of the foot is actually quite tough. Robbins et al. (1993) studied pain threshold by testing abrasion resistance on the hairy skin which covers most of the body compared to the glabrous skin (located on palms and sole) on the feet. A load approximating the vertical impact force during running was applied to the heel of the foot. In contrast a much lower load (< 15%) was applied to the thigh. Immediately after as well as 24 hours later the site on the bottom of the foot showed significantly less redness and sensitivity than the hairy site (Robbins *et al.*, 1993) showing that the skin on the plantar surface is more robust than commonly thought and will adapt to increased activity by adding layers and creating calluses.

Based on this information, research suggests that by removing shoes, runners may be more apt to utilize their feet as they were intended. Barefoot running may increase the activity of the smaller muscles of the lower leg and foot that are used for balance and avoidance behavior while running (Eils *et al.*, 2002; Robbins & Gouw, 1991). According to Robbins and colleagues (1993) the skin on the bottom of the foot is not as delicate as commonly thought. Actual injury due to cuts, blisters, and other acute injuries may not be a factor with increased barefoot activity.

Impact and shock attenuation

At impact a large amount of energy is created by the collision of the foot and ground. The main areas the energy can go are to the shoe, through the heel pad, and transferred through the pronation rate of the foot. Impact force and the shock wave it creates are considered primary contributors to lower extremity joint injuries (Hreljac, 2004; Hreljac *et al.*, 2000). The most common reason (60%) for overuse injury in runners is training errors (S. L. James et al., 1978). One of the most common training errors is not allowing enough recovery time for the micro tears of the soft tissue and bones to heal before the next run.

This risk of injury is compounded by individual biomechanical stride characteristics and anatomical features. When comparing injured and injury free runners with no significant training differences, Hreljac et al. (2000) found significant anatomical differences in hamstring flexibility (injured less flexible than non-injured) and significant biomechanical differences in impact peak (higher in injured) and loading rate (injured greater) of vertical ground reaction force (Hreljac *et al.*, 2000).

A trend was found toward an increased rate of pronation for injury free runners. This could be a protective mechanism such that the foot is more stable in preparation for push off. In barefoot running there is a tendency to land with less eversion and more knee flexion (de Wit *et al.*, 2000; Van Woensel & Cavanagh, 1992). It may be that theses changes are related the trend of a mid-foot strike pattern rather than the heel strike pattern found in shod runners. However in the same study by de Wit and colleagues (2000), barefoot runners had a much higher loading rate which according to Hreljac would increase the likelihood of injury. A review on impact and overuse injuries in runners was completed by Hreljac (2004); his recommendation for decreasing running injuries in the shod population was to decrease the impact force and increase the rate of pronation. Barefoot running can possibly accomplish this goal. A decreased foot angle at contact may lead to a mid-foot strike pattern which then may possibly decrease the impact force at contact (Cavanagh, 1989). Also, a decreased angle of supination at contact has been found in barefoot runners which not only increases the rate of pronation, but the foot makes contact with the ground in a more pronated state.

In barefoot running the impact force is found to occur within the first 5-15 ms (de Wit *et al.*, 2000; McNair & Marshall, 1994). The time of the impact phase for shod running is closer to 30 ms (de Wit *et al.*, 2000; McNair & Marshall, 1994). In either case, this is not enough time for closed-loop kinematic adaptations due to geometry changes or muscle activation, so the entire load of the impact is taken on by the foot at the location of contact (Chi & Schmitt, 2005). However, there is little evidence that barefoot runners actually land on the heel of the foot at impact even when instructed to (de Wit *et al.*, 2000; Divert *et al.*, 2004). Increased loading rate has been associated with increased transient acceleration at the shank (Lafortune *et al.*, 1996; McMahon *et al.*, 1987). The energy from impact needs to be attenuated in some way so that the shock wave does not reach the sensitive tissues of the brain at the same level as at the shank. Many theories have been developed as to where this absorption or attenuation occurs including lower extremity geometry changes at impact (Derrick, 2004; Derrick & Mercer, 2004; Hamill *et al.*, 1995; Lafortune *et al.*, 1996; McMahon *et al.*, 1987; Wright *et al.*, 1998).

The majority (> 75%) of runners have a heel strike pattern when running at moderate speeds (< 5 m/s; Aerts & De Clercq, 1993; Kerr *et al.*, 1983). Becker (1989) hypothesized that the technically accomplished runner avoids heel contact. In this way they avoid the passive forces at impact. Anecdotally when people begin to run barefoot without directional guidance, there is a trend toward a mid-foot strike pattern. Studies have shown a similar trend when midsole stiffness increases in running shoes (Hennig *et al.*, 1996). Inherently runners may be attempting to avoid the high impact that would be associated with heel contact. Because of the increased number of runners that are training barefoot a website has been developed to help disseminate barefoot training and information for the barefoot community (Saxton). On the training page of the website (http://www.barefootrunning.org), Saxton describes how to run barefoot:

1. "Vertical torso, but allow it to twist. Hips rotate with your legs, shoulders rotate with your arms.
2. Bent knees, ankles, and hips
3. Pull the feet up, quickly, 180, or MORE, steps per minute!
4. Hips fall forward, while tucked under the torso. Lean from the ankles, not the waist.
5. Relax, relax, relax..."

The importance of this is barefoot runners do have to re-learn how to run. This may not be so much to avoid injury, but to adapt their feet and legs to running without shoes.

Comparison of shod and barefoot running

Most literature reports dramatic differences between barefoot and shod running when looking at spatio-temporal parameters such as stride length, stride rate, and contact time when running velocity is held constant. Kinematic variables have also been reviewed, when barefoot running is compared to different shod conditions there was always a significant difference between the barefoot and shod conditions, but no difference was observed between shoe conditions (de Wit *et al.*, 2000; Kurz & Stergiou, 2003; Kurz *et* *al.*, 2003). In general sagittal plane kinematics have been evaluated, but even when examining frontal plane kinematics (Burkett *et al.*, 1985) the variables are significantly different when comparing barefoot and shod running. For example, linear translation of the patella from the center of the body was not significantly different between barefoot and shod, but frontal plane knee joint angle (varus) significantly increased when shoes were worn (Burkett *et al.*, 1985). This is likely due to the stable shoe forcing the foot and ankle into a specific position and that translating up to the knee and hip joints.

Stacoff et al. (2000) found no difference in calcaneal eversion, internal tibial rotation, and movement coupling when using bone mounted markers and comparing shod and barefoot conditions. The suggestion of this study was that previous studies were not accurately describing the foot and tibial movement by using shoe and skin mounted markers. It is still not well understood how much marker movement affects kinematic measurements. This is evidence that researchers need to be careful in comparing results of studies with differing methods of marker placement or marker models.

While conducting a research study any parameters that may be controlled usually are. In this way much of the researchers looking at barefoot running have constricted footstrike patterns to be as if it is the same as running in shoes. For people who normally ambulate with shoes this may be an accurate assumption as they may naturally run in a similar manner to how they run in shoes. However, it is conjectured that runners who are trained to run barefoot will run with a mid-foot strike pattern and this will change the heel contact force, and the impact moderating behavior of the foot and lower extremity. Most barefoot running studies try to ensure a heel-toe strike pattern (Bergmann *et al.*, 1995; de

Cock *et al.*, 2005; Divert *et al.*, 2004; Kurz & Stergiou, 2003; Stacoff *et al.*, 2000) which may not be the most natural footstrike pattern for barefoot running.

Oleson and colleagues (2005) compared the bending stiffness of the forefoot with that of running shoes. They reported that the forefoot does not behave as a simple spring, but as an active time-dependent mechanism. For the four shoes tested, the bending stiffness was much less than that of the feet tested. They also determined that forefoot stiffness and shoe bending stiffness act in parallel and that the majority of the stiffness of the shod foot is due to the foot itself (Oleson *et al.*, 2005). Therefore, running shoes with typical variations of bending stiffness around the metatarsalphalangeal joint will have insignificant effects on running performance. For the present study the test shoe has no outsole and deep grooves in the midsole to add flexibility and motion to the shoe. This increased flexibility of the test shoe may have no effect on midstance variables based on the results from Oleson and colleagues.

Summary

Running shoes have evolved over the years and for many different reasons. As biomechanists attempt to analyze how the changes in shoe cushioning affect running mechanics by investigating kinematics and kinetics of runners in varying shoes, they still only can tell how the body is reacting and can not directly relate this information to injury rates, or specific injuries.

One footwear company has moved away from adding new systems to the shoe and has actually removed components of the shoe. The idea behind this shoe is that the foot and shank actually get stronger as the shoe is worn because the shoe makes the runner work, not visa versa. Ideally, the stronger the foot and shank are, the fewer injuries will develop. However, more scientific research needs to be completed to determine if there are benefits to injury rate or foot/leg strength from barefoot activities.

The relationship between arch height and running injury has been investigated. Pes planus (i.e., low arch) has been shown to increase the likelihood of running injury (Hreljac *et al.*, 2000). Arch height has also been investigated in children related to the commonality of shoe wearing. For children who wear shoes, normal and high arches are rarely found even at young ages (Echarri & Forriol, 2003). However, if children are allowed to run around barefoot rather than in shoes, the chances of a normal height arch to develop are greater (Bhaskara Rao & Joseph, 1992).

Robbins and colleagues (1991, 1989, 1993, 1987, 1988) have investigated the benefits of bare feet and the possible detrimental effect of wearing shoes. They observed that the arch height could be rehabilitated by increasing barefoot activities (Robbins & Hanna, 1987). They also determined that modern athletic footwear may attenuate the sensory response of the foot to varying surface influences (Robbins & Gouw, 1991). Barefoot activities have been associated with injury to the plantar surface of the foot from stepping on sharp stones or glass, however, the glabrous skin on the bottom of the foot is very robust and will adapt to increased activity by adding layers and creating calluses (Robbins *et al.*, 1993).

The majority of shod runners (>75%) have a heel strike when their foot contacts the ground while running at moderate speeds (< 5 m/s; Kerr *et al.*, 1983). Anecdotally, barefoot runners will switch to a mid-foot landing pattern with no guidance of how to contact the ground. This change may be due to an avoidance of the high impact of a heel strike with no heel protection. However, most barefoot running studies try to ensure a heel-toe foot strike pattern (Bergmann *et al.*, 1995; de Cock *et al.*, 2005; Divert *et al.*, 2004; Kurz & Stergiou, 2003; Stacoff *et al.*, 2000) which may not be the natural running style while barefoot.

In conclusion, with all of the changes of running shoes over the years, injury rates have not changed significantly. This review investigated possible benefits of barefoot running from experiments completed in laboratory settings. Researchers have observed differences between standard running shoes and running barefoot and hypothesized benefits to anatomical structures from barefoot activities. An experiment that would benefit the area of research surrounding barefoot running would be to test the flexible shoe (Nike Free 5.0) designed to mimic running with bare feet against barefoot running to determine if the significant differences still exist, or if runners will change their running mechanics in these shoes perform similar to running while barefoot.

CHAPTER 3

METHODS

Subjects

Nine recreational (minimum 10 miles/week) female runners (26.9 ± 4.0 years, 168 ± 7.5 cm, 63.7 ± 5.9 kg) were recruited for this study from the UNLV student body and the local community. One subject's data was removed from the analysis because they were outside of the accepted age range. All subjects were familiar with treadmill running before testing. All subjects were informed of the procedures and signed an informed consent approved by the Office for the Protection of Research Subjects review board from the University of Nevada, Las Vegas before beginning the study.

Instrumentation

Lower body reflective markers (25-mm) were placed on specific anatomical landmarks following the Plug-in Gait model (Vicon Peak, Oxford Metrics, Oxford, UK; marker locations: anterior superior iliac spine, posterior superior iliac spine, thigh, lateral epicondyle of the knee, lateral shank, lateral malleolus, heel, and 2nd metatarsal head of each leg; Figure 2) and tracked with a 12-camera Vicon™ Motion Analysis system at 120 Hz. Before data collection each day, the motion capture system was calibrated per manufacturer's instructions. The subjects ran on a commercial grade treadmill (Precor USA, model C966). The kinematic data were collected using Workstation (Vicon Peak,

v. 4.6) software, and processed using Matlab 6.5 and Microsoft Excel for Windows. Subjects ran under two conditions: 1) Test shoes (Nike Free 5.0 running shoe) and 2) barefoot. All shoes worn were US women's size 8.5, 9, and 9.5.

The test shoes' rearfoot impact characteristics were evaluated using an Impact Testing System (Exeter Research Inc., Brentwood, NH). The impact testing procedure involved 10 pre-impacts with a mass of 8.5 kg dropped from a height of 50 cm followed by 28 impacts (Figure 1). The impact data for each trial were sorted based on the force results and the middle 20 data points were used in the analysis. Based on the impact testing results with respect to peak acceleration, the shoes were categorized as having a medium stiffness (12.6 ± 0.04 g's) relative to Kurz and Stergiou (2003).

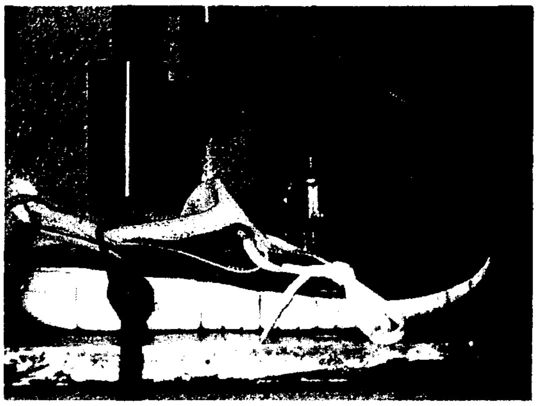

Figure 1. Impact testing of test shoes.

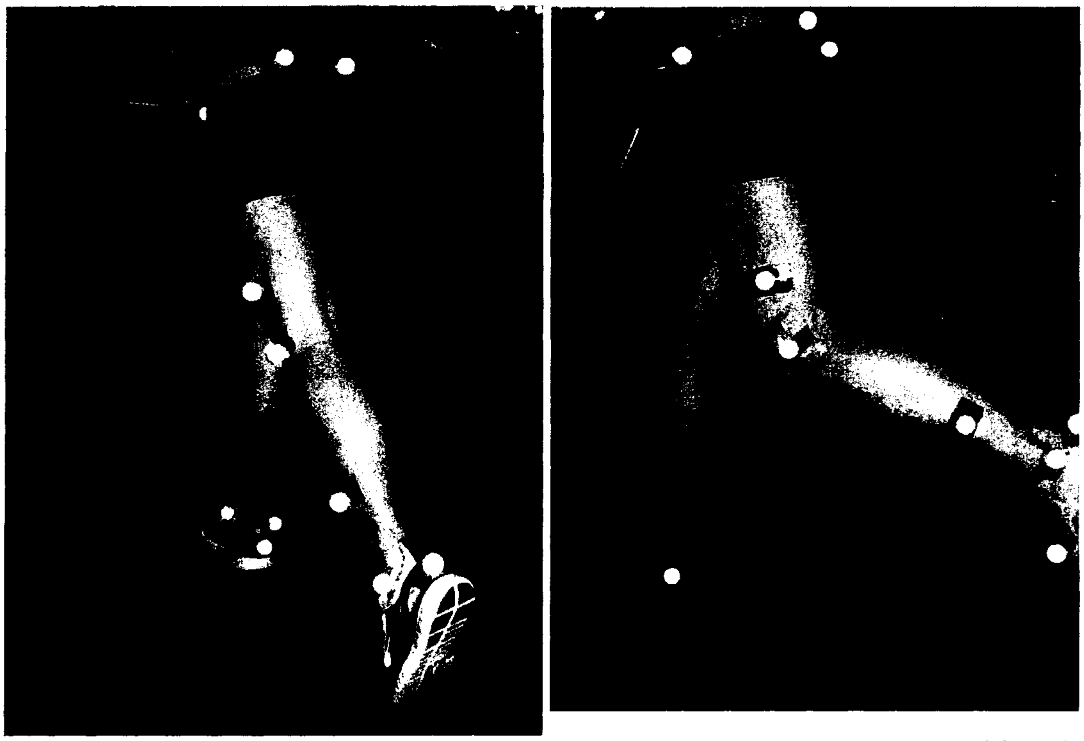

Figure 2. Illustration of subject instrumented for data collection; shod condition (left) and barefoot condition (right).

Procedure

Foot Arch Index (AI) was determined for each subject using a footprint technique adapted from Cavanagh and Rodgers (1987). Details of the procedure used can be found in Appendix III. Per Cavanagh and Rodgers (1987), AI was defined as: pes cavus ≤ 0.21, $0.21 <$ normal < 0.26, pes planus ≥ 0.26. The AI was used to quantify any effects of changes in running mechanics between the shod and barefoot conditions.

Reflective markers were placed on each subject using a combination of liquid, aerosol, and tape adhesives. These markers tracked the motion of the pelvis, thigh, shank, and feet on both lower extremities, however only the right leg was used for kinematic analysis. The subjects were asked to warm up for 5-minutes wearing their own running shoes to become familiar with the treadmill (White *et al.*, 2002) while avoiding accommodating to either of the test conditions. During the warm up period the subjects were instructed to select a pace that would be similar to a pace that they would be comfortable at for a 25 minute training run (average pace = $2.9 \pm 0.4\ m \cdot s^{-1}$). This was the pace for both conditions of the experiment. The subjects did not see the visual display of the speed at which they were running. The researcher checked the speed once the subject had completed their warm-up. After the warm-up, the markers were placed on the feet of the subject depending on the first test condition (either test shoes or barefoot). For the test shoe condition, the anatomical landmarks were palpated through the shoe to accurately place the markers. A static trial was collected for the motion capture data analysis. Because time was a variable of interest for this study, the treadmill was brought up to the preferred speed by the researcher and the subject was asked to carefully step onto the treadmill. The running condition lasted for 8 minutes; 15 consecutive strides of kinematic data were collected at 4 equally distributed times within the 8 minutes for a total of 4 sets of data (first 30 seconds of the condition, at 2:45 minutes, at 5:00 minutes, and at 7:15 minutes (end of condition)) collected for each subject-condition. Once the subject was done with the first condition they were given 5 minutes to rest and drink water. This time allowed the researcher to change the markers on the feet and set up for the second condition. The data collection for the second condition was the same as the first with only a change in shod status. Condition assignment was counterbalanced among runners.

Data reduction

Three-dimensional position data were processed using the Plug-in Gait model included in the Vicon Motion Capture software. To run this model the position data were low-pass filtered with a quintic spline at a mean standard error of 15 (Woltring, 1985). The anthropometric data for each subject (knee width, ankle width, and leg length) was input into the model for each subject so that the static model could be created from the individual static data. This way the subject measurements were stored and a dynamic model could be created for each subject. The dynamic model generated virtual markers and trajectory data for hip, knee, and ankle joint centers and also calculated kinematic values such as angles and angular velocities. Within each data set, ten consecutive strides (stride 3-12 out of the 15 collected) were extracted for data analysis. For each stride the angle and angular velocity data of the sagittal knee and ankle for the right leg were analyzed. For the knee, full extension was 0° and flexion indicated with increasing angles. For the ankle, foot flat was 0° with positive angles indicating dorsiflexion and negative angles plantarflexion.

Kinematic analysis of stance phase

For this study, stance phase was determined using the kinematic markers to define ground contact and toe off for each step. These points were determined based on minimum angular acceleration of the foot and leg segments respectively as per Hreljac and Stergiou (2000) (Figure 3).

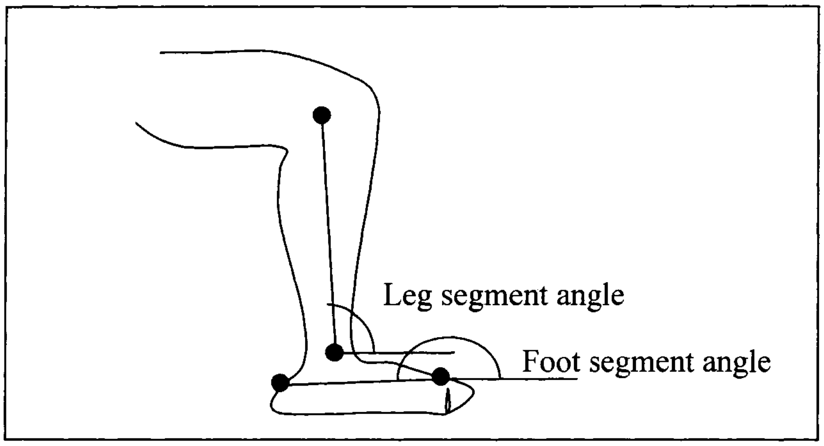

Figure 3. Location of the kinematic markers for analysis of heel contact and toe off during running.

Ground contact was defined at the point where the angular acceleration of the foot segment (heel marker to 2nd metatarsal marker) was a minimum or the jerk was equal to zero. Toe-off was defined as the point where the angular acceleration of the leg segment was minimum (knee marker to ankle marker) and the jerk of the segment was equal to zero (Figure 4).

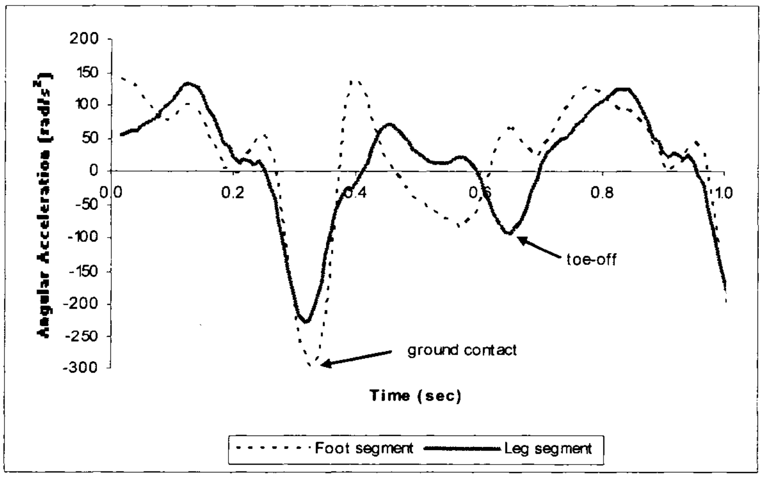

Figure 4. Location of ground contact and toe off taken from the acceleration curves of the foot and leg respectively.

The location at which the angular jerk was equal to zero did not always occur in a frame where the kinematic data was recorded, as data were collected at 120 Hz, the time of ground contact or toe off occasionally occurred between frames. Because of this, times were linearly interpolated between frames to locate the actual time of the event.

The sagittal plane kinematic variables of interest (knee angle, ankle angle, and knee angular velocity) were identified at ground contact and the spatio-temporal variables of stride length, the distance between consecutive heel strikes of the right foot, and stride rated were calculated. The time of toe off was used to determine the end of the stance phase. The data for each stance phase were normalized to 100% of stance. The total time of stance phase was recorded as contact time. The maximum knee angle and knee angular velocity during stance phase were recorded along with the temporal location of each as a percent of stance and compared between conditions. These values for each time trial were averaged and compared between the two footwear conditions at each time interval as well as between time intervals of each footwear condition to determine if the runners had any accommodation to the conditions. Custom MatLab programs were written to complete this analysis (Appendix IV).

Variability analysis of knee and ankle angles

The ten strides for each time condition (first 30 seconds of the condition, at 2:45 minutes, at 5:00 minutes, and at 7:15 minutes (end of condition)) were normalized to 100% of stance phase for each footwear condition creating 4 ensemble graphs for each subject for both the ankle and knee flexion angles. These ensemble graphs were used to compare the variability based on spanning set methodology of each trial-condition per

Kurz and Stergiou (2004) (see Appendix III for complete methods on spanning set analysis).

Statistical analysis

The kinematic dependant variables of interest were peak knee angle and peak angular velocity of the knee and their temporal locations within stance phase as well as knee angle, ankle angle, and knee angular velocity at heel contact, and spatio-temporal variables of contact time, stride rate, and stride length. These variables have been shown to be statistically different when comparing shod and barefoot running (de Wit *et al.*, 2000). The dependant variables of variability for the knee and ankle flexion angles over stance phase were also investigated because they have also been shown to be statistically different when comparing shod and barefoot running (Kurz & Stergiou, 2003; Kurz *et al.*, 2003).

The independent variables were footwear condition (test shoes or barefoot) and time (0:30, 2:45, 5:00, 7:15 minutes) during condition. The group effect of time on footwear condition adaptation was analyzed using a 2 (footwear condition) x 4 (time) analysis of variances (ANOVA) for each dependent variable with repeated measures on both conditions. Any accommodations to the conditions over time or differences between footwear were determined from this analysis.

CHAPTER 4

RESULTS

Kinematics

The interaction of time x footwear was not significant for any of the kinematic dependant variables analyzed ($p > 0.05$). Also, only the temporal location (% of stance) of the peak knee angular velocity in stance phase was different across time ($p > 0.05$). The results of the footwear main effect are described based on the kinematic variable of interest.

Knee angle at contact. Knee angle at contact was not influenced by any interactions of footwear and time, $F_{(3, 24)} = 0.382, p > 0.05$, there was also no adaptation of the knee angle at contact over time, $F_{(3, 24)} = 0.077, p > 0.05$. There was no significant main effect due to footwear (test shoes or barefoot), $F_{(1, 8)} = 0.003, p > 0.05$ (Table 1, Figure 5).

Knee angular velocity at contact. Knee angular velocity at contact was not influenced by any interactions of footwear and time, $F_{(3, 24)} = 0.693$, $p > 0.05$, there was also no adaptation of the knee angular velocity at contact over time, $F_{(3, 24)} = 0.511$, $p > 0.05$. There was no significant main effect due to footwear, $F_{(1, 8)} = 2.516, p > 0.05$ (Table 1).

Ankle angle at contact. Ankle angle at contact was not influenced by any interactions of footwear and time, $F_{(3, 24)} = 1.061, p > 0.05$, there was also no adaptation of the ankle angle at contact over time, $F_{(3, 24)} = 0.490, p > 0.05$. There was a significant main effect of footwear, $F_{(1, 8)} = 12.325, p = 0.008$ (Table 1, Figure 5). The angle of the ankle in the barefoot condition (mean = 7.45° ± 6.07°) was significantly less dorsiflexed at contact than in the shod condition (mean = 15.87° ± 3.59°).

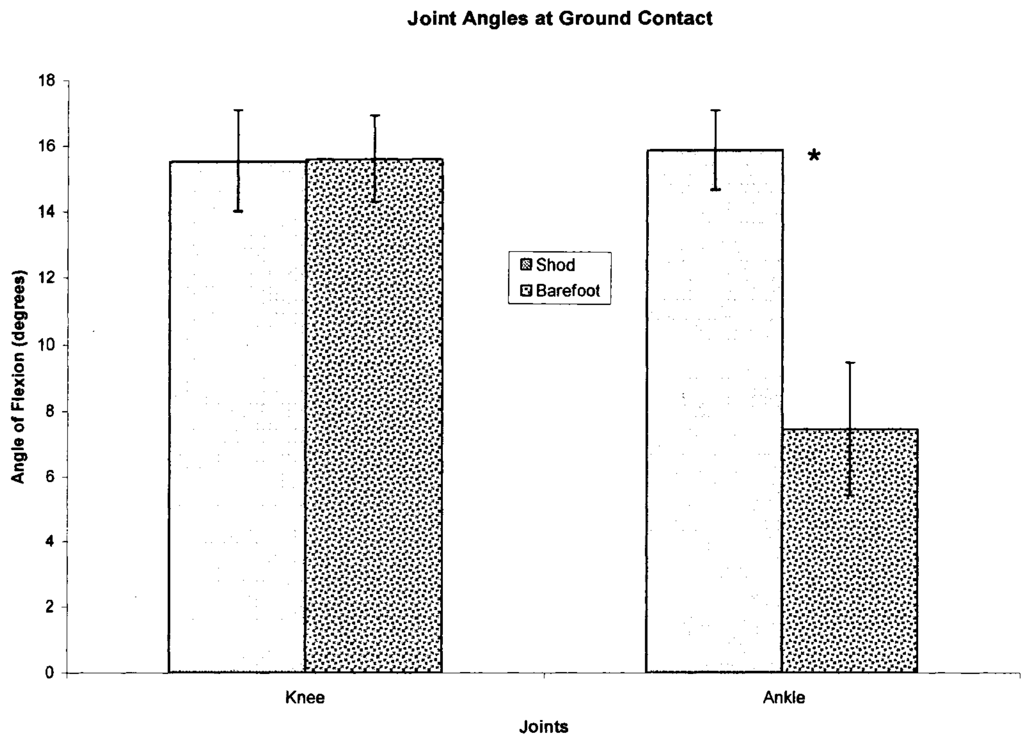

Figure 5. Illustration of the knee and ankle flexion angles at contact with standard error bars. There was no significant difference between barefoot and shod conditions at the knee. There was a significant difference in the ankle angle. A neutral ankle angle is 0° with dorsiflexion positive and plantar flexion negative.

Peak knee angle. Peak knee angle over stance phase was not influenced by any interactions of footwear and time, $F_{(3, 24)} = 1.105, p > 0.05$, there was also no adaptation of the maximum knee angle over time, $F_{(3, 24)} = 0.352, p > 0.05$. Peak knee angle was different between footwear conditions, $F_{(1, 8)} = 166.447, p < 0.0001$ (Table 1). The maximum angle of the knee during stance phase in the barefoot condition was significantly more extended by 3.67° than when wearing the test shoes.

Timing of peak knee angle. The temporal location (% of stance) of the peak knee angle in stance phase was not influenced by any interactions of footwear and time, $F_{(3, 24)} = 0.643$, $p > 0.05$, there was also no adaptation of the timing of the maximum knee angle over time, $F_{(3, 24)} = 0.688$, $p > 0.05$. The temporal location of the peak knee angle in stance phase was not different between footwear conditions, $F_{(1, 8)} = 2.317$, $p > 0.05$ (Table 1).

Peak knee angular velocity. Peak knee angular velocity over stance phase was not influenced by any interactions of footwear and time, $F_{(3, 24)} = 0.415$, $p > 0.05$, there was also no adaptation of the maximum knee angle over time, $F_{(3, 24)} = 0.369$, $p > 0.05$. However, maximum knee angular velocity was different between footwear conditions, $F_{(1, 8)} = 11.836$, $p = 0.009$ (Table 1). The maximum rate of change of the knee angle during the stance phase in the barefoot condition (mean = 357.55°/sec ± 42.90°/sec) was significantly slower than in the shod condition (mean = 421.90°/sec ± 82.23°/sec).

Timing of peak knee angular velocity. The temporal location (% of stance) of the peak knee angular velocity in stance phase was not influenced by any interactions of footwear and time, $F_{(3, 24)} = 1.149$, $p > 0.05$. There was, however, accommodation of the timing of the maximum knee angular velocity over time occurred, $F_{(3, 24)} = 3.275$, $p = 0.038$. This accommodation was observed in the timing of the peak angular velocity with the end of the trial (7:15 min.) occurring significantly later in stance phase than the initial two times (0:30 and 2:45 min.), but no difference noted between the first two time conditions (0:30 and 2:45 min.) or the last two time conditions (5:00 and 7:15 min.)

(Figure 6). The temporal location of the peak knee angular velocity in stance phase was not different between footwear conditions, $F_{(1, 8)} = 0.965, p > 0.05$.

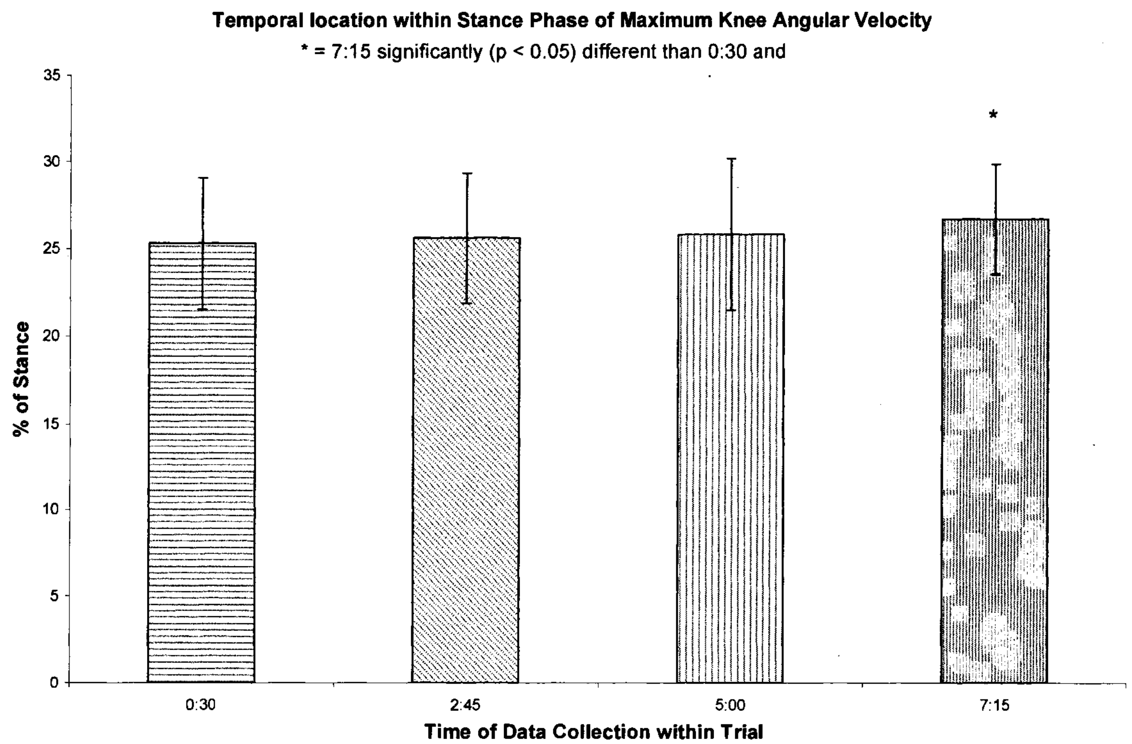

Figure 6. Illustration of the effect of running time on the temporal location within stance phase of the maximum knee angular velocity.

Table 1. Footwear condition means (SD) as well as mean values for each time condition within the footwear conditions; * = significant differences due to footwear, *t = significant differences due to time.

	Barefoot							Test Shoes					
	Time Conditions							Time Conditions					
	0:30	2:45	5:00	7:15	mean	(SD)		0:30	2:45	5:00	7:15	mean	(SD)
Variables at Contact													
Knee angle (°)	15.61	15.29	15.77	15.71	15.60	(3.94)		15.43	16.20	15.47	15.08	15.55	(4.86)
Ankle angle (°)	8.07	7.30	7.03	7.38	**7.44**	(6.07)	*	16.10	15.87	15.89	15.60	**15.87**	(3.59)
Knee angular velocity ($°\cdot sec^{-1}$)	-114.91	-95.31	-77.86	-114.15	-100.56	(135.17)		-25.19	-55.49	-27.27	-40.79	-37.19	(78.42)
Variables at Midstance													
Maximum Knee angle (°)	45.59	45.89	45.67	45.99	**45.78**	(1.59)	*	49.79	49.45	49.09	49.47	**49.45**	(1.95)
Timing (% of Stance)	46.27	45.55	45.00	45.68	45.63	(3.76)		44.57	44.90	44.46	44.37	44.58	(2.01)
Maximum Knee angular velocity ($°\cdot sec^{-1}$)	358.85	356.91	358.65	355.81	**357.55**	(42.90)	*	422.06	414.16	424.70	426.70	**421.90**	(82.23)
Timing (% of Stance)	26.65	26.27	26.32	**27.28**	26.63	(5.72)	*t	23.93	24.92	25.31	**26.09**	25.06	(2.44)
Spatio-Temporal Variables													
Contact Time (msec)	32.23	32.27	32.32	32.52	**32.34**	(0.02)	*	31.35	30.46	31.07	31.59	**31.12**	(0.02)
Stride Length (m)	2.08	2.08	2.10	2.08	**2.09**	(0.29)	*	2.14	2.13	2.14	2.15	**2.14**	(0.32)
Stride Rate (Hz)	1.41	1.41	1.40	1.41	**1.41**	(0.10)	*	1.38	1.38	1.37	1.37	**1.38**	(0.10)
Variability Variables													
Knee Flexion	1.16	1.12	0.87	1.15	1.07	(0.34)		0.89	1.27	1.22	0.73	1.03	(0.40)
Ankle Flexion	0.61	0.57	0.82	0.66	0.67	(0.34)		0.45	0.50	0.60	0.52	0.51	(0.17)

Stance time. The duration of foot contact was not influenced by the interaction between footwear condition and time ($F_{(3, 24)}$ = 1.177, $p > 0.05$) there was also no main effect on stance time due to time with $F_{(3, 24)}$ = 1.263, $p > 0.05$ (Table 1). There was a significant main effect of footwear on stance time, $F_{(1, 8)}$ = 9.968, $p = 0.013$. The time the foot was in contact with the ground in the barefoot condition was 12 msec (3.8%) longer than while wearing the test shoes.

Stride length. Stride length was not influenced by the interaction between footwear condition and time ($F_{(3, 24)}$ = 0.699, $p > 0.05$). There was also no main effect due to time with $F_{(3, 24)}$ = 0.927, $p > 0.05$ (Table 1). Stride length was influenced by footwear condition, $F_{(1, 8)}$ = 24.601, $p = 0.001$. The stride length while running barefoot was 2.5% shorter than while wearing the test shoes.

Sride rate. Stride rate was not influenced by the interaction between footwear condition and time ($F_{(3, 24)}$ = 0.913, $p > 0.05$), there was also no main effect due to time with $F_{(3, 24)}$ = 0.804, $p > 0.05$ (Table 1). However, there was a significant main effect of footwear on stride rate, $F_{(1, 8)}$ = 39.322, $p = 0.0002$, with the stride rate in the barefoot condition on average 2.5% higher than the test shoe condition.

Variability

The variability of neither the knee flexion angle nor the ankle flexion angle was influenced by footwear, time, or an interaction between the two main effects ($p > 0.05$).

Knee angle variability. The variability of the knee angle was not influenced by the interaction between footwear condition and time $F_{(3, 24)}$ = 1.298, $p > 0.05$. The knee joint variability was also not influenced by either main effect of footwear condition or time with $F_{(1, 8)}$ = 0.112, $p > 0.05$, and $F_{(3, 24)}$ = 0.298, $p > 0.05$, respectively (Table 1, Figure

7). Slightly greater variability was observed for the barefoot condition than the shod condition.

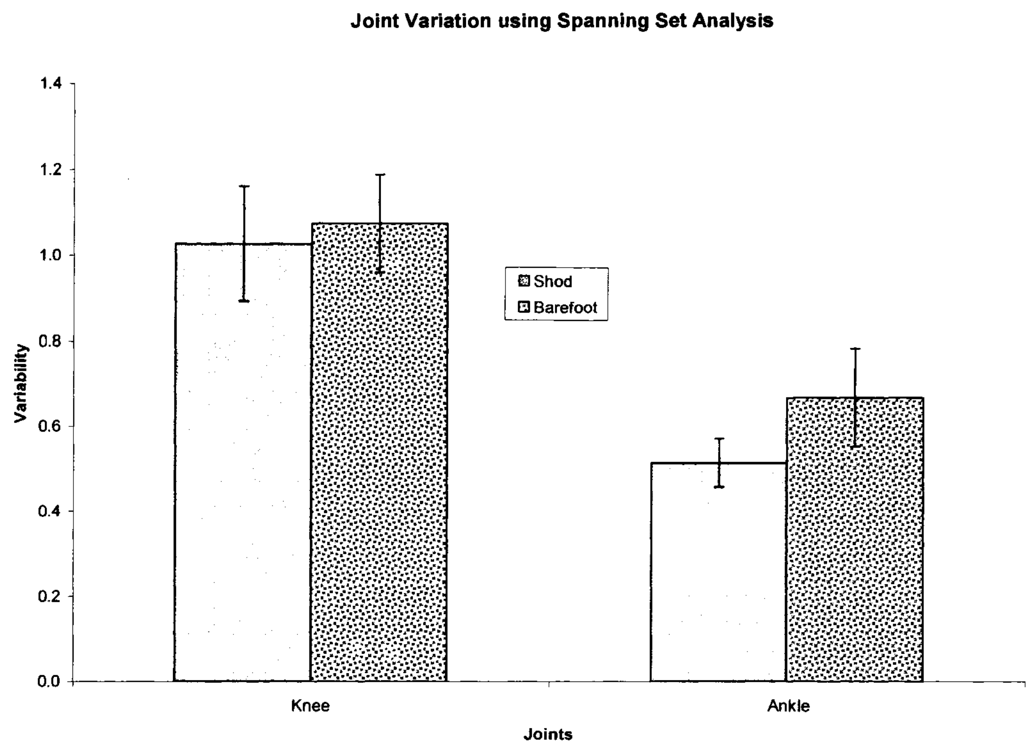

Figure 7. Knee and ankle variability showed no significant difference when comparing barefoot and shod conditions.

Ankle angle variability. The variability of the ankle angle was not influenced by the interaction between footwear condition and time $F_{(3, 24)} = 0.182$, $p > 0.05$. The ankle angle variability was also not influenced by either footwear condition or time with $F_{(1, 8)} = 2.341$, $p > 0.05$, and $F_{(3, 24)} = 1.527$, $p > 0.05$ respectively (Table 1, Figure 7). The ankle angle variability in the barefoot condition (mean = 0.67 ± 0.34) was slightly greater than that observed in the shod condition (mean = 0.51 ± 0.17), but was not statistically significant.

Additional Measurements

Arch Index. Classification of arch type using AI was done in accordance with Cavanagh and Rogers (1987) as: pes cavus ≤ 0.21, 0.21 < normal < 0.26, pes planus ≥ 0.26. The right foot of each subject was analyzed and three of the subjects were observed to have normal arch height and five of the subjects feet were pes planus (flat feet). One subject was found to have pes cavus (high arches) (Table 2).

Table 2. Arch index results for the right and left foot for all subjects.

	1	2	3	4	5	6	7	8	9
R	0.27*	0.24+	0.28*	0.17	0.32*	0.27*	0.21+	0.25+	0.33*
L	0.27*	0.21+	0.28*	0.20	0.30*	0.25+	0.22+	0.29*	0.33*

* = pes planus
+ = normal

CHAPTER 5

DISCUSSION

Kinematics

Based on the results of this study, the running mechanics of the subjects while wearing the test shoes was similar to their mechanics while running with bare feet. At ground contact the knee angle and angular velocity were not different nor were the variability of the knee or ankle joint angles over the entire stance phase which were different when comparing barefoot to standard shoes (de Wit *et al.*, 2000; Kurz & Stergiou, 2003). There were differences however, in the ankle joint angle at contact as well as the peak knee angle and peak knee angular velocity located in mid-stance which also was different between barefoot running and running in standard shoes. The importance of this is that the running mechanics measured in the test shoe condition were a hybrid of the barefoot and shod mechanics as described in previous literature (de Wit *et al.*, 2000; Kurz & Stergiou, 2003; McNair & Marshall, 1994), and it appears that the general running pattern while running in the test shoes was similar to that of a barefoot runner with the only differences due to perceptual effects of cushioning in the shoe.

While the majority of runners (> 75%) have a heel strike pattern when running at a moderate speeds (< 5 m/s; Aerts & De Clercq, 1993; Kerr *et al.*, 1983), these studies have analyzed shod runners only. For the current study, the runners in the test shoe condition did in fact exhibit a heel strike pattern based upon the ankle angle data at ground contact. However, the ankle was more plantar flexed at ground contact in the barefoot condition suggesting a mid- or forefoot strike pattern at ground contact. The knee angle at contact was not different between the two footwear conditions. This observation is similar to that of de Wit et al. (2000) who reported that for all speeds measured (3.5, 4.5, and 5.5 $m \cdot s^{-1}$) the ankle angle at contact was more plantar flexed but they observed the knee was also more flexed while running barefoot compared to shod running over ground. McNair and Marshall (1994) tested runners on a treadmill and reported similar results where the ankle angle was more plantar flexed throughout the stride cycle while running barefoot with minimal difference at the knee when compared to shod running. The likely reason that the current study results differ at the knee from de Wit and colleagues (2000), but not from McNair and Marshall (1994) is due to testing method differences. The current study as well as McNair and Marshall's study in 1994 was completed on a treadmill while de Wit et al. (2000) had subjects run over ground. It is unknown whether the lack of a difference at the knee was due to the difference in kinematics of running on a treadmill versus over ground rather than the kinematics while wearing the test shoe truly being similar to the barefoot condition. Becker (1989) has hypothesized that the technically accomplished runner avoids heel contact. In this way they avoid passive impact forces. The barefoot runners in the current study may also be attempting to avoid these passive impact forces.

In the current study, the knee angle as well as the knee angular velocity at ground contact was not different between running in the test shoe and barefoot running. However while comparing barefoot to shod conditions, de Wit and colleagues (2000) reported a significant difference in both of these variables due to footwear condition at ground contact where the knee was more flexed and a larger angular velocity was observed in the barefoot condition. McNair and Marshall (1994) reported the knee to be only slightly more extended at ground contact while barefoot. Again, the difference of results between the current study and those of de Wit et al. (2000) is likely due to the difference in test methods (i.e., over ground versus treadmill).

The maximum knee angle at midstance was 7.4% more extended in the barefoot condition while maximum knee flexion velocity was observed to be 17% less for the runners while barefoot compared to wearing the test shoes in the current study. Barefoot running has been compared to running on a hard surface or as a very hard shoe midsole (de Wit *et al.*, 2000; Hardin *et al.*, 2004; McNair & Marshall, 1994, 1992). Kinematic adaptations to different types of surfaces and footwear have been reported previously. Researchers have observed maximum knee flexion (de Wit *et al.*, 2000; McNair & Marshall, 1994) and maximum knee angular velocity (de Wit *et al.*, 2000; Hardin *et al.*, 2004) changed with modifications in either surface or footwear. For example, similar to the current study, maximum knee flexion angle was reported as less (i.e., the knee was more extended) while barefoot than shod running (de Wit *et al.*, 2000; McNair & Marshall, 1994). Maximum knee flexion velocity has been reported to increase with an increase of surface stiffness (Hardin *et al.*, 2004), but no difference was reported between shoes of varying midsole stiffness (Hardin *et al.*, 2004). Whereas, de Wit and colleagues showed an increase in maximum knee flexion velocity as running velocity increased, and in agreement with the current study, at slower running speeds (3.5 $m \cdot s^{-1}$) the knee flexion velocity was smaller for the barefoot condition than shod. Therefore, the "harder" condition had a slower maximum knee flexion velocity. The treadmill surface stiffness changes of Hardin and colleagues (2004) may have influenced their runners more than the change from a shod to a barefoot state. These results may be evidence that barefoot running may not be analyzed correctly as a hard surface compared to shod running. The runners may not be using leg and ankle stiffness to adjust their mechanics from shod to barefoot running. The results of the current study may be different from Hardin et al. (2004) and because they ensured their subjects were all heel-toe runners to limit the influence of footstrike pattern on ankle stiffness. For the current study, ground contact characteristics were not checked prior to data collection and directions of how to contact the ground were not given so that each runner would run as comfortably as possible in both footwear conditions. This way the runners were allowed to naturally change from a heel-toe contact pattern in the test shoes to a mid- or forefoot landing while barefoot if it was more comfortable. Most studies comparing barefoot to shod running ensure runners are heel strikers as well as ask them to run heel-toe in all conditions. While this keeps the two conditions as similar as possible, if the runners are changing a natural or comfortable running style just to ensure a heel strike, these researchers may be biasing their results.

The spatio-temporal parameters, such as ground contact duration, stride length and stride rate are basic kinematic descriptors of gait. In the present study, the duration of ground contact was observed to be longer in the barefoot condition than in the test shoe condition. In contrast, ground contact time was reported to be shorter for barefoot running than shod running (de Wit *et al.*, 2000). These differences between studies could possibly be due to protocol differences in measuring ground contact between the experimental protocol of the current study versus the protocol used by de Wit et al.

(2000). For example, de Wit and colleagues (2000) had their subjects run over ground and measured ground contact based on reaching a minimum force threshold on the force plate. For the current study the subjects ran on a treadmill and ground contact and toe off were determined based on kinematic markers per Hreljac and Stergiou (2000). Prior to collecting data for the current study, pilot data were recorded comparing the two methods (GRF versus kinematics) of tracking ground contact and toe off on 18 running trials of a single subject in both the barefoot and test shoe conditions. When comparing these two methods, the RMS difference for identifying ground contact was determined. The mean RMS difference at ground contact between GRF and kinematics for the barefoot condition was 9.4 msec with the kinematic method occurring slightly earlier. The RMS difference for toe off was 28 msec with the kinematic data occurring later. This produced a consistently longer stance time when kinematic values were was used to measure ground contact for the barefoot condition. A similar trend occurred when comparing the test shoe condition. The total error comparing contact time determined from ground reaction force and that from kinematics for the barefoot condition was 37.4 msec, while the total error for the test shoe condition was 39.2 msec. Initially, this appeared to be a relatively constant error and a small difference in contact time, but may lead to an explanation of why the barefoot condition had a longer contact time than the test shoe condition in the current study. The difference observed between the barefoot and test shoe condition was 1 ± 2 msec, while the difference in error alone was almost 2 msec. Based on these results, the kinematic method per Hreljac and Stergiou (2000) may not be a valid measure of ground contact and toe off for barefoot running. In the future, a more precise method of measuring ground contact time may be beneficial in any future barefoot studies such as using pressure measuring insoles or running over a force plate.

In the current study, stride rate was observed to be faster for barefoot running than running in the test shoe while on the treadmill. As previously described, de Wit et al. (2000) had their subjects running over ground. De Wit and colleagues also constrained speed, while runners in the current study were allowed to select a comfortable running speed. In both studies the same speed was used for each of the footwear conditions. Even with all of these differences, the literature supports the findings of the current study and reports that step rate is higher for barefoot than shod running (de Wit *et al.*, 2000) at multiple speeds while running over ground. The step rate reported by de Wit and colleagues (2000) was found by measuring the horizontal distance the center of mass traveled through stance phase, whereas stride rate in the current study was defined as the time between consecutive right footfalls.

Stride length was also observed to be shorter for barefoot running than running in the test shoes. While analyzing step length de Wit and colleagues (2000) reported the same trend when comparing barefoot to shod running over ground. An increase in stride length has been reported to increase impact characteristics (Mercer *et al.*, 2002). This suggests that runners are attempting to decrease the impact at contact by decreasing the stride length while running barefoot.

The variability of the knee and the ankle joint angles over stance phase resulted in no difference between footwear conditions. When comparing barefoot to shod running on a treadmill, Kurz and Stergiou (2003) found the barefoot variability at both the knee and ankle was much greater than the variability at the same joints while running in shoes.

Based on the lack of a difference in the variability of the joint motion in the two test conditions, running in the test shoes may be similar to that while running barefoot. The total variability of both the knee (barefoot: 1.07 ± 0.34; test shoes: 1.03 ± 0.40) and ankle (barefoot: 0.67 ± 0.34; test shoes: 0.51 ± 0.17) for both the barefoot and test shoe conditions were much smaller than reported by Kurz and Stergiou (2003) at the knee (barefoot: 9.1 ± 4.9; hard soled shoe: 4.6 ± 1.7; soft soled shoe: 5.0 ± 2.0) and ankle (barefoot: 7.2 ± 3.5; hard soled shoe: 2.9 ± 1.0; soft soled shoe: 2.5 ± 0.9). Kurz & Stergiou (2003) impact tested their shoes as: soft = 10.5 ± 1.0 g's and hard = 15.1 ± 0.3 g's; test shoe = 12.6 ± 0.04 g's and defined as a moderate stiffness. Differences in these studies that could affect the results are possibly the subject pool (male versus female), the running speed (preferred at 3.24 ± 0.85 $m \cdot s^{-1}$ versus preferred at 2.9 $m \cdot s^{-1}$), the method of data collection (180 Hz video camera versus 120 Hz motion capture system), or runner experience (average 44.5 $km \cdot week^{-1}$ versus minimum 10 $miles \cdot week^{-1}$). Also, Kurz and Stergiou (2003) used a 7th order polynomial for all of their spanning set analysis resulting in a statistical power of 0.88 for the knee and 0.98 for the ankle. For the current study polynomials ranging between 8th and 14th order were used to calculate the spanning sets resulting in statistical power of 0.91 for the knee and 0.90 for the ankle.

Confounding factors

There are a few factors that may have had a confounding effect on the results of the current study. All of the runners were minimally recreational runners averaging a minimum of 10 $miles \cdot week^{-1}$; however the experience level of the runners was quite varied. None of the runners had experience running in the test shoes prior to data collection. The amount of barefoot activity of the subjects prior to testing was not tracked. However, in conversations with the subjects post-testing, most of them commented on how they were not used to running barefoot and it felt very different. Therefore, both the test shoes and the barefoot conditions appeared to be novel tasks for all of the subjects. It is unknown if the level of experience in shod running may have an influence on the running mechanics observed. Based on Gentile's Two Stages of Skill Learning (1972), less experienced performers may restrict the degrees of freedom and therefore reduce the variability in novel situations, whereas experienced persons will be able to diversify or keep their movements more fluid and maintain a high level of variability in a novel situation of a known task (Gallahue & Ozmun, 2006). The importance of this lies in the fact that the subjects for the current study had a wide range of running experience. While they all trained a minimum of 10 miles·week^{-1}, some would just go out for runs, some have completed 5 or 10k races, and some were competitive runners. An analysis of each subject's individual response would help to understand if there is in fact an experience response in the measured variables.

The subjects tested were all female runners. It is not known how differently a group of male runners may kinematically accommodate to running between the same two footwear conditions. Hennig (2001) compared ground reaction forces, tibial accelerations, rear foot motion, and plantar pressures and observed differences due to gender. Differences between the genders were present primarily in passive vertical force where women had a smaller impact force than men runners, and in landing where women had higher medial loads at contact with more pronation while men had larger loads at the heel suggesting a softer landing pattern for female runners (Hennig, 2001). This suggests that examining the pronation rates of runners while barefoot compared to running in the test shoes would be helpful in understanding differences in loading of the lower extremity at ground contact. Ferber et al. (2003) compared lower extremity mechanics between genders and found no difference in peak knee flexion angle or peak knee flexion velocity. This suggests that for the current study the there should be no differences between genders for the current dependant variables of interest.

Another factor that may have had an influence on the results of the current study was the method of testing. The runners in the current study ran on a treadmill. The results may have been different if they had run over ground. For example, de Wit et al. (2000) found a difference between barefoot and shod conditions at contact for the knee flexion angle as well as the ankle angle at contact while running over ground, whereas McNair and Marshall (1994) only found a difference between conditions at the ankle while running on a treadmill. The results of the current study are similar to those of McNair and Marshall (1994) indicating the effects found at contact may be due to treadmill running rather than the footwear condition (i.e., test shoes versus barefoot).

The marker placement of the foot markers may have also affected ankle angle results. The toe marker was placed at the 2nd metatarsal head and this location was palpated through the shoe to make sure they were in the same location in both conditions. The heel marker based on the model was placed on the heel such that the vertical distance from the ground was approximately equal to that of the toe marker. This may cause issues due to the fact that the bare foot was flat on the ground and therefore the static location of the markers was in a neutral location. However, in the test shoe condition, the shoe has approximately 8° of plantarflexion built in with a thicker sole at the heel than toe. Therefore, the markers were aligned such that the heel and toe were level, but the foot within the shoe was at a slight angle of plantar flexion. The heel marker was placed approximately 2 cm lower on the foot in the test shoe condition, than in the barefoot condition. This difference was within the error of the model as the markers are 2.5 cm in diameter. Therefore, it is likely that any differences induced by the inclination of the shoe did not affect the results of the current study.

Initially, an accommodation of kinematics or stride characteristics over each 8 minute running trial was expected for each footwear condition. However, the lack of a significant effect due to time suggests all subjects were accommodating their running strategies from the beginning of each trial and maintained this strategy for the entire 8 minute test period. Time (5 min.) was allowed for the runners to get used to the speed that they would be running during the test conditions. This warm-up was not completed in either of the test conditions, rather the subjects were asked to warm up in their personal running shoes. The amount of time for the subjects to warm-up was established per White et al. (2002). However, no adjustment to any of the measured kinematic variables was observed over the entire 8 minutes of either running condition. Therefore, by 30 seconds (first recorded data of each condition) into the condition they had adapted their running style for each condition. As there was no difference in running style across the entire 8 minute trial, suggesting fatigue was not an issue. This brings into question the need for extended time at any specific running condition before data collection. Having long conditions may not be necessary to study how runners' accommodate to different running shoe conditions.

The dependant variables of interest for the current study allowed for a general comparison in running mechanics while running in the test shoes compared to barefoot.

However, because the analysis of discrete points within a running pattern can never fully describe the entire pattern, these may have not been the best variables to use to get a complete understanding of how the two conditions may truly conform. The variables chosen were valid based on previous literature comparing barefoot to shod running, but it is possible that they did not provide a complete description of running with the flexible test shoe. A more detailed analysis of kinematic variables including pronation rate, ground reaction forces, joint moments, and/or landing patterns would be helpful to propel the basic understanding of how people run while barefoot and how these test shoes may affect running patterns compared to both barefoot running and running in standard running shoes.

The differences observed in this study between running barefoot and while wearing the test shoes all originated in the ankle angle at ground contact. Subjects may have changed ankle angle at ground contact in the barefoot condition to decrease the local pressure under the heel, and therefore limit their impact shock. If the bare foot is thought of as a shoe with a very thin, hard sole, this is in agreement with Hennig et al. (1996) who found heel loading decreased and more of the weight was carried in the forefoot at landing while wearing shoes with harder soles. Based on the observations made, it is hypothesized that the kinematic changes observed were caused by the cushioning properties of the test shoe. For example, the runners' ankle angle at contact probably increased during the test shoe versus barefoot simply because of the perception of heel protection. Runners are used to wearing shoes with cushioning in the heel and having a heel-strike at ground contact. Initially it was thought that the flexibility allowed by the shoe would influence the dependant variables measured. However, even with this increased flexibility of the test shoes, heel cushioning took precedence and the runners did not have the same foot angle at contact as when they were barefoot. Runners in the current study actually had a greater foot angle (15.5° ± 3.5°) while wearing the test shoes even than was reported (7.8° ± 5°) in standard running shoes by de Wit and colleagues (2000). However, a key difference in the protocol used in the current study compared to de Wit et al. (2000) was the test methods in that the current study used a treadmill while they had their subjects run over ground. McNair and Marshall (1994), who also used a treadmill in data collection, graphically displayed similar results to the current study with a knee angle of 18-20° for shod running at ground contact.

In the current study, the barefoot condition resulted in a more horizontal foot position at contact, flexed knee at contact, and knee extending into the beginning of stance before flexing again to accept the full body weight at mid-stance. From these observations, the shock of impact was possibly reduced by the runners using the arch and musculature of the foot rather than flexion of the knee joint and leg musculature. In the test shoe condition, the foot was dorsiflexed at contact with a straighter knee. Functionally, as the foot extended downward to approach the flat foot at midstance, the knee flexed to attenuate some of the shock created at the heel interface of impact and maintained that flexion through stance phase. Therefore, the knee flexed much more in the test shoe condition than the barefoot condition. This is similar to the description of the shod running mechanics compared to the barefoot running mechanics by de Wit and colleagues (2000) while running over ground.

One area that may be of interest for future studies is dynamic landing patterns in these flexible shoes versus barefoot conditions. In the current study, static arch index was used to try to provide some explanation of any differences in accommodation to barefoot running or running in the test shoe based on arch height. From the results of this test, there was no correlation between the static arch height measured and the dynamic running kinematics. However, static arch definitions rarely transfer to dynamic movements (Lees, 2005). A possible way to monitor a dynamic landing pattern and assess the differences between the current test shoe and a barefoot condition would be to incorporate an in shoe pressure system while running.

To further examine the variability between and among subjects, supplementary analysis could be conducted using a single subject design per Bates et al. (1992, 2003). This analysis may provide insight into individual adaptation strategies of barefoot running and running in the test shoes. This could result in possibly regrouping the runners into more specific categories such as competitive runners and purely recreational runners.

Variability

Based upon the observation that variability of kinematic patterns did not differ between conditions, it is hypothesized that any benefits that may exist from barefoot activities may also be gained while wearing these test shoes. The flexibility of the shoe appeared to allow the foot to move freely and therefore closely represent a barefoot running pattern over stance phase. It is thought that increasing variability of characteristics during the performance of repetitive motions like running and walking may help reduce chronic injury via increasing the variability of gross motions (Dufek, 2002), increasing the variability of the timing between coupled joint motions (Hamill *et al.*, 1999), and correlating joint moments and injury proneness (James *et al.*, 2000).

Hamill et al. (1999) examined variability of lower extremity joint coordination and reported that injured runners exhibited less variability than non-injured. James et al. (2000) observed a similar relationship between overuse injuries and variability. The current study investigated joint flexion angle variability over stance phase. That is, the magnitude of the difference in joint angle among all the steps in a single trial. In a similar method of investigation, Kurz and Stergiou (2003) reported that barefoot runners had more joint angle variability than shod runners especially around ground contact and toe off. Because the test shoes in the current study displayed a similar magnitude of variability as running barefoot, they may have a positive influence on running injuries. It is possible the repetitive motion will be more variable in these flexible shoes than in standard shoes.

Conclusion

Based on the results of this study, the running kinematics of the subjects while wearing the test shoes was similar to their kinematics while running with bare feet. It is hypothesized that the kinematic changes while wearing the test shoes may be a hybrid of a barefoot running style and a shod running style. This is because any differences between the test shoe and barefoot running appear to stem from the dissimilarity of heel cushioning properties of wearing a shoe compared to being barefoot. Most of the dependant variables investigated were at discrete points in the stance phase of running, but the variability over the entire running pattern was also investigated and no difference was observed in the variability of either the knee or the ankle flexion angles over stance phase. Finally no adaptation to either footwear condition occurred over time. Therefore in both conditions the subjects changed their running style from their initial steps on the treadmill. It is still not known how different running kinematics would be while running in these test shoes compared to standard running shoes. Further investigation into joint range of motion, or joint coordination strategies need to be completed to further analyze the relationship between barefoot running and running in these flexible test shoes.

APPENDIX I

LIMITATIONS, ASSUMPTIONS, DEFINITIONS,

and STATISTICAL HYPOTHESES

LIMITATIONS

- The size of the shoes available, women's size 8.5-9.5, this limits the population to be studied as many female runners have smaller feet than studied.
- The study only included female recreational runners; the results therefore can not be inferred to other groups. Maximum weekly mileage was not limited or tracked, so the range of running experience was quite varied.
- The study was conducted on a treadmill, while the shoes were designed for running on grass. Different results may be observed for over ground running.
- The study only compared barefoot to the test shoe, there was no direct comparison to a standard shoe. Therefore, no assumptions can be drawn as to the kinematic similarities or differences between the test shoe and a standard shoe.

ASSUMPTIONS

- The study was limited to recreational female runners (minimum 10 miles/week). It was assumed that all female runners would have similar running patterns regardless of running experience.
- Static arch height would influence a dynamic activity such as running.
- Both barefoot running and the test shoes were to novice conditions for all runners.

DEFINITIONS

- Kinematics – a branch of dynamics that deals with aspects of motion apart from considerations of mass and force.
- Kinetics – a branch of science that deals with the effects of forces upon the motions of material bodies or with changes in a physical system.
- Stance – the phase of gait where the foot is in contact with the ground.
- Shod – to wear shoes.
- Chronic or Overuse Injuries – Injuries occurring when the musculoskeletal system receives repeated stress over a long period of time, causing fatigue effects beyond the capabilities of a specific structure.

STATISTICAL HYPOTHESES

Research Hypotheses:

Knee angle at contact, ankle angle at contact, knee angular velocity at contact, peak knee angle, the temporal location within stance phase of the peak knee angle, peak knee angular velocity, the temporal location within stance phase of the peak knee angular velocity, contact time, stride length, stride rate, the knee flexion angle variability, and the ankle flexion angle variability will all differ between test shoe and bare foot conditions.

Null Hypotheses:

Knee angle at contact, ankle angle at contact, knee angular velocity at contact, peak knee angle, the temporal location within stance phase of the peak knee angle, peak knee angular velocity, the temporal location within stance phase of the peak knee angular velocity, contact time, stride length, stride rate, the knee flexion angle variability, and the ankle flexion angle variability will not differ between test shoe and bare foot conditions.

APPENDIX II

INFORMED CONSENT, PROJECT ORGANIZER FORM, and

TEST DAY SCRIPT

UNLV

UNIVERSITY OF NEVADA LAS VEGAS

Department of Kinesiology

INFORMED CONSENT

TITLE OF STUDY: Kinematic analysis of running barefoot compared to Nike Free 5.0.

INVESTIGATOR/S: Janet Griffin, Dr. John Mercer, Kaori Teramoto, Julia Freedman, David DeLion, Amanda Tritsch

CONTACT INFORMATION: If you have any questions or concerns about the study, please contact Janet Griffin at 895-3419, or Dr. Mercer at 895-4672.

Purpose of the Study

You are invited to participate in a research study. The purpose of this study is to investigate how you run while wearing test shoes (Nike Free 5.0) and while running barefoot.

Participants

You are being asked to participate in the study because you currently run either for competition or for exercise at least 10 miles per week, capable of running on a treadmill, and have no injury or condition that interferes with your ability to run.

Procedures

If you volunteer to participate in this study, you will be asked to report to the Biomechanics Laboratory once for about 1-2 hours. During this session, you will be asked to run on a treadmill while wearing shoes and while barefoot. You will be asked to select a preferred pace for both running conditions to reproduce the type of running you do on a regular basis.

During both running conditions, you will be instrumented with reflective markers placed on your body at specific anatomical landmarks. Tape and spirit gum (skin adhesive which is water soluble) will be used to secure these markers to your skin. A Motion Capture instrument will track these markers during your movements. Additionally we will place an accelerometer on your foot (or shoe) and secure it with tape to track specific aspects of your running motion.

Benefits of Participation

There may be no direct benefits to you as a participant in this study. However, we hope to better understand the design characteristics of these special shoes.

Risks of Participation

There are risks involved in all research studies. This study may include only minimal risks. This study does not require you to engage in any activity that is unusual or unfamiliar. Please be aware, however, that lower extremity joint and muscle injury is always possible in any running activity. You will be running for 8 minutes barefoot on a treadmill and may get minor scratches or irritation to the soles of your feet and/or under side of your toes. You will be asked to warm-up prior to testing, such that you feel physically prepared to perform the running activity. Both running conditions are designed to be of submaximal effort.

Cost /Compensation

There will not be financial cost to you to participate in this study. The study will take 1-2 hours of your time. You will not be compensated for your time. The University of Nevada, Las Vegas may not provide compensation or free medical care for an unanticipated injury sustained as a result of participating in this research study.

Contact Information

If you have any questions or concerns about the study, you may contact at **702-895-3419**. For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted you may contact **the UNLV Office for the Protection of Research Subjects at 702-895-2794.**

Voluntary Participation

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

Confidentiality

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

Participant Consent:

I have read the above information and agree to participate in this study. I am at least 18 years of age.

Signature of Participant ______________________________ Date ______________

Participant Name (Please Print) ________________________

Participant Note: Please do not sign this document if the Approval Stamp is missing or is expired.

Biomechanics Laboratory
Project Organization

Project	Comparison of Lower Extremity Kinematics of Barefoot running and running in Nike Free 5.0
Date of Consent	November 27, 2006
Test Date(s)	12/05 – 11/06
Subject Name	
Subject ID #	S10
Date of Birth/Age	
Gender	Male ☐ Female ☐
Height	cm
Weight	kg
Gait Model Measurements	
Lower Body	Left Right
Leg Length	cm cm
Knee Width	cm cm
Ankle Width	cm cm
Location of Files (i.e. path name)	Biomech/Janet Griffin/Thesis/S10
Conditions: **ORDER:** shod → barefoot	C1: barefoot preferred pace: ____ mph _____ m/s C2: shod
Scores: **T1: ~30s** **T2: ~2:45** **T3: ~5:00** **T4: ~7:15**	Time of trials: C1 C2 t1: t1: t2: t2: t3: t3: t4: t4:
Notes **Shoe Size:**	☐ Kinematic Labelling done ☐ Kinematic Analysis done ☐
Tester	Janet Griffin

Test Day Script

1. Record Height and Weight, measure knee width, ankle width and leg length. 5 min
2. Get arch index paintings. Paint each foot with subject standing on force plate. Have them step down to 50% weight, then lift foot. Clean off foot and then repeat with other foot. 5 min
3. Place markers in lower extremity plug-in gait model except foot markers. 15 min
4. Have subject begin warm up on treadmill allowing them to increase the speed to a comfortable pace. 5 min
5. Have subject step off of treadmill. Document speed of preferred pace. Offer water. Have subject prepare for first condition (put on test shoes, take off shoes). Apply markers to foot/shoe. 2-3 min
6. Get treadmill up to speed. Have subject step on. Begin recording data for 15 consecutive strides @ 30sec. on treadmill. 1-2 min
7. Record data @ 2:45 minutes, 5 minutes, and 7:15 minutes of running for 15 consecutive strides. 8 min
8. Have subject step off of treadmill. Offer water. Have subject prepare for second condition (put on test shoes, take off shoes). Apply markers to foot/shoe. 5 min
9. Get treadmill up to speed. Have subject step on. Begin recording data for 15 consecutive strides within the first minute on treadmill. 1-2 min
10. Record data @ 2:45 minutes, 5 minutes, and 7:15 minutes of running for 15 consecutive strides. <u>8 min</u>

60 minutes

APPENDIX III

ARCH INDEX DEFINITION and SPANNING SET ANALYSIS

ARCH INDEX DEFINITION

Foot Arch Index (AI) was determined for each subject using a footprint technique adapted from Cavanagh and Rodgers (1987). Subjects stood full weight on a force plate on one foot while black paint was applied to the foot to be printed. They then stepped down onto a piece of paper and stood with 50% body weight measured with the force platform. The subject then moved their weight back to the foot on the platform and the paper was set aside. To measure the AI, a foot axis line was drawn on the foot print from the tip of the second toe to the center of the heel. Two lines were then drawn perpendicular to the foot axis, one tangential to the most posterior aspect of the heel and one tangential to the most anterior aspect of the foot excluding the toes in front of the metatarsal heads. The foot was then trisected into equal parts dividing the foot into forefoot, mid-foot, and rearfoot sections. The footprint area of interest was then copied onto a piece of graph paper with 2mm boxes. The area of each of the three parts of the foot was determined by the area of the boxes within each outlined section. AI was defined as the area of the mid-foot divided by the total area of the foot (Cavanagh & Rodgers, 1987). AI was defined according to Cavanagh and Rodgers (1987) as high: $AI \leq 0.21$, normal: $0.21 < AI < 0.26$, or low: $AI \geq 0.26$.

SPANNING SET ANALYSIS

Spanning set analysis is based on the idea that the standard deviations of a curve can be described as vectors around the mean. The larger the distance is between the two vectors, the greater the span of the plane between the vectors (Kurz & Stergiou, 2003; Kurz et al., 2003). The 10 strides used in the kinematic analysis were also used for the spanning set analysis. The knee and ankle flexion angle data were normalized to 100% of stance phase and averaged over the 10 strides. Composite graphs were created with standard deviation curves above and below the mean. Polynomials were defined using the least squares method to describe the standard deviation curves (e.g. equations 1, 2) where p(t) was one standard deviation curve and g(t) was the other.

$$p(t) = \sum_{n=0}^{\infty} a_n t^n = a_0 + a_1 t + a_2 t^2 + \ldots \quad (1)$$

$$g(t) = \sum_{n=0}^{\infty} b_n t^n = b_0 + b_1 t + b_2 t^2 + \ldots \quad (2)$$

The polynomials were then mapped to a vector space that defined the vectors in the spanning set (equation 3) creating two vectors **u** and **v** from p(t) and g(t) respectively. For the current study polynomials between 6th order and 15th order were iteratively mapped to the standard deviation curves and displayed on a graph. The order of the polynomial that most closely matched visually (mean of 10.8 ± 1.4 for the knee and 9.5 ± 0.9 for ankle) was used and the root mean square error between the chosen polynomial and the curve it represented was recorded for validation purposes. The statistical power calculated for the knee was 0.92 and 0.90 for the ankle.

$$[f]_B = \begin{pmatrix} a_0 & b_0 \\ \cdot & \cdot \\ \cdot & \cdot \\ a_n & b_n \end{pmatrix} \qquad (3)$$

To determine the magnitude of the spanning set the root mean square was found between vectors **u** and **v** using equation 4.

$$y = \|\mathbf{u} - \mathbf{v}\| \qquad (4)$$

In this way the total variability of the movement was then determined to be a single number, the root mean square of the difference between the two polynomial vectors that made up the standard deviation curves of that movement. MatLab programs were written to complete this analysis (Appendix IV).

APPENDIX IV

MATLAB PROGRAMS

Main Program:

```
%JanetThesis.m
%Written Summer 2006
%jrg
%
%Program to determine stance phase using Hreljac & Stergiou
%(2000) Med. Biol. Eng. Comput., 38, 503-506.  It will output the knee and
%ankle flexion angle over stance as well as knee and ankle flexion angle at
%ground contact, peak knee angle and time in stance, peak knee angular
%velocity and time in stance.
%
%Next step is to interpolate to 100%
%

clc
clear;
clear all;
fclose('all');

temporary_directory = pwd;
fprintf(1,'\n\nProcessing\n\n');

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

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

```
directory               = 'C:\biomech\Thesis\ViconExportedData\S10'; %directory where
data is located
outputdirectory             = 'C:\biomech\Thesis\MatLabOutput'; %directory where data is
placed

outputfile              = 's10c1t3out.xls';
outputfileSpanSet       = 'SpanSetS10C1T3.xls';
outputfileKVectors      = 'KVectorsS10C1T3.xls';
outputfileAVectors      = 'AVectorsS10C1T3.xls';
outputfileRMS           = 'SSrmsS10C1T3.xls';

precision       = 4;        %output precision
VectorPrecision = 9;    %output precision for polynomial vector for Spanning Set
searchwindow   = 10;    %number of points for searching for the max/min
npeaks      = 15;   %number of strides to look for

savedata        = 'yes';
savefiles       = 'no';

%==================================
%Variable Definition
%==================================

ViconHeaders = 8;
ViconCols = 20;
ViconFs = 120;
dt = 1/ViconFs;

TimeCol = 2;
%Variables that will help determine stance phase
KneeX = 3;  KneeY = 4;  KneeZ = 5;
AnkleX = 6; AnkleY = 7; AnkleZ = 8;
HeelX = 9;  HeelY = 10; HeelZ = 11;
ToeX = 12;  ToeY = 13;  ToeZ = 14;
%Variables for analysis
KneeFlex = 15;
AnkleFlex = 18;

% Open files

filenumber = 0;

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

```
        %keep loop counter
        filenumber = filenumber+1;

        %open a file
        [kindata, inputfile]      = OG_openJG(s, c, t, directory, '.txt', '.aot', ViconCols,
inf, ViconHeaders);

        %Assign variables from the data
        KinTime = kindata(:, TimeCol);

        KneeYdata = kindata(:, KneeY); KneeZdata = kindata(:, KneeZ);
        AnkleYdata = kindata(:, AnkleY); AnkleZdata = kindata(:, AnkleZ);
        HeelYdata = kindata(:, HeelY); HeelZdata = kindata(:, HeelZ);
        ToeYdata = kindata(:, ToeY); ToeZdata = kindata(:, ToeZ);
        GrndYdata = HeelYdata - 100; GrndZdata = HeelZdata;

%==================================================================
        %     Calculate Ground Contact and Toe Off
%==================================================================

        GCTOjg

%==================================================================
        %     Calculate Variables of interest (Knee Flexion Angle, Angular
        %     Velocity & Time of max, Ankle Plantarflexion Angle, Contact time)
%==================================================================

        KneeAnkleVars

%==================================================================
        %     Get data for Spanning Set Analysis
%==================================================================

        SpanSet

%==================================================================
        %     Save Variables of interest out
%==================================================================

        %save all data per trial

        for i = 1:10
           ss(i) = s;
           cc(i) = c;
           tt(i) = t;
```

```
        end

        %complile data for a treadmill running condition:
        % Subject Condition Trial GCtime TOtime ConTime
        %   KFlxCon AFlxCon PkKTheta PkKThetaTime stPkKTheta
        %   PkKOmega PkKOmegatime stPkKOmega
        %   save out the middle 10 strides (3-12)
        alldataSingle(:,:) = [ss' cc' tt' GCtime(3:12)' TOtime(3:12)' ConTime(3:12)' ...
             KneeFlexCon(3:12)' AnkleFlexCon(3:12)' ...
             Thetapeak(3:12)' ThetaStep(3:12)'/ViconFs ThetaStance(3:12)' ...
             Velpeak(3:12)' VelStep(3:12)'/ViconFs VelStance(3:12)' ...
          ];% ...

        clear ss cc tt;

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



%output data using a function 'my_save'
if strcmp(savedata, 'yes')
  my_save(outputdirectory, outputfile, alldataSingle, precision);
end

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

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

%identify done processing
fprintf(1, '\ndone\n\n');

%----------------------------clean up--------------------------------
%       clear;
```

Program to open the files:

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

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

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

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

     f_name = ['s' subj 'c' cond 't' tri ];   %JG - Removed datatype from here and from the
function
     fprintf(1,f_name); fprintf(1,'\n');
     inputfileroot = f_name;

    %create filenames
    inputfile    = [f_name datain];      %*.prn
    grfout                = [f_name dataout];    %*.grf

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

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

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

     %open peak input file
    eval(file_name);

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

```
        end

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

    %read in data
    A = fscanf(fid, '%f', [columns rows]);
    tempdata = A';
%close files
fclose('all');
```

Program for determining ground contact and toe off:

```
%GCTOjg.m
%Written Summer 2006
%jrg
%
%Program to determine stance phase using Hreljac & Stergiou
%(2000) Med. Biol. Eng. Comput., 38, 503-506.
%
%================================================================
%       Calculate Ground Contact
%================================================================

%Define the Foot Segment from Heel and Toe marker data
for i = 1:length(kindata)
  HeelGrnd(i) = sqrt((GrndYdata(i) - HeelYdata(i))^2 + (GrndZdata(i) -
HeelZdata(i))^2);
  HeelToe(i) = sqrt((ToeYdata(i) - HeelYdata(i))^2 + (ToeZdata(i) - HeelZdata(i))^2);
  ToeGrnd(i) = sqrt((ToeYdata(i) - GrndYdata(i))^2 + (ToeZdata(i) - GrndZdata(i))^2);
end

% foot segment angle with ground
for i = 1:length(kindata)
  FootTheta(i) = acos((ToeGrnd(i)^2 - HeelGrnd(i)^2 - HeelToe(i)^2)/-(2 * HeelGrnd(i)
* HeelToe(i)));   %radians
end

%foot segment angular velocity using first central difference method
FootAngVel = dxdt(FootTheta, dt);

%foot segment angular acceleration using first central difference method
FootAngAcc = dxdt(FootAngVel, dt);
```

```
%The maximum foot angular acceleration is used as the criterion to
%estimate the time of ground contact (gc) this is also when the jerk is
%== 0.
%foot segment angular jerk using first central difference method
FootAngJerk = dxdt(FootAngAcc, dt);

% determine get the points right around Jerk == 0 where t1 = the TIME of the last
% negative value of the foot segment jerk just before crossing 0, t2 is
% the TIME of the first positive value of the foot angular jerk after
% crossing 0; FootAngJerkT1, or FootAngJerkT2 are the foot segmental
% jerk at time t1 and t2 respectively and tInt is the time interval
% (also equal to dt) - This isn't at all points where the jerk is = 0,
% just near the times where FootAngVel is near the minimums.

%---------GRAPH USING Foot Acceleration TO FIND 15 PEAKS FOR GC---------------
%
GCfindPeaksJG

% Use the equation from Hreljac & Stergiou (2000) to
% interpolate exact time of ground contact from the minimum
% acceleration data found in the graphs.
for i = 1:npeaks
   if FootAngJerk(peakpos(i)) == 0;
      FJerkT1(i) = FootAngJerk(peakpos(i)-1);
      FJerkT2(i) = FootAngJerk(peakpos(i)+1);
   else
      FJerkT1(i) = FootAngJerk(peakpos(i));
      FJerkT2(i) = FootAngJerk(peakpos(i)+2);
   end
   GCtime(i) = KinTime(peakpos(i)) + (FJerkT1(i)/(FJerkT1(i) - FJerkT2(i)))*dt;
end

GrndYdata = AnkleYdata - 100;
GrndZdata = AnkleZdata;

%============================================================
%      Calculate Toe Off
%============================================================

%Calculate Leg segment from knee and ankle marker data
for i = 1:length(kindata)
   KneeGrnd(i) = sqrt((GrndYdata(i) - KneeYdata(i))^2 + (GrndZdata(i) -
KneeZdata(i))^2);
   AnkleKnee(i) = sqrt((AnkleYdata(i) - KneeYdata(i))^2 + (AnkleZdata(i) -
KneeZdata(i))^2);
```

```
   AnkleGrnd(i) = sqrt((AnkleYdata(i) - GrndYdata(i))^2 + (AnkleZdata(i) -
GrndZdata(i))^2);
end

% leg segment angle
for i = 1:length(kindata)
   LegTheta(i) = acos((KneeGrnd(i)^2 - AnkleKnee(i)^2 - AnkleGrnd(i)^2)/(-2 *
AnkleKnee(i) * AnkleGrnd(i)));   %radians
end

%leg segment angular velocity using first central difference method
LegAngVel = dxdt(LegTheta, dt);

%leg segment angular acceleration using first central difference method
LegAngAcc = dxdt(LegAngVel, dt);

%The minimum leg angular acceleration is used as the criterion to
%estimate the time of toe off (to) this is also when the jerk is
%== 0.

%foot segment angular jerk using first central difference method
LegAngJerk = dxdt(LegAngAcc, dt);

% determine get the points right around Jerk == 0 where t1 = the TIME of the last
% negative value of the foot segment jerk just before crossing 0, t2 is
% the TIME of the first positive value of the foot angular jerk after
% crossing 0; FootAngJerkT1, or FootAngJerkT2 are the foot segmental
% jerk at time t1 and t2 respectively and tInt is the time interval
% (also equal to dt) - This isn't at all points where the jerk is = 0,
% just near the times where FootAngVel is near the minimums.

% Should we set it up so that we pick the angle mins and then use a range around
% that point to find where Jerk crosses 0?

%---------GRAPH USING LEG IMPACT TO FIND 15 PEAKS FOR GC---------------%

TOfindPeaksJG

% Use the equation from Hreljac & Stergiou (2000) to
% interpolate exact time of toe off from the minimum
% acceleration data found in the graphs.

for i = 1:npeaks
  if LegAngJerk(peaklpos(i)) == 0;
     LJerkT1(i) = LegAngJerk(peaklpos(i)-1);
     LJerkT2(i) = LegAngJerk(peaklpos(i)+1);
```

```
  else
    LJerkT1(i) = LegAngJerk(peaklpos(i));
    LJerkT2(i) = LegAngJerk(peaklpos(i)+2);
  end
  TOtime(i) = KinTime(peaklpos(i)) + (LJerkT1(i)/(LJerkT1(i)-LJerkT2(i)))*dt;
end
```

Program for finding the minimums from the foot segment for ground contact

```
%GCfindPeaksJG.m
%
%Identify leg peaks during running on treadmill
%

  point1 = round(length(FootAngAcc)/2);
  point2 = length(FootAngAcc);

figure('position', [100 80 1000 400])

fprintf(1,'\nIdentify local minimums.\n')

plot(KinTime(10:point1),FootAngAcc(10:point1), 'k');
hold on
ylabel('foot acceleration (rad/s/s)')
xlabel('time (s)')
title('Foot Angular Acceleration During Treadmill Running')

%find peaks
numberofpeaks = input('    How many minimums? ');
fprintf(1,'\n');

for i = 1:numberofpeaks

  %get graph information
  [xpos, ypos]   = ginput(1);
  xpos           = round(xpos*ViconFs);

  %identify start and end point to search for max
  start          = xpos - searchwindow;
  endsearch      = xpos + searchwindow;

  %check for searching beyond data set
  if (start<1)
    start=1;
  end
```

```
    if (endsearch>length(FootAngAcc))
      endsearch = length(FootAngAcc);
    end

    footpeak(i)     = min(FootAngAcc(start:xpos+searchwindow));
    temppeakpos     = find(FootAngAcc(start:xpos+searchwindow)==footpeak(i));
    temppeakpos(2)  = 0;
    peakpos(i)      = temppeakpos(1);
    peakpos(i)      = peakpos(i) + (start)-1;

    plot(KinTime(peakpos(i)),FootAngAcc(peakpos(i)), 'ro')
    drawnow

end
pause(0.5)

%repeat if number of peaks was less than 10
if numberofpeaks < npeaks
    close(gcf)
    figure('position', [100 80 1000 400])

    plot(KinTime(point1+1:point2),FootAngAcc(point1+1:point2), 'b');
    hold on
    ylabel('foot acceleration (rad/s/s)')
    xlabel('time (s)')
    title('Foot Angular Acceleration During Treadmill Running')

    %find peaks
    numberofpeaks2 = npeaks-numberofpeaks;

    for i = numberofpeaks+1:numberofpeaks2+numberofpeaks
      %get graph information
      [xpos, ypos]    = ginput(1);
      xpos            = round(xpos*ViconFs);

      %identify start and end point to search for max
      start           = xpos - searchwindow;
      endsearch       = xpos + searchwindow;

      %check for searching beyond data set
      if (start<1)
        start=1;
      end

      if (endsearch>length(FootAngAcc))
        endsearch = length(FootAngAcc);
```

```
        end

        footpeak(i)      = min(FootAngAcc(start:xpos+searchwindow));
        temppeakpos      = find(FootAngAcc(start:xpos+searchwindow)==footpeak(i));
        temppeakpos(2)  = 0;
        peakpos(i)       = temppeakpos(1);
        peakpos(i)       = peakpos(i) + (start)-1;

        plot(KinTime(peakpos(i)),FootAngAcc(peakpos(i)), 'ro')
        drawnow

    end
end

pause(0.5)

clear tempeakpos i start endsearch numberofpeaks numberofpeaks2 xpos ypos;

close
```

Program for finding the toe off minimums from the leg segment

```
%OGTMleg
%
%Identify leg peaks during running on treadmill
%
   point1 = round(length(LegAngAcc)/2);
   point2 = length(LegAngAcc);

figure('position', [100 80 1000 400])

fprintf(1,'\nIdentify local minimums.\n')

plot(KinTime(10:point1),LegAngAcc(10:point1), 'k');
hold on
ylabel('Leg acceleration (rad/s/s)')
xlabel('time (s)')
title('Leg Angular Acceleration During Treadmill Running')

%find peaks
numberofpeaks = input('     How many minimums? ');
fprintf(1,'\n');

for i = 1:numberofpeaks

   %get graph information
```

```
    [xpos, ypos]   = ginput(1);
    xpos           = round(xpos*ViconFs);

    %identify start and end point to search for max
    start          = xpos - searchwindow;
    endsearch      = xpos + searchwindow;

    %check for searching beyond data set
    if (start<1)
       start=1;
    end

    if (endsearch>length(LegAngAcc))
       endsearch = length(LegAngAcc);
    end

    Legpeak(i)     = min(LegAngAcc(start:xpos+searchwindow));
    temppeakpos    = find(LegAngAcc(start:xpos+searchwindow)==Legpeak(i));
    temppeakpos(2) = 0;
    peaklpos(i)    = temppeakpos(1);
    peaklpos(i)    = peaklpos(i) + (start)-1;

    plot(KinTime(peaklpos(i)),LegAngAcc(peaklpos(i)), 'ro')
    drawnow

end
pause(0.5)

%repeat if number of peaks was less than 10
if numberofpeaks < npeaks
    close(gcf)
    figure('position', [100 80 1000 400])

    plot(KinTime(point1+1:point2),LegAngAcc(point1+1:point2), 'b');
    hold on
    ylabel('Leg acceleration (rad/s/s)')
    xlabel('time (s)')
    title('Leg Angular Acceleration During Treadmill Running')

    %find peaks
    numberofpeaks2 = npeaks-numberofpeaks;

    for i = numberofpeaks+1:numberofpeaks2+numberofpeaks
       %get graph information
       [xpos, ypos]   = ginput(1);
       xpos           = round(xpos*ViconFs);
```

```
        %identify start and end point to search for max
        start           = xpos - searchwindow;
        endsearch       = xpos + searchwindow;

        %check for searching beyond data set
        if (start<1)
            start=1;
        end

        if (endsearch>length(LegAngAcc))
            endsearch = length(LegAngAcc);
        end

        Legpeak(i)      = min(LegAngAcc(start:xpos+searchwindow));
        temppeakpos     = find(LegAngAcc(start:xpos+searchwindow)==Legpeak(i));
        temppeakpos(2)  = 0;
        peaklpos(i)     = temppeakpos(1);
        peaklpos(i)     = peaklpos(i) + (start)-1;

        plot(KinTime(peaklpos(i)),LegAngAcc(peaklpos(i)), 'ro')
        drawnow

    end
end

pause(0.5)

clear tempeakpos i start endsearch numberofpeaks numberofpeaks2 xpos ypos;

close
```

Program for finding the key dependent knee and ankle variables:

```
%KneeAnkleVars.m
%Written Summer 2006
%jrg
%
%Program to determine select the knee and ankle variables at contact, as
%well as peak flexion angle and angular velocity and times of occurrance
%within stance phase.
%
%=====================================================================
%       Calculate Variables of interest (Knee Flexion Angle, Angular
%       Velocity & Time of max, Ankle Plantarflexion Angle, Contact time)
%=====================================================================
```

```
% Find knee and ankle angle
AnkleTheta = kindata(:, AnkleFlex);
KneeTheta = kindata(:, KneeFlex);

% Interpolate the Knee and Ankle Angle data to find the angles at
% Ground Contact
for i = 1:npeaks
   KneeFlexCon1(i) = KneeTheta(floor(GCtime(i)*ViconFs));  %Knee Flexion Angle at
frame before contact
   AnkleFlexCon1(i) = AnkleTheta(floor(GCtime(i)*ViconFs)); %Ankle Flexion Angle
at frame before contact
   FramePrior2Contact(i) = floor(GCtime(i)*ViconFs);      %Frame before contact
   FlexCon2(i) = FramePrior2Contact(i) + 1;              %Frame after contact
   KneeFlexCon(i) = KneeFlexCon1(i) + (GCtime(i)-
KinTime(FramePrior2Contact(i)))/(KinTime(FlexCon2(i))-
KinTime(FramePrior2Contact(i)))*(KneeTheta(FlexCon2(i))-
KneeTheta(FramePrior2Contact(i)));
   AnkleFlexCon(i) = AnkleFlexCon1(i) + (GCtime(i)-
KinTime(FramePrior2Contact(i)))/(KinTime(FlexCon2(i))-
KinTime(FramePrior2Contact(i)))*(AnkleTheta(FlexCon2(i))-
AnkleTheta(FramePrior2Contact(i)));
end

%Find maximum knee angular velocity during stance phase
KneeFlexVel = dxdt(KneeTheta, dt);

% Graph the knee flexion velocity and knee flexion over stance
% as bounded by GCtime and TOtime - not normalized to 100% of
% stance.  Select peak Knee Angular Velocity and the peak Knee
% Angle for output
%

FindVelPeaksJG

%Find the location within stance phase (%stance) that peak Knee
%Flexion Velocity  and peak Knee Flexion occurs.  Also find
%contact time.
for i = 1:npeaks
   VelStance(i) = ((Velpeakpos(i)- peakpos(i))/(peaklpos(i) - peakpos(i)))*100;
   VelStep(i) = (Velpeakpos(i) - peakpos(i));
   ThetaStance(i) = ((Thetapeakpos(i) - peakpos(i))/(peaklpos(i) - peakpos(i)))*100;
   ThetaStep(i) = (Thetapeakpos(i) - peakpos(i));
   ConTime(i) = (TOtime(i) - GCtime(i));
   KneeFlexVelCon1(i) = KneeFlexVel(floor(GCtime(i)*ViconFs));  %Knee Flexion
Angle at frame before contact
```

```
   KneeFlexVelCon(i) = KneeFlexVelCon1(i) + (GCtime(i)-
KinTime(FramePrior2Contact(i)))/(KinTime(FlexCon2(i))-
KinTime(FramePrior2Contact(i)))*(KneeFlexVel(FlexCon2(i))-
KneeFlexVel(FramePrior2Contact(i)));
end
```

Program for finding the peaks of the knee angle and angular velocity curves:

```
%FindVelPeaksJG
%
%Identify leg velocity peaks during running on treadmill
%
fprintf(1,'\nIdentify velocity peak for first leg peak.')

figure('position', [100, 100, 500, 500])
headsearchwindow = 10;

for i = 1:npeaks

   startplot   = peakpos(i);
   endplot     = peaklpos(i);

   %plot
   subplot(2,1,1)
   plot(KinTime(startplot:endplot),KneeTheta(startplot:endplot),'k')
   hold on
   %plot(KinTime(peakpos(i)),KneeTheta(peakpos(i)),'ro')
   %plot(KinTime(peakpos(i+1)),KneeFlexVel(peakpos(i+1)),'ro')
   hold off
   title('Knee Flexion Angle')
   ylabel('Angle (deg)')

   subplot(2,1,2)
   plot(KinTime(startplot:endplot),KneeFlexVel(startplot:endplot),'k')
   hold on
   title('Knee Flexion Angular Velocity')
   ylabel('Angular Velocity (rad/s)')
   xlabel('Time (s)')

   %find head peak
   %get graph information
   [xpos, ypos]   = ginput(1);
   xpos           = round(xpos*ViconFs);

   %identify start and end point to search for max
   start          = xpos - headsearchwindow;
```

```
    endsearch      = xpos + headsearchwindow;

    %check for searching beyond data set
    if (start<1)
       start=1;
    end

    if (endsearch>length(KneeFlexVel))
       endsearch = length(KneeFlexVel);
    end

    Velpeak(i)     = max(KneeFlexVel(start:xpos+headsearchwindow));
    temppeakpos    = find(KneeFlexVel(start:xpos+headsearchwindow)==Velpeak(i));
    temppeakpos(2)  = 0;
    Velpeakpos(i)  = temppeakpos(1);
    Velpeakpos(i)  = Velpeakpos(i) + (start)-1;

    plot(KinTime(Velpeakpos(i)),KneeFlexVel(Velpeakpos(i)), 'ro')
    drawnow
    pause(0.1)
    hold off

end

close(gcf)

fprintf(1,'\nIdentify angle peak for first leg peak.')

figure('position', [100, 100, 500, 500])
headsearchwindow = 10;

for i = 1:npeaks

    startplot  = peakpos(i);
    endplot     = peaklpos(i);

    %plot
    subplot(2,1,1)
    plot(KinTime(startplot:endplot),KneeFlexVel(startplot:endplot),'k')
    hold on
    hold off
    title('Knee Flexion Angular Velocity')
    ylabel('Angular Velocity (rad/s)')

    subplot(2,1,2)
    plot(KinTime(startplot:endplot),KneeTheta(startplot:endplot),'k')
```

```
    hold on
    title('Knee Flexion Angle')
    ylabel('Angle (deg)')
    xlabel('Time (s)')

    %find head peak
    %get graph information
    [xpos, ypos]   = ginput(1);
    xpos           = round(xpos*ViconFs);

    %identify start and end point to search for max
    start          = xpos - headsearchwindow;
    endsearch      = xpos + headsearchwindow;

    %check for searching beyond data set
    if (start<1)
       start=1;
    end

    if (endsearch>length(KneeTheta))
       endsearch = length(KneeTheta);
    end

    Thetapeak(i)    = max(KneeTheta(start:xpos+headsearchwindow));
    temppeakpos     = find(KneeTheta(start:xpos+headsearchwindow)==Thetapeak(i));
    temppeakpos(2)  = 0;
    Thetapeakpos(i) = temppeakpos(1);
    Thetapeakpos(i) = Thetapeakpos(i) + (start)-1;

    plot(KinTime(Thetapeakpos(i)),KneeTheta(Thetapeakpos(i)), 'ro')
    drawnow
    pause(0.1)
    hold off

end

close(gcf)
```

Program to determine the spanning set variables:

```
%SpanningSet.m
%
%Written Summer 2006
%jrg
%
```

```
%This program will take the stance phase data from JanetThesis.m which
%includes time data, knee angle, and ankle angle data from each of 10 strides.
%These data are then interpolated to 101 data points which is 100% of stance
%and then averaged together and a confidence interval (standard deviation)
%is calculated for a mean/sd curve.  Polynomials are fit to the standard
%deviation curves.  The coefficients of the polynomials are then made into
%vectors and the root mean square of the difference of the upper and the lower
%polynomial is the Spanning Set Variability.
%=========================================
%Define stance phase of each step. Start at the frame before ground contact
%and end at the frame after toe off.  This is not iterative.
%=========================================

data = kindata(:,:);
FramePrior2Contact(1) = floor(GCtime(1)*ViconFs);          %Frame before contact
FrameAfterToeOff(1) = ceil(TOtime(1)*ViconFs);             %Frame after toe off
data = [data(FramePrior2Contact(1):FrameAfterToeOff(1), :)]; %All columns of data in
the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time = linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time = linspace(0, 100, 100/step+1)';
kdata1 = [time kdata];
%    my_save(directory, 'Intkneedata1.txt', kdata, precision)

step = 1;
time = linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata1 = [time adata];
%    my_save(directory, 'Intankledata1.txt', adata, precision)
%========================Next Stride=====================%
data = kindata(:,:);
FramePrior2Contact(2) = floor(GCtime(2)*ViconFs);          %Frame before contact
FrameAfterToeOff(2) = ceil(TOtime(2)*ViconFs);             %Frame after toe off
data = [data(FramePrior2Contact(2):FrameAfterToeOff(2), :)]; %All columns of data in
the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);
```

```
step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata2 = [time kdata];
%    my_save(directory, 'Intkneedata2.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata2 = [time adata];
%    my_save(directory, 'Intankledata2.txt', adata, precision)
%=========================Next Stride=====================%
data = kindata(:,:);
FramePrior2Contact(3) = floor(GCtime(3)*ViconFs);             %Frame before contact
FrameAfterToeOff(3) = ceil(TOtime(3)*ViconFs);                %Frame after toe off
data = [data(FramePrior2Contact(3):FrameAfterToeOff(3), :)]; %All columns of data in
the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata3 = [time kdata];
%    my_save(directory, 'Intkneedata3.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata3 = [time adata];
%    my_save(directory, 'Intankledata3.txt', adata, precision)
%=========================Next Stride=====================%
data = kindata(:,:);
FramePrior2Contact(4) = floor(GCtime(4)*ViconFs);             %Frame before contact
FrameAfterToeOff(4) = ceil(TOtime(4)*ViconFs);                %Frame after toe off
data = [data(FramePrior2Contact(4):FrameAfterToeOff(4), :)]; %All columns of data in
the rows GC->TO

timedata = data(:, TimeCol);
```

```
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata4 = [time kdata];
%    my_save(directory, 'Intkneedata4.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata4 = [time adata];
%    my_save(directory, 'Intankledata4.txt', adata, precision)
%==========================Next Stride=====================%
data = kindata(:,:);
FramePrior2Contact(5) = floor(GCtime(5)*ViconFs);          %Frame before contact
FrameAfterToeOff(5) = ceil(TOtime(5)*ViconFs);            %Frame after toe off
data = [data(FramePrior2Contact(5):FrameAfterToeOff(5), :)]; %All columns of data in
the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata5 = [time kdata];
%    my_save(directory, 'Intkneedata5.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata5 = [time adata];
%    my_save(directory, 'Intankledata5.txt', adata, precision)
%==========================Next Stride=====================%
data = kindata(:,:);
FramePrior2Contact(6) = floor(GCtime(6)*ViconFs);          %Frame before contact
FrameAfterToeOff(6) = ceil(TOtime(6)*ViconFs);            %Frame after toe off
data = [data(FramePrior2Contact(6):FrameAfterToeOff(6), :)]; %All columns of data in
the rows GC->TO
```

```
timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata6 = [time kdata];
%    my_save(directory, 'Intkneedata6.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata6 = [time adata];
%    my_save(directory, 'Intankledata6.txt', adata, precision)
%=========================Next Stride====================%
data = kindata(:,:);
FramePrior2Contact(7) = floor(GCtime(7)*ViconFs);          %Frame before contact
FrameAfterToeOff(7) = ceil(TOtime(7)*ViconFs);              %Frame after toe off
data = [data(FramePrior2Contact(7):FrameAfterToeOff(7), :)]; %All columns of data in
the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata7 = [time kdata];
%    my_save(directory, 'Intkneedata7.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata7 = [time adata];
%    my_save(directory, 'Intankledata7.txt', adata, precision)
%=========================Next Stride====================%
data = kindata(:,:);
FramePrior2Contact(8) = floor(GCtime(8)*ViconFs);          %Frame before contact
FrameAfterToeOff(8) = ceil(TOtime(8)*ViconFs);              %Frame after toe off
```

```
data = [data(FramePrior2Contact(8):FrameAfterToeOff(8), :)]; %All columns of data in
the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata8 = [time kdata];
%    my_save(directory, 'Intkneedata8.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata8 = [time adata];
%    my_save(directory, 'Intankledata8.txt', adata, precision)
%=========================Next Stride====================%
data = kindata(:,:);
FramePrior2Contact(9) = floor(GCtime(9)*ViconFs);           %Frame before contact
FrameAfterToeOff(9) = ceil(TOtime(9)*ViconFs);              %Frame after toe off
data = [data(FramePrior2Contact(9):FrameAfterToeOff(9), :)]; %All columns of data in
the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata9 = [time kdata];
%    my_save(directory, 'Intkneedata9.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata9 = [time adata];
%    my_save(directory, 'Intankledata9.txt', adata, precision)
%=========================Next Stride====================%
data = kindata(:,:);
```

```
FramePrior2Contact(10) = floor(GCtime(10)*ViconFs);            %Frame before contact
FrameAfterToeOff(10) = ceil(TOtime(10)*ViconFs);               %Frame after toe off
data = [data(FramePrior2Contact(10):FrameAfterToeOff(10), :)]; %All columns of data
in the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata10 = [time kdata];
%    my_save(directory, 'Intkneedata10.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata10 = [time adata];
%    my_save(directory, 'Intankledata10.txt', adata, precision)
%=========================Next Stride====================%
data = kindata(:,:);
FramePrior2Contact(11) = floor(GCtime(11)*ViconFs);            %Frame before contact
FrameAfterToeOff(11) = ceil(TOtime(11)*ViconFs);               %Frame after toe off
data = [data(FramePrior2Contact(11):FrameAfterToeOff(11), :)]; %All columns of data
in the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata11 = [time kdata];
%    my_save(directory, 'Intkneedata11.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata11 = [time adata];
%    my_save(directory, 'Intankledata11.txt', adata, precision)
```

```
%=========================Next Stride====================%
data = kindata(:,:);
FramePrior2Contact(12) = floor(GCtime(12)*ViconFs);          %Frame before contact
FrameAfterToeOff(12) = ceil(TOtime(12)*ViconFs);             %Frame after toe off
data = [data(FramePrior2Contact(12):FrameAfterToeOff(12), :)]; %All columns of data
in the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata12 = [time kdata];
%    my_save(directory, 'Intkneedata12.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata12 = [time adata];
%    my_save(directory, 'Intankledata12.txt', adata, precision)
%=========================Next Stride====================%
data = kindata(:,:);
FramePrior2Contact(13) = floor(GCtime(13)*ViconFs);          %Frame before contact
FrameAfterToeOff(13) = ceil(TOtime(13)*ViconFs);             %Frame after toe off
data = [data(FramePrior2Contact(13):FrameAfterToeOff(13), :)]; %All columns of data
in the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata13 = [time kdata];
%    my_save(directory, 'Intkneedata13.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
```

```
adata13 = [time adata];
%    my_save(directory, 'Intankledata13.txt', adata, precision)
%===========================Next Stride=====================%
data = kindata(:,:);
FramePrior2Contact(14) = floor(GCtime(14)*ViconFs);              %Frame before contact
FrameAfterToeOff(14) = ceil(TOtime(14)*ViconFs);                 %Frame after toe off
data = [data(FramePrior2Contact(14):FrameAfterToeOff(14), :)]; %All columns of data
in the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata14 = [time kdata];
%    my_save(directory, 'Intkneedata14.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata14 = [time adata];
%    my_save(directory, 'Intankledata14.txt', adata, precision)
%===========================Next Stride=====================%
data = kindata(:,:);
FramePrior2Contact(15) = floor(GCtime(15)*ViconFs);              %Frame before contact
FrameAfterToeOff(15) = ceil(TOtime(15)*ViconFs);                 %Frame after toe off
data = [data(FramePrior2Contact(15):FrameAfterToeOff(15), :)]; %All columns of data
in the rows GC->TO

timedata = data(:, TimeCol);
kneedata = data(:, KneeFlex);
ankledata = data(:, AnkleFlex);

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
kdata = interp1(timedata, kneedata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
kdata15 = [time kdata];
%    my_save(directory, 'Intkneedata15.txt', kdata, precision)

step = 1;
time= linspace(timedata(1), timedata(end), 100/step+1)';
```

```
adata = interp1(timedata, ankledata, time, 'linear');
time= linspace(0, 100, 100/step+1)';
adata15 = [time adata];
%    my_save(directory, 'Intankledata15.txt', adata, precision)

%==========================
% Open up the Interpolated files to average the data
% and create mean/sd plots  Start with the knee data.
%==========================

AveKnee = (kdata3 + kdata4 + kdata5 + kdata6 + kdata7 + kdata8 ...
   + kdata9 + kdata10 + kdata11 + kdata12)/10;
StdevKnee = sqrt(((kdata3.^2 + kdata4.^2 + kdata5.^2 + kdata6.^2 + kdata7.^2 +
kdata8.^2 ...
   + kdata9.^2 + kdata10.^2 + kdata11.^2 + kdata12.^2)/10)-AveKnee.^2);
KPlusSD = AveKnee(:,2) + StdevKnee(:,2);
KMinusSD = AveKnee(:, 2) - StdevKnee(:, 2);

AveAnk = (adata3 + adata4 + adata5 + adata6 + adata7 + adata8 ...
   + adata9 + adata10 + adata11 + adata12)/10;
StdevAnk = sqrt(((adata3.^2 + adata4.^2 + adata5.^2 + adata6.^2 + adata7.^2 + adata8.^2
...
   + adata9.^2 + adata10.^2 + adata11.^2 + adata12.^2)/10)-AveAnk.^2);
APlusSD = AveAnk(:,2) + StdevAnk(:,2);
AMinusSD = AveAnk(:, 2) - StdevAnk(:, 2);

%==============================================
% Find the polynomial to fit best starting with a 6th order polynomial and
% ranging to a 10th order.  Plot the polynomials on the graph and then save
% out the best poly as a vector for the Spanning set analysis.
%==============================================

warning off MATLAB:polyfit:RepeatedPointsOrRescale;

for p= 6:1:15

   plot(time, AveKnee(:, 2), 'k --');
   hold on
   plot(time, KPlusSD, 'r');
   hold on
   plot(time, KMinusSD, 'r');
   hold on
   ylabel('Knee Angle (degrees)')
   xlabel('Percent Stance (%)')
   title('Average Knee Angle Over Stance')
```

```
   KneeUpper = polyfit(time, KPlusSD, p);
   KneeTop = polyval(KneeUpper, time);
   plot(time, KneeTop, 'g --');
   KneeLower = polyfit(time, KMinusSD, p);
   KneeBot = polyval(KneeLower, time);
   plot(time, KneeBot, 'g --');
   drawnow
   pause(3)
   hold off

   KneeRMS(p) = rms(KneeTop'- KPlusSD');

end

fprintf(1,'\n');
Kpoly = input('    Which polynomial was the best fit for the curves? ');
fprintf(1,'\n');
KneeUpper = polyfit(time, KPlusSD, Kpoly)
KneeLower = polyfit(time, KMinusSD, Kpoly)

%==========================================
% Now go for the ankle graphs
%==========================================
for p= 6:15

   plot(time, AveAnk(:, 2), 'k --');
   hold on
   plot(time, APlusSD, 'r');
   hold on
   plot(time, AMinusSD, 'r');
   hold on
   ylabel('Ankle Angle (degrees)')
   xlabel('Percent Stance (%)')
   title('Average Ankle Angle Over Stance')

   AnkleUpper = polyfit(time, APlusSD, p);
   AnkTop = polyval(AnkleUpper, time);
   plot(time, AnkTop, 'g --');
   AnkleLower = polyfit(time, AMinusSD, p);
   AnkBot = polyval(AnkleLower, time);
   plot(time, AnkBot, 'g --');
   drawnow
   pause(3)
   hold off

   AnkleRMS(p) = rms(AnkTop' - APlusSD');
```

```
end

fprintf(1,'\n');
Apoly = input('    Which polynomial was the best fit for the curves? ');
fprintf(1,'\n');
AnkleUpper = polyfit(time, APlusSD, Apoly)
AnkleLower = polyfit(time, AMinusSD, Apoly)

%========================================
% Determine the spanning set value for the knee and ankle
%========================================

KneeSS = rms(KneeUpper'- KneeLower')
AnkleSS = rms(AnkleUpper' - AnkleLower')

%========================================
% Comment out from here down if included in another program, else, leave
% uncommented
%========================================

for i = 1:length(KneeUpper)
   ss(i) = s;
   cc(i) = c;
   tt(i) = t;
end

alldataKVectors(:,:) = [ss' cc' tt' KneeUpper' KneeLower'];
clear ss cc tt
for i = 1:length(AnkleUpper)
   ss(i) = s;
   cc(i) = c;
   tt(i) = t;
end

alldataAVectors(:,:) = [ss' cc' tt' AnkleUpper' AnkleLower'];
clear ss cc tt

alldataSpanSet(:,:) = [s' c' t' KneeSS' AnkleSS'];

for i = 1:15
   ss(i)= s;
   cc(i) = c;
   tt(i) = t;
   pp(i) = i;
   kk(i) = Kpoly;
```

```
  aa(i) = Apoly;
end
alldataRMS(:,:) = [ss' cc' tt' pp' kk' KneeRMS' aa' AnkleRMS'];
clear ss cc tt


%output data using a function 'my_save'
if strcmp(savedata, 'yes')
  my_save(outputdirectory, outputfileSpanSet, alldataSpanSet, precision);
  my_save(outputdirectory, outputfileKVectors, alldataKVectors, VectorPrecision);
  my_save(outputdirectory, outputfileAVectors, alldataAVectors, VectorPrecision);
  my_save(outputdirectory, outputfileRMS, alldataRMS, precision);
end

%----------------------------clean up---------------------------------
%       clear;
```

Program for function to save the files out:

```
%Function: my_save(directory, filename, data, precision)
%
%This function will save data to a specified file with a specified precision
%

function my_save(directory, filename, data, precision)

    %initialize variable
    all_column_info = [];

    %change directory
        temp = pwd;
        eval(['cd ' directory]);

    %open the file to write to
        fid=fopen(filename, 'w');

    %make quote notation
        q="";

    %check the size of the data array
        [rows columns] = size(data);

    %Create the necessary write commands

        column_precision = int2str(precision);
        column_info = ['%5.' column_precision 'f'];
```

```
    for i = 1:columns
            all_column_info = [column_info ' ' all_column_info];
    end

%transpose the output data array because the print command writes
%column 1, then column 2, ...
    data=data';

%create command line
    print_command = ['fprintf(fid,' q all_column_info '\n' q ', data);'];

%save data
    eval([print_command]);

%close file
    fclose(fid);

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

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Abstracts:
Griffin JR, Mercer JA, Dufek JS. (2006). *Preliminary Analysis of the Kinematic Comparison of Running Barefoot and in the Nike FREE 5.0 on a Treadmill.* 27th Annual Meeting, Southwest American College of Sports Medicine

Bhanot, K, Mercer JA, Dufek JS, Freedman, J, House T, Griffin JR, (2006). *Effect of Change in Running Speeds on Shock Attenuation among Children.* 27th Annual Meeting, Southwest American College of Sports Medicine

Griffin JR, Dufek JS, Mercer JA, Teramoto K, DeLion D. (2006). *Lower Extremity Geometry as a Predictor of Shock Attenuation during Running.* Medicine & Science in Sports & Exercise: Volume 38(5) Supplement May 2006 p S122-S123.

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Thesis Title:
Kinematic comparison of Running Barefoot and in the Nike Free 5.0

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