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The effects of local muscle fatigue on shock attenuation characteristics during running

Kaori Teramoto
University of Nevada, Las Vegas

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THE EFFECTS OF LOCAL MUSCLE FATIGUE ON SHOCK ATTENUATION CHARACTERISTICS DURING RUNNING

by

Kaori Teramoto
Bachelor of Science
Utah State University
2003

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
August 2006

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Kaori Teramoto

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The Effects of Local Muscle Fatigue on Shock Attenuation Characteristics During Running

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

Master of Science in Kinesiology

Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

The Effects of Local Muscle Fatigue on Shock Attenuation Characteristics During Running

by

Kaori Teramoto

John A. Mercer, Ph.D., Examination Committee Chair
Associate Professor of Kinesiology
University of Nevada, Las Vegas

The purpose of this study was to examine shock attenuation (SA) characteristics as well as stride characteristics before and after a fatigue protocol of the ankle dorsiflexors while running on a treadmill. Thirteen females (25.4 ± 3.8 yrs; 63.2 ± 8.9 kg; 164.3 ± 3.1 cm) ran at the same (preferred) speed prior to and following bilateral local muscle fatigue of the ankle dorsiflexors. The fatigue protocol consisted of five sets of maximal concentric and eccentric contractions with a 15-second rest between the sets. Accelerometers (1004 Hz) were securely mounted on the distal aspect of the tibia and on the forehead. Head impact acceleration (ahead) and leg impact acceleration (aieg) over 10 consecutive strides per subject-condition were selected and used to quantify SA. Paired t-tests were used to compare each dependent variable (SA, ahead, aieg, stride frequency, stride length) between conditions (running before vs. after the fatigue protocol). Results indicated SA was 4.2% greater when running after the fatigue protocol [78.4 ± 6.1 % (mean ± std)] than when running before the fatigue protocol (74.2 ± 6.6 %; p < .05). Additionally, aieg was, on average, 1.7 g greater during running after (6.0 ± 2.4 g) than
before (4.3 ± 1.6 g) the fatigue protocol (p < .05). a\textsubscript{head} exhibited no significant
difference before and after the fatigue protocol. Furthermore, stride frequency was 1.4%
greater when running after the fatigue protocol (p < .05). There was no statistical
difference in stride length (p = .053). These results indicate that SA and a\textsubscript{leg} were
sensitive to local muscle fatigue, with more shock being attenuated through body along
with increased a\textsubscript{leg} during fatigued running. The increased a\textsubscript{leg} and SA suggest that local
muscle fatigue contributes to the incapability of the musculoskeletal system to maintain
the impact acceleration at the leg segment level; however, runners' systems may have
adjusted to compensate for local fatigue. Therefore, the ankle dorsiflexors may play a
role in the development of running related injuries.
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ACKNOWLEDGMENTS

There are so many people who helped and guided me to pursue my goal of gaining an education in the United States of America. I would like to thank all of the faculty at the University of Nevada, Las Vegas, and at Utah State University, especially Dr. John A. Mercer, who has been a patient and generous mentor and advisor to me. His excellent scientific expertise and his friendly character helped me develop my research idea freely. I would also like to thank Dr. Janet S. Dufek, who always gave me energy as I worked on my projects and thesis. I thank them for their help and encouragement when I was struggling. I wish to thank Dr. Brent C. Mangus, who has helped me relax with his knowledge and understanding of Japanese people and the culture. I also appreciate the expertise of Dr. Edward S. Neumann, who has taught me important aspects of human gait.

There are also specific people, graduate student-colleagues: Julia Freedman who helped me collect data, Janet Griffin who inspired me with her deep knowledge of our field, and Tiffany Zachry, who taught me the importance of writing. I have learned much through interacting with friends in the lab: Dave Delion, Amanda Tritsch, Katie Orzechowski, and Anthony House. I thank them for their patience and humor.

I could not have achieved this goal without the love from my family: my parents, Takeshi and Kuniko Akinaga, my sisters, Maki and Yusa. Although they live far away from the U.S., their love and support has always reached me. Finally, I wish to thank my husband, Masaru-san for his support during our Master’s degree pursuits. I believe his bold and clear-sighted vision has been and will be helpful for our successful journey.
CHAPTER 1

INTRODUCTION

Running is a popular activity for many people to include in their daily exercise since it is a convenient activity and can induce physiological stress to increase general fitness. Unfortunately, many runners have an experience of running-related injuries in their lower extremities; especially overuse running injuries (James, Bates, & Osternig, 1978; Nigg, 1986). The incidence of overuse running injuries in the lower extremities among runners range up to 75% (Van Mechelen, 1995; Macera, 1992), with 70 to 80% of all running-related injuries occurring at the knees and below (Van Mechelen, Hlobil, & Kemper, 1992). Examples of overuse running injuries are: patella femoral pain syndrome, tibial stress syndrome, tibial stress fracture, and Achilles tendonitis (Taunton, Ryan, Clement, McKenzie, Lloyd-Smith, & Zumbo, 2002). One of several hypotheses is that overuse running injuries occur when the musculoskeletal system undergoes repetitive forces, which generates a fatigue effect over time beyond the capability of the specific structure to repair on normal biology (Stanish, 1984). However, the exact mechanism of overuse running injuries is not fully understood.

Overuse running injuries result from a complex interaction of many factors (Messier, Davis, Curl, Lowery, & Pack, 1991). These factors can be classified as either extrinsic or intrinsic factors (Messier, & Pittala, 1988). Extrinsic factors are identifiable factors external to a runner that increase the runner's risk of overuse running injuries such as
training errors (James et al., 1978; Messier et al., 1991). Training errors include a sudden increase in weekly running distance without gradual build-up, and/or a sudden change in running surfaces (James et al., 1978; Messier et al., 1991; Brill, & Macera, 1995). For example, James et al. (1978) reported that 60% of running-related injuries were associated with training errors. Intrinsic factors are identifiable factors within a runner. One example is anatomical abnormality (James et al., 1978; Messier, & Pittala, 1988). It has been reported that a runner’s range of plantar and dorsiflexion is related to overuse running injuries (Messier, & Pittala, 1988). Messier and Pittala (1988) reported that a group of runners with a great range of motion in plantar and dorsiflexion had more injuries than a group with less range of motion in the ankle joint.

There is a wealth of research examining extrinsic and intrinsic features by studying kinetics (e.g. GRF) and/or kinematics (e.g. position of the foot) during running in order to understand overuse running injury mechanisms; however, there is no research suggesting a link between SA during the foot-ground contact and overuse injuries. In order to better understand the mechanism of overuse running injuries, it is essential to evaluate additional biomechanical measures such as SA at the foot-ground contact.

There is little research on the role muscle fatigue may play in overuse injuries. A role of muscles is to dissipate and/or neutralize the stress on bones by eccentric contraction that acts opposite to a bending moment (Hill, 1962). Therefore, muscle weakness or fatigue may reduce the ability of muscle to work as a shock absorber. Since some magnitude of shock is attenuated as a result of the muscle contractions, the musculoskeletal system may receive greater stress if the muscles are fatigued. Researchers examined the effects of whole body fatigue on SA concurrent with $a_{leg}$ and
head impact accelerations ($a_{\text{head}}$) during the foot-ground contact of running (Mercer, Bates, Dufek, & Hreljac, 2003; Derrick, Dereu, & Mclean, 2002). However, it does not necessarily mean that the local muscles of the lower extremities were fatigued when the effects of whole body fatigue were investigated. In order to understand how muscles contribute to SA during running, it is helpful to generate local muscle fatigue and examine SA characteristics.

Presently, there is limited research on how muscle fatigue influences SA during running. Furthermore, there is little or no research on how fatigue of specific muscles may influence SA. This knowledge is important in order to understand features that influence SA – how SA may play a role in overuse injury mechanisms. Therefore, the purpose of this study was to examine the effects of local muscle fatigue of the ankle dorsiflexors on shock attenuation as well as stride characteristics during running.

**Purpose of the Study**

The purpose of this study was to examine the effects of local muscle fatigue of the ankle dorsiflexors on shock attenuation as well as stride characteristics during running.

**Research Hypothesis**

**Research Hypothesis:** Shock attenuation during running will differ between non-fatigued and fatigued ankle dorsiflexors.

**Null Hypothesis:** Shock attenuation during running will not differ between non-fatigued and fatigued ankle dorsiflexors.
1. Independent variable: Fatigue level

2. Dependent variable: Shock attenuation, leg impact acceleration, head impact acceleration, stride frequency, and stride length
Definitions

**Acceleration**: Rate of change in velocity.

- **Head impact acceleration** \( (a_{\text{head}}) \): The acceleration recorded by an accelerometer mounted on the forehead.
- **Leg impact acceleration** \( (a_{\text{leg}}) \): The acceleration recorded by an accelerometer mounted on the medial aspect of the distal tibia.

**Fatigue**: Reduction in the force generating capacity.

- **Local muscle fatigue**: Reduction in the force generating capacity of a single muscle group.
- **Whole body fatigue**: Overall cardiovascular and muscular fatigue.

**Overuse running injuries**: Injuries occurring when the musculoskeletal system receives stress over a period of time, causing fatigue effects beyond the capabilities of a specific structure.

**Shock attenuation (SA)**: The process of attenuating shock during locomotion and therefore reducing the impact magnitude between segments of the body. Operationally, it is the measure of peak impact reduction of leg acceleration and head acceleration. The formula is:

\[
SA = \left(1 - \frac{\text{Head Impact Acceleration}}{\text{Leg Impact Acceleration}}\right) \times 100
\]

**Shock wave**: Wave initiated by the foot-ground contact and travels through the musculoskeletal system up to head. It is typically seen in the head profile approximately 10 ms after it is seen in the leg profile (Derrick, Hamill, Caldwell, & Graham, 1998).
**Stance phase**: The period from the initial contact to toe off.

**Stride frequency**: Linear kinematic parameter. The number of strides taken in a given amount of time.

**Stride length**: Linear kinematic parameter. The distance covered by one stride.

**Assumptions**

1. The validity and reliability of the results relied on the subjects. It was assumed that all instructions were given to the subjects, and that they followed the instructions during the experiments.

2. The subjects were healthy collegiate females. They had no history of surgical intervention, chronic pain, orthotic use or current injury in their lower extremities and had experience of treadmill running.

**Limitations**

1. The results of the study cannot be inferred to the groups of people other than healthy collegiate female populations.

2. The termination point of the fatigue protocol depends upon the mixture of central fatigue (performer’s psychological limit) and peripheral fatigue (performer’s physiological limit). It does not necessarily mean that a subject’s local muscle becomes fatigued when the subject terminated the fatigue protocol.
CHAPTER 2

REVIEW OF THE LITERATURE

Shock Attenuation

Shock attenuation (SA) is the phenomenon of decreasing the magnitude of the shock wave during running. The shock wave is generated each time a runner’s foot contacts the ground. It transfers eventually all the way up to the top of the runner’s head. In addition, it runs through the musculoskeletal system components such as muscles and bones, and soft tissue such as fat. These structures absorb the shock wave together with joint movements such as knee flexion (Derrick, 2004). To quantify SA, the accelerations of two different segments are measured during running. Typically, one acceleration is recorded at the medial aspect of distal tibia and the other at the forehead along with the midline of the body. These sites are commonly chosen for measuring SA (Mercer, Vance, Hreljac, & Hamill, 2002; Mercer, Devita, Derrick, & Bates, 2003; Derrick et al., 1998; Teramoto, Griffin, Dufek, Mangus, & Mercer, 2005). SA was also obtained by acceleration of tibia and sacrum (Mizrahi, Verbitsky, & Isakov, 2000a; Voloshin, Mizrahi, Verbitsky, & Isakov, 1998). In addition to acquiring SA by the accelerations of different segments, it has been quantified using the ground reaction force (GRF) (Lafortune, Lake, & Hennig, 1995). Lafortune et al. (1995) used GRF and tibial acceleration to understand the transmission of the shock wave during the stance phase of running. To understand
the relationship between the GRF and acceleration, the concept of the GRF will be discussed in later of this chapter.

One method of quantifying SA is to extract the acceleration peaks from the time domain data set, and evaluate how much acceleration is reduced between different segments of the body (Teramoto et al., 2005).

![Stance Phase Data](image)

**Figure 1:** Typical leg acceleration profiles during running for a subject. The discrete points between B and E represent the foot-ground interaction during running.
Stance Phase

Figure 2: Typical head acceleration profiles during running for a subject. The first peak was selected as the head impact acceleration and used to quantify SA.

The accelerometer data from the tibia (leg impact acceleration or $a_{\text{leg}}$) and the forehead (head impact acceleration or $a_{\text{head}}$) allow one to calculate SA and determine how much shock is absorbed. SA is calculated by the following equation:

$$SA = \left(1 - \frac{\text{Head Impact Acceleration}}{\text{Leg Impact Acceleration}}\right) \times 100$$

Factors Influencing Shock Attenuation

SA is quantified by the acceleration of different segments; therefore, the factors, which influence accelerations experienced by the body segments, can affect SA. The acceleration representing the rate of body segments' velocities, depends on the magnitude of the GRF (Derrick, 2004; Lafontune et al., 1994). In addition, the relationships between position, velocity, acceleration, and the GRF curves are strongly related one another.
(Bobbert, Schamhardt, & Nigg, 1991). Therefore, theoretically any changes in position, velocity, acceleration, and the GRF influence SA.

Ground Reaction Force (GRF)

One of the factors affecting SA is the GRF. According to Newton’s third law, “... to every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal and directed to contrary parts” (Hamill & Knutzen, pp 352, 2003). When a runner's foot strikes the ground, the surface pushes back against the runner with equal force in the opposite direction, which is referred to as GRF (Liu & Nigg, 1999; Hamill & Knutzen, 2003).

The GRF is measured using force plates, and is subdivided into three components: vertical force (vGRF), anterior posterior force (Fy), and medio-lateral force (Fx) (Nigg, 1986; Hamill & Knutzen, 2003). The vGRF – time profile provides useful information in order to evaluate vertical impacts on the human body while running (Feehery, 1986; Messier et al., 1991), to develop shoe midsoles (Nigg, 1986), and to understand etiologic factors associated with overuse running injuries (Messier et al., 1991).

Typically, vGRF has two distinctive force peaks during a stance phase of running (Figure 3).
When a runner’s foot strikes the ground, the vGRF increases to the first peak within the first 10% of the stance phase, or the first 10 – 30 ms (F1 in the Figure 3) (Hreljac, 2004). The first peak is referred to as passive peak (Hamill & Knutzen, 2003). It is also called passive peak because the time of occurrence is too short, therefore humans cannot manipulate the peak by muscle control (Nigg, 1986). However, the impact forces presented by vGRF during this phase are influenced by different factors (Liu & Nigg, 1999). One of the examples is the footfall pattern of the runners (Hamill & Knutzen, 2003; Cavanagh & Lafortune, 1980). This suggests that this phase of Fz is determined by the runners’ kinematics of the lower extremities prior to the contact with the ground. In other words, the magnitude of vGRF during this phase can alter if the runners change their geometry of lower extremities before the ground contact.

The second peak is referred to as active peak which occurs within the latter 60 – 75% of the stance phase (F2 in Figure 3) (Hreljac, 2004). During this period, the foot pushes
the ground backward and in return the ground accelerates the body off the ground (Hamill & Knutzen, 2003). According to Nigg (1986), the movements such as walking and running styles greatly contribute to the changes during this phase.

Ground Reaction Force and Overuse Running Injuries

Forces measured with a force platform, the GRF may provide significant information about overuse running injuries (Messier et al., 1991; Cavanagh, & Lafortune, 1980). Running is a series of collisions with the ground and a runner strikes about 600 times per kilometer (McMahon, & Greene, 1979; Cavanagh, & Lafortune, 1980). In addition, a runner experiences 1.5 to 5 body weights during the stance phase of running (Cavanagh, & Lafortune, 1980). The greater forces within the short periods of time can be associated with overuse running injuries (Clement, Taunton, & Smart, 1984). However, we need to use caution when discussing the relationship between GRF and overuse running injuries. There is a misinterpretation that the GRF acts on the lower extremities only, which leads to overuse running injuries in legs or feet (Hamill, & Knutzen, 2003). The force is applied at the foot first at the ground contact; however, it reflects the acceleration of a runners’ center of mass.

After a runner receives impact forces, as measured by GRF, the forces are reduced by human’s rigid structures such as the curves of vertebral columns, bones, articular cartilage in synovial joints, as well as soft structures such as muscles, ligaments, tendons, and synovial fluid (Nordin, & Frankel, 2001). These structures attenuate some of the forces, however, other forces transmit through the musculoskeletal systems. If the unattenuated forces are applied repeatedly above the tensile limit of a runner’s specific structure over time, then it can cause overuse running injuries (Rolf, 1995).
The rate of change in the GRF to the passive peak is referred to as the loading rate (Fig 1) (Hamill & Knutzen, 2003). Some authors examined the relationship between loading rate and injuries (Radin, Yang, Riegger, Kish, & O'Connor, 1991; Richie, DeVries, & Endo, 1993). Radin et al. (1991) identified biomechanical differences in gait patterns between a group of individuals which experienced mild knee pain and a group that had no knee pain. The specific finding of the study was that the knee pain group applied Fz that was more quickly and greater magnitude of impact forces than no knee pain group (Radin et al., 1991). These findings suggest that a greater impact force, within a short period of time, is associated with a higher risk of injury. The loading rate to passive peak seems to be a good indicator to understand the relationship between Fz and the occurrence of overuse running injuries.

Fatigue

Although the exact cause of muscle fatigue still remains unclear, there are factors that have been accepted as contributors to muscle fatigue. In order to conduct a fatigue protocol, it is important to understand the concept of muscle fatigue, therefore, the factors are discussed in this section.

Muscle fatigue is defined as the inability of muscle to maintain the force during sustained or repeated muscle contractions (Gibson, & Edwards, 1985). The causes of muscle fatigue involve either central or peripheral factors. Central fatigue is attributed to the reductions in the number of functioning motor units or in motor unit firing frequency, originated in the central nervous system (Powers, & Howley, 2004). Central fatigue includes a performer’s motivation or psychological limit, which may impair transmission
of the neural signal to the spinal cord and alter the state of fatigue (Powers, & Howley, 2004). Therefore, the psychological state of an individual performer should be taken into consideration when a fatigue protocol is conducted for research. Peripheral fatigue makes much more sense intuitively; it appears to be local fatigue affecting an isolated muscle group. Peripheral fatigue is firstly induced by metabolic inhibition of the contractile process and excitation-contraction coupling failure (Schillings, Stegeman, & Zwarts, 2005). The metabolic inhibition is caused by the accumulation of metabolites such as inorganic phosphate (Pi) and hydrogen ions (H\(^+\)). The accumulation of these substances (Pi and H\(^+\)) affects neuromuscular transmission and the muscle cell membrane. As a result, force generation by the muscle fiber is hampered (Powers, & Howley, 2004).

Booth and Thomason (1991) point out that measurements for muscle fatigue should be conducted immediately after a fatigue protocol or else the fatigue may be underestimated. Since speed of recovery from fatigue induced by the fatigue protocol can influence the measurements, it is necessary for researchers to design fatigue studies carefully.

**Fatigue and impact forces**

The effects of fatigue on impacts during running have been investigated. However, most of the research related to fatigue has focused on general metabolic fatigue and not on local muscle fatigue. Derrick, Dereu, and Mclean (2002) proposed that SA increased during fatigued running. Specifically, they found that leg peak acceleration significantly increased (6.11 ± 0.96 g to 7.38 ± 1.05 g), and head peak acceleration remained constant (1.56 ± 0.29 g to 1.66 ± 0.26 g). Similarly, Voloshin et al. (1998) observed an increase in leg peak acceleration during 30 minutes run among participants in the fatigue group.
They did not obtain head peak acceleration and did not present SA data. However, if they observed that head peak acceleration decreased or remains constant, they would have acquired greater SA for the fatigued group. Contrary to these findings, Mercer, Bates, Dufek, and Hreljac (2003) reported that SA did not increase during fatigued running. Moreover, there was not a significant difference in leg impact peak acceleration between non-fatigued and fatigued conditions. They mentioned that the complexity of fatigue and individual runners’ experience during a fatigue condition might yield different outcomes between studies.

Whether local muscle fatigue plays a role in SA during running is unclear. Flynn, Holmes, and Andrews (2004) investigated the effect of local muscle fatigue on the acceleration of the tibia by using the human pendulum methods. Their findings were that the leg peak acceleration significantly decreased following a fatigue protocol, which is contrary to the results of whole body fatigue. However, these findings might not represent dynamic biomechanics such as running or walking.

**Local Muscle Fatigue and Running**

Local muscle fatigue has been defined as a reduction in generating force by a specific site of muscle group (Mercer, Kindling, Arata, Hreljac, Dufek, & Bates, 1998). There has been a limited amount of research examining the effect of local muscle fatigue on running. Christina et al. (2001) examined the effect of local muscle fatigue on the GRF and ankle joint motion during running. They evaluated a) passive peak, b) active peak, c) loading rate to passive peak, and d) ankle angle at heel contact. It was observed that the loading rate to the passive peak in the Fz profile significantly increased following a fatigue protocol of the ankle dorsiflexors (Christina et al., 2001). In addition,
dorsiflexion angles between the toe and tibia, significantly decreased with fatigued ankle dorsiflexors (Christina, White, & Gilchrist, 2001).

In another study examining the relationship between the local muscles (quadriceps and hamstrings) fatigue on running mechanics, Mercer et al. (1998) found that there were not significant differences in maximum knee flexion between fatigued and non-fatigued conditions. The authors point out one possible explanation of these results. They reported that participants might not conduct an intense fatigue protocol. From this, central fatigue, which is described as a psychological fatigue, might occur. Hollege et al. (1997) state that central fatigue becomes major limitation in sports. Therefore, in the fatigue study, it is challenging to have participants reach the point where a single muscle group becomes fatigued.

Ankle Dorsiflexors

Ankle dorsiflexors include three major muscles: tibialis anterior, extensor digitorum longus, and extensor hallucis longus (Perry, 1992). For this study purpose, all three muscles are discussed together as ankle dorsiflexors. The size of the ankle dorsiflexors is not large compared to other muscle groups in the lower extremities, suggesting that the muscle groups do not generate much force (Powers, & Howley, 2004). Wickiewicz, Roy, Powell, Perrine, and Edgerton (1984) reported that the ankle dorsiflexors generated only 7.9% of the torque of the knee extensors, for example.

However, there are many roles that the ankle dorsiflexors play for human movements. The ankle dorsiflexors become active before and after the stance phase of the gait cycle (Perry, 1992). Specifically, electromyography (EMG) of the ankle dorsiflexors suggest
that these muscles fire in the two phases of the gait cycle: just before the initial contact (terminal swing phase); and initial contact. Totally, the ankle dorsiflexors are active for 50 – 80% of the running cycle (Reber, Perry, & Pink, 1993), suggesting that there is a higher risk of being fatigued. In addition, it appears that a fast eccentric contraction of the ankle dorsiflexors occur during the foot-ground contact phase of running, which attenuates shock (Gerritsen, Van den Bogert, & Nigg, 1995; Perry, 1992). Furthermore, it seems that the ankle dorsiflexors is among the muscles influencing by aging in the lower extremity of old fallers (Gehlsen, & Whaley, 1990).

Therefore, local muscle fatigue of the ankle dorsiflexors may be linking to a reduction or loss of the control of the movement around ankle, which results in changes in the initial ankle position during the foot-ground contact.

### Summary of Literature Review

Running is an activity that requires repetitive collisions with the ground, which can lead to high risk of overuse running injuries. The shock wave generated during the foot-ground contact is attenuated not only externally but also internally through the musculoskeletal structures of a runner. SA is a measure of the magnitude of impact force reduction between segments. Commonly it is quantified by a differential between the leg and head peak accelerations.

There is no research suggesting a link between the SA measure and the occurrence of overuse running injuries. However, a runner’s kinetic and kinematic behaviors or his/her running mechanics can reflect the SA measure. In addition, there is a wealth of research investigating the relationship between kinetic and kinematic variables and overuse injuries.
running injuries. Therefore, this literature review highlighted research investigating the change in the GRF, and its relationship with overuse running injuries.

In order to understand fatigue, the concept of muscle fatigue was discussed. The causes of muscle fatigue are categorized as either central or peripheral factors. Central fatigue includes a performer’s motivation, which may impair transmission of the neural signal to the spinal cord. Peripheral fatigue involves the accumulation of metabolites, which inhibits force generation by the muscle fiber. Both factors are important when the fatigue exercise is conducted in the laboratory setting.

The effects of fatigue on impacts during running have been investigated. However, the majority of research has focused on general metabolic fatigue. This literature review introduced studies with the type of fatigue regarding the leg and head peak accelerations, since these accelerations can affect SA. Regardless of the number of literature (Derrick et al., 2002; Mercer et al., 2003; Mercer 1999), the results are not consistent, perhaps because of the complexity of fatigue and individual runners’ experience during a fatigue condition.

Further, whether local muscle fatigue plays a role in SA during running is unclear. There has been a limited amount of research examining the effect of local muscle fatigue on running. The literature review included one study examining the GRF and another evaluating the knee flexion angles following a local fatigue exercise. The results of the former study (Christina et al., 2001) showed the differences between non-fatigued and fatigued running. However, the researchers of the latter study (Mercer et al., 1998) reported that there were not significant differences between two conditions.
In order to understand the role ankle dorsiflexors play in overuse running injuries, local ankle dorsiflexors fatigue was examined. The range of motion of the ankle dorsiflexors is not large; therefore, the muscle group does not generate much force compared to other muscle groups. However, ankle dorsiflexors are active for 50 to 80% of the running cycle. In addition, the ankle dorsiflexors attenuate impact forces at the foot-ground contact via eccentric contraction. Moreover, the ankle dorsiflexion strength is significantly diminished as we age compared to other muscle groups in the lower extremities (Gehlsen, & Whaley, 1990). Impact forces are firstly applied at the foot, and the forces have to be attenuated more by other musculoskeletal structures such as knee, hip joints unless the ankle dorsiflexors contract eccentrically. By fatiguing ankle dorsiflexors, it can be possible to understand the joint protective mechanisms and to determine how a runner manages impact forces during running.
CHAPTER 3

METHODS

Subjects

Thirteen female participants volunteered for this study (mass: 63.2 ± 8.9 kg; height: 164.3 ± 3.1 m; age: 25.4 ± 3.8 yrs, APPENDIX B). All subjects had no history of surgical intervention, chronic pain, orthotic use or current injury in their lower extremities and had experience of treadmill running. Prior to the data collection, the subjects gave written informed consent as approved by the Institutional Review Board at the University of Nevada, Las Vegas.

Instrumentation

After a self-directed warm-up, the subjects were instrumented with two uni-axial accelerometers (PCB Piezotronics, model #352C68-6 and #352C68; mass = 2 grams each) to record accelerations of leg and head segments. One accelerometer was mounted on the distal anterior-medial aspect of the tibia, and the other on the forehead along the midline of the body. The sensitive axes of each accelerometer were aligned vertically. Since accelerometers are sensitive to the movements of the soft tissue such as fat (Saha, & Lakes, 1977), the two accelerometers were fitted tightly using a compressive bandage and headgear. Accelerometer data were recorded at 1004 Hz using Bioware (Kistler; version: 3.21) data acquisition software for approximately 30 seconds to capture at least
10 consecutive strides. To selectively generate fatigue of the ankle dorsiflexors, DARD® (Power Systems Corp.) was chosen (Figure 4). DARD® is designed to isolate and strengthen the ankle dorsiflexors for enhancing performance in athletic situations. The subjects were provided a pair of laboratory running shoes (adidas; 606001) to wear during testing.

Experimental Protocol

The purpose of the experiment was to record acceleration data for leg and head segments as well as stride characteristics during running prior to and following a fatigue protocol. Thus, subjects completed two running conditions: running before and after completing a fatigue protocol. All subjects performed a two-minute running bout during which time data were collected for each condition. Following a self-directed warm-up of jogging for 3 minutes, the subjects ran the first condition (non-fatigued) at a “preferred speed” (20 minute jogging pace) and then, the subjects ran at the same speed as the first condition after completing a fatigue protocol.

Fatigue Protocol

After accelerometry data were collected for the non-fatigued running condition, each subject underwent the protocol for fatigue of the ankle dorsiflexors. Initially, the range of ankle motion was measured using a goniometer (APPENDIX B). Ankle dorsiflexors were fatigued bilaterally using repetitive concentric and eccentric contractions performed by an exercise device called DARD® (Figure 4). The participants sat on a mat and performed repetitive ankle upward (dorsiflexion) and downward (plantarflexion)
movements using the DARD®. Subjects were required to complete 5 sets before the data collection for the fatigued running condition. The subjects were instructed to complete as many repetitions as possible within each set until they were not able to continue the fatigue protocol. Therefore, the total number of repetitions for each set of the fatigue protocol was dependent on each individual subject (APPENDIX B). The first set of the protocol was used as a gauge to determine the necessary resistance plates for each individual participant. If the participant could dorsiflex more than 45 repetitions using 20 pounds (9.07 kg), one weight plate (10 pounds: 4.54 kg) was added to the exercise device. If less than 30 repetitions could be completed, one weight plate was removed. A metronome was set at 60 beats per minutes to maintain rhythm of the exercise. Subjects carried out a single cycle of the continuous ankle exercise in two seconds. Subjects were required to select a number in the fatigue severity scale during a rest of 10 seconds between sets (APPENDIX A). The DARD® was positioned next to the treadmill and allowed the subjects to move from the DARD® to the treadmill quickly after completing 5 sets. Once the fatigue protocol was completed, participants transferred immediately from the DARD® to the treadmill, and ran at the same speed as the first condition.
Data Reduction

The accelerometer data were converted to ASCII format and processed using custom laboratory software, MATLAB (version 6.5) for analysis (APPENDIX A). The steps included extracting ten data sets of leg and head accelerations during the stance phase for each condition. The criteria for extracting data were made relative to the leg acceleration profile (Figure 5). The peak impact accelerations for 10 consecutive strides for each condition were determined. Typical leg and head acceleration profile are illustrated in Figure 5 and Figure 6. Peak impact accelerations at the leg and head were extracted to quantify SA between two segments using the following equation.

\[
SA = \left( 1 - \frac{\text{Head Impact Acceleration}}{\text{Leg Impact Acceleration}} \right) \cdot 100
\]
Figure 5: Leg impact acceleration peaks chosen for quantifying shock attenuation.

Figure 6: Head impact acceleration peaks chosen for quantifying SA.

Data Analysis

The study design was repeated measure with the factor “fatigue level” (non-fatigue & fatigue) being within subjects. The dependent variables of interest were SA, leg peak
acceleration, head peak acceleration, stride frequency, and stride length. The independent variable of interest was fatigue level (i.e., non-fatigued, fatigued). Each dependent variable was analyzed independently across fatigue levels using paired $t$-test. Alpha level was set at .05.
CHAPTER 4

RESULTS

The amount of impact experienced by the leg (leg impact peak) and the amount of shock attenuated by the body (shock attenuation) were influenced while the runners' ankle dorsiflexors were fatigued. Shock attenuation (SA) was 4.2% greater when running after the fatigue protocol (78.4 ± 6.1%; p < .05) compared to running before the fatigue protocol (74.2 ± 6.6%) (Table 1; p < .05). Leg impact accelerations (\(a_{\text{leg}}\)) before and after the fatigue protocol were 4.3 ± 1.6 g and 6.0 ± 2.4 g, respectively, and were 40% greater during running with fatigued ankle dorsiflexors (Table 1; p < .05). Head impact accelerations (\(a_{\text{head}}\)) prior to and following the fatigue protocol were 1.1 ± 0.3 g and 1.2 ± 0.3 g, respectively, and were not different during running with or without fatigued ankle dorsiflexors (Table 1; p > .05).

<table>
<thead>
<tr>
<th>Head Impact Acceleration (g)</th>
<th>Non-fatigued 1.1 ± 0.3 g</th>
<th>Fatigued 1.2 ± 0.3 g*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg Impact Acceleration (g)</td>
<td>4.3 ± 1.6 g</td>
<td>6.0 ± 2.4 g*</td>
</tr>
<tr>
<td>Shock Attenuation (%)</td>
<td>74.2 ± 6.6 %</td>
<td>78.4 ± 6.1 %*</td>
</tr>
</tbody>
</table>

\* p < 0.05

Table 1: Group mean and standard deviation values for impact accelerations recorded at the head and leg segments as well as SA before and after the fatigued protocol.
Stride frequency was 1.4% greater when running after the fatigue protocol (non-fatigued: \(1.41 \pm 0.008\) Hz; fatigued: \(1.43 \pm 0.008\) Hz). There was a significant difference in stride frequency between non-fatigued and fatigued running in the ankle dorsiflexors (\(p < .05\)). Stride length before and after the fatigued protocol were 2.03 ± 0.07m and 2.02 ± 0.07m, respectively. There were no differences for stride length for either non-fatigued and fatigued running (\(p > .05\)).

Figure 7: Mean and standard error values for SA during non-fatigued and fatigued running. SA was 4.2% greater during the fatigued condition (\(p < .05\)).
Figure 8: Leg impact acceleration (Leg) and head impact acceleration (Head) during non-fatigued and fatigued running. $a_{leg}$ increased 40% during fatigued running ($p < .05$).

Figure 9: Stride frequency during non-fatigued and fatigued running. Stride frequency while fatigued increased ($p < .05$).
Figure 10: Stride Length during non-fatigued and fatigued running. There was no significant difference between conditions (p > .05).
CHAPTER 5

DISCUSSION

The purpose of this study was to examine shock attenuation (SA) characteristics during running following local muscle fatigue of the ankle dorsiflexors. The main observation was that when the ankle dorsiflexors were fatigued, SA increased by 4.2% compared to when the muscles were not fatigued (Table 1). Based upon this observation, the hypothesis that SA at the foot-ground contact of running would differ between non-fatigued and fatigued ankle dorsiflexors is tenable. Mathematically, the change in SA was due to a 40.0% increase in the leg impact accelerations (a_\text{leg}) while there was no significant change in the head impact accelerations (a_\text{head}) (Table 1).

Orientation of Accelerometers

One concern about the results of the present study was the possibility that the orientation of the leg accelerometer might have changed between the non-fatigued and fatigued running conditions. Derrick et al. (1998) observed the relationship between leg orientation at foot-ground contact of running and the stride length because the leg orientation changed as stride length was altered. It was reported that the maximal leg angles (deviation from the vertical line) was 2 degrees among different stride length conditions, and the leg impact acceleration was less than a 0.1 g change (Derrick et al., 1998). In the present study, there was little change in stride length between the non-
fatigued and fatigued running conditions, suggesting that the orientation of the leg
accelerometer may not have influenced the results.

Running Behavior during Non-fatigued Condition

Although there is little research on the effects of local muscle fatigue on SA, there is
a growing body of literature regarding SA during a variety of non-fatigued running
conditions. For example, during non-fatigued running at a constant speed, the
magnitudes of SA, a_{leg}, and a_{head} reported by Derrick et al. (2002) were 74.5 ± 5.4%, 1.6 ±
0.3g, and 6.1 ± 0.9g, respectively. Likewise, Teramoto et al. (2005) reported that SA was
84.4 ± 5.2%, the a_{head} was 0.5 ± 0.2g, and the a_{leg} was 3.0 ± 0.9g while running on a
treadmill with a medium level of shock absorption. In addition, Mercer et al. (2003)
observed that during non-fatigued running, a_{head} was 1.5 ± 0.5g and a_{leg} was 5.0 ± 1.6g.
Since SA was 74.2 ± 6.3%, a_{head} was 1.1 ± 0.3g, and a_{leg} was 4.3 ± 1.6g in the present
study, the results are reasonably similar to the previous findings when runners were not
fatigued.

Effects of Fatigue on Running

Local Acceleration and Shock Attenuation

To my knowledge, there have been no published studies on the effects of ankle
dorsiflexor muscle fatigue on SA. However, Mercer (1999) studied the influence of local
quadriiceps fatigue on SA. Contrary to the present findings, Mercer (1999) reported a
decrease in SA as a result of quadriiceps muscle fatigue. Furthermore, Mercer (1999)
reported an increase in a_{head} and a decrease in a_{leg} — and these observations are different
compared to what was observed in the present study. However, it seems that local muscle fatigue does influence SA, but the exact influence seems to be dependent on the specific muscles that are fatigued.

*Ground Reaction Force and Joint Angle*

Although there is limited research on the influence of local muscle fatigue on SA, there is at least one comparable work investigating how local muscle fatigue influences the vertical ground reaction force and joint motions. Christina et al. (2001) examined the changes in the vGRF and the sagittal ankle angle during running prior to and following a fatiguing exercise of the ankle dorsiflexors. It was reported that the magnitude of passive peak and loading rate of the passive peak in the vGRF while fatigued, were greater than during non-fatigued running. In addition, Christina et al. (2001) observed that the runners' ankle angle was less dorsiflexed during fatigued running. The importance of this observation is that there seems to be a relationship between lower extremity geometry at impact and impact characteristics. Gerritsen et al. (1995) demonstrated that the magnitude of passive peak and loading rate in the vGRF increased as the initial angle between the foot and the ground at impact decreased. Although Christina et al. (2001) did not measure leg accelerations, the observation of increased passive peak and loading rate with local fatigue seems consistent with the observation of increased $a_{leg}$ since there does seem to be a relationship between vertical ground reaction force and $a_{leg}$ during the foot-ground contact phase of running (Gerritsen, et al., 1995; Lafortune et al., 1995). The increase in $a_{leg}$ observed in the present study may be a result of changing lower extremity geometry at impact, which may have caused an increase in the passive peak and loading rate in the vertical ground reaction force.
Whole Body Fatigue on Shock Attenuation Characteristics

In a study of how whole body fatigue may influence SA, Derrick et al. (2002) reported that SA increased during an exhaustive run at a constant speed. The increase in SA from 74.5 ± 5.4% (non-exhaustive run) to 77.5 ± 4.1% (exhaustive run) was due to increased $a_{leg}$ from 6.1 ± 0.9 g (non-exhaustive run) to 7.4 ± 1.1 g (exhaustive run) along with no changes in $a_{head}$ (1.6 ± 0.3 g; non-exhaustive run, 1.7 ± 0.3 g; exhaustive run). Similarly, other researchers reported an increase in $a_{leg}$ during 30 minutes of exhaustive running (Volosin et al., 1998; Verbitsky, Mizrahi, Voloshin, Treiger, & Isakov, 1998; Mizrahi et al., 2000a). However, these researchers did not report head impact accelerations. If the impact accelerations were recorded and remained the same between non-fatigued and fatigued conditions, as is usually the case, it would be expected that SA would have increased. An explanation for the similar results between the present study examining the influence of local muscle fatigue and the previous studies examining the influence of whole body fatigue is that the runners' ankle dorsiflexors may have fatigued during the exhaustive running.

In contrast, Mercer et al. (2003) demonstrated that fatigued running at a constant speed caused a decrease in SA from 87.5% (non-fatigued run) to 81.9% (fatigued run). There was no significant difference in impact accelerations recorded from the head or leg segments during non-fatigued and fatigued runs (Mercer et al., 2003). The reason for the different outcomes between the study done by Mercer et al. (2003) and the previous studies is not clear. Mercer et al. (2003) conjectured that the differences could have been due to the level of fatigue runners achieved since they used a different fatigue protocol (i.e., graded exercise test) that involved changes in running speed compared to the
protocol that required the subjects to run at a constant speed of running to exhaustion (Derrick et al., 2002). These findings may suggest that runners respond to fatigue differently when they do not run at a constant speed.

**Individual Subject Response to Fatigue**

It is presently not clear how fatigue protocols influence the fatigue response relative to SA. For example, the termination point of a fatigue protocol may determine the level of fatigue that can be achieved. In the study of Christina et al. (2001), the subjects performed 15 repetitions of concentric and eccentric contraction exercises of the ankle dorsiflexors at a level of 30%, 50%, and 75% of the ankle’s 1 RM. At each level, the subjects were required to continue the exercise until their range of motion of the ankle joints decreased. In the present study, the fatigue protocol was terminated when the subjects could no longer keep up with the rhythm of the metronome (60 bpm), and/or could no longer reach 50% of the range of ankle motion. Although consistent criteria were used to end the fatigue protocol, there was a possibility that some subjects may not have reached fatigue. In order to determine an individual subject’s unique level of fatigue objectively, a fatigue severity scale was used (1 – None, 2 – Very mild, 3 – Mild, 4 – Moderate, 5 – Severe, and 6 – Very severe; APPENDIX A) after each set of the fatigue protocol. Subjects reported an average of 5.1 ± 0.4 points on the severity scale. In addition, eleven of the 13 subjects reported a fatigue level of 6 (very severe) after the 5 sets were completed, suggesting that they reached a relatively high intensity of fatigue before the test was terminated (Figure 11). However, since there was a range of severity responses, it is likely that subjects experienced different levels of fatigue compared to each other (APPENDIX B).
To explore whether or not the subjects responded uniquely to the fatigue of the ankle dorsiflexors, individual data sets were examined regarding all variables: SA, leg impact acceleration, head impact acceleration. In addition, stride frequency and stride length were also inspected in order to compare the non-fatigued run with the fatigued run.

To examine whether individual subject’s SA, $a_{\text{leg}}$, and $a_{\text{head}}$ changed meaningfully following the fatigue protocol, the criteria were determined based on the research and literature. The change in SA above and below 3%, the change in $a_{\text{leg}}$ above 0.5 g were considered meaningful (Figure 12; Figure 13) since it was observed that at least 3% of change in SA and 0.5 g of change in $a_{\text{leg}}$ were meaningfully different between conditions in several studies (Derrick et al., 2002; Teramoto et al., 2005). In addition, the changes within the range of ± 3% of SA and ± 0.5 g of $a_{\text{leg}}$ were considered as non-significant (Mercer et al., 2003; Teramoto, et al., 2005). Previous studies indicate that the head
impact accelerations are relatively stable within a 0.3 g range (Mercer et al., 2003; Derrick et al., 2002; Hamill, Derrick, & Holt, 1995). Thus, the range within ± 0.3 g for the head impact accelerations was considered as non-significant (Figure 14).

Figure 12: The difference in SA for the non-fatigued and fatigued running conditions. The range within the dotted lines is determined as not significant change.
Figure 13: The difference in $a_{\text{leg}}$ for the non-fatigued and fatigued running conditions. The leg impact acceleration below the dotted line is determined as not significant change.

Figure 14: The difference in $a_{\text{head}}$ for the non-fatigued and fatigued running conditions. The head impact acceleration between the dotted lines is determined as not significant change.
Six of the 13 subjects had at least a 6.0% change in SA after the fatigue protocol (Figure 12). The other seven subjects did not have a meaningful increase or decrease in SA (Figure 12). Ten of the 13 subjects had at least a 0.5 g change in a_{leg} while fatigued, with the remaining subjects having no real change in a_{leg} (Figure 13). Eleven of the 13 subjects had no real change in a_{head}, with the remaining two subjects having at least 0.3 g change in a_{head} (Figure 14).

Among the 13 subjects, there was a wide range of responses to fatigue from −2.6% to 14.0% changes for SA and 0% to 4.4% changes for a_{leg}. Furthermore, even though there was no change in a_{head} statistically for the group between conditions, two of the subjects actually had quantitatively greater a_{head} than the criteria of above 3 g (Figure 14). The reasons for the wide range of responses to fatigue by the subjects were not clearly evident. It is conjectured that the wide range of response was due to the manner of how a subject accommodated to fatigue and/or the magnitude of actual fatigue elicited. Further research is needed to better understand the importance of individual responses to fatigue.

As secondary kinematic parameters, stride frequency and stride length were also examined. Eleven of the 13 subjects increased stride frequency while fatigued (a mean increase of 2%; Figure 15). Among the 13 subjects, there was a range of responses to fatigue from −3% to 4% changes in stride frequency. There was no statistical difference in stride length (p = 0.053); however, 11 of the 13 subjects decreased stride length during the fatigue run (a mean decrease of 1.6%; Figure 16). Based on these observations, it is clear that the individual subjects had unique responses to local muscle fatigue in the present study.
Figure 15: The change in stride frequency for individual subjects between non-fatigued and fatigued conditions.

Figure 16: The change in stride length for individual subjects between non-fatigued and fatigued conditions.
Hypotheses Explaining the Observations in the Present Study

There are three plausible hypotheses explaining why leg impact acceleration – and therefore, SA – changed when a runner was fatigued in the present study. These are: the change in the runner’s lower extremity geometry; a loss and/or reduction of shock absorbing capability of the ankle dorsiflexors; and a combination of these two hypotheses.

Lower Extremity Geometry Alterations

The change in \( a_{\text{leg}} \) while running with ankle dorsiflexor fatigue may have been due to alterations in geometry of the lower extremities. The present study does not provide any direct measurement of joint angles in the lower extremities or control the lower extremity geometry. Therefore, it is not possible to compare the changes in geometry in the lower extremities before and after the fatigue protocol. However, a simulation conducted by Gerritsen et al. (1995) suggests that a less dorsiflexed foot angle at impact would allow the passive peak in the vertical reaction force increased by 85 N per degree of dorsiflexion (Gerritsen et al., 1995). The importance of this study is that the mathematical modeling and simulation was undertaken simply to understand the relationship between kinematics at the foot-ground contact of running and passive peak in the vertical ground reaction force.

Loss or Reduction of Shock Absorbing Capability of Muscles

A secondary hypothesis explaining the increase in \( a_{\text{leg}} \) when a runner’s ankle dorsiflexors became fatigued is that there was a loss or reduction of the muscles’ shock absorbing capability. Flynn et al. (2004) examined the effect of local muscle fatigue on the \( a_{\text{leg}} \) using a human pendulum approach. The importance of the study was to have observed a local muscle response (i.e. muscles’ structure whether it is stiff or less stiff) to
fatigue while the subjects were not allowed to alter their geometry in the lower extremities. Using this approach, it was possible to control kinematic parameters such as joint angles, velocity, and positions at impact, which are considered as the factors that influence SA characteristics (Derrick, 2004). Flynn et al. (2004) reported that the $a_{leg}$ decreased following a fatigue protocol. A possible explanation for the $a_{leg}$ decrease is that the muscles became less stiff as a result of losing tension generation capability while fatigued, which leads to attenuating more impact than muscles with greater stiffness (Flynn et al., 2004).

**A Combination of the Two Hypotheses**

The third possibility is that a combination of these two hypotheses occurs as a response to fatigue. When the ankle dorsiflexors are impaired as a result of local muscle fatigue, it would seem that the eccentric contraction of the ankle dorsiflexors that allows controlled plantarflexion at the foot-ground interaction was impaired. This could lead to less dorsiflexion of the ankle at contact and an increase in leg impact characteristics (i.e., the magnitude of the passive peak). Christina et al. (2001) reported that the foot angle became less dorsiflexed at the foot-ground contact concurrent with the increase in the passive peak in the vertical ground reaction force when runners' ankle dorsiflexors were fatigued. Similarly, Derrick et al. (2002) observed that during a fatigued run, the knee angle became more flexed which allowed the $a_{leg}$ to increase. The findings by Christina et al. (2001) could be an indication that the ankle dorsiflexed less at the foot-ground contact following the fatigue protocol in the present study. In addition, the results from studies conducted by Derrick et al. (2002) suggest that lower extremity geometry
alterations at the foot-ground contact influence the magnitude of $a_{leg}$ and passive peak in the vertical ground reaction force in the present study.

From these previous studies, it seems that a change in the lower extremity geometry, which occurred as a result of the change in muscles function, resulted in increased leg impact acceleration – and therefore, SA – when runners' local muscles were fatigued.

Implications for Change in Shock Attenuation Characteristics

Shock Attenuation Characteristics and Overuse Running Injuries

The present study does not provide direct evidence associating SA characteristics with overuse running injuries. However, SA is a biomechanical measure that can identify changes in the runners' capabilities of attenuating shock at the foot-ground contact, and overuse running injuries are related to the repetitive collisions between the foot and the ground. Given that, the accelerometry data used to quantify SA may be valid to understand overuse running injuries. Since muscle fatigue is one of the factors associated with overuse running injury, and the ankle dorsiflexors are active for 50 – 80% of the running cycle (Reber et al., 1993), it was hypothesized that the ankle dorsiflexor fatigue would result in changes in SA characteristics during running. The increase in SA following fatigue in the present study suggests that musculoskeletal system attenuated impact by the time the impact reached to the head level. In addition, the increase in $a_{leg}$ while fatigued indicates that the ankle dorsiflexors play an important role in attenuating shock initiated at the foot-ground contact.

Nordin and Frankel (2001) postulated that muscle fatigue is associated with bone injuries. Figure 17 is an injury model which illustrates that bone injuries may result from
either a failure of the shock attenuating capability of the muscle(s) at the foot-ground contact or a change in running pattern when muscle fatigue is present. If a runner maintains a running behavior following fatigue, the impact initiated at the foot-ground contact would not be attenuated because of a loss or reduction of force generating capability of muscles. If this were the case, the reduced attenuation at the leg level would cause an increase in impact at other musculoskeletal structures such as the thigh, pelvis, and spine. If a runner changes the kinematic geometry such as joint angles, stride frequency, and stride length, abnormal or unique loading would be applied to musculoskeletal structures. According to this injury model, in either case, runners end up having a higher risk of running injuries such as overuse running injuries.
Injury

Strenuous exercise

Fatigued muscle

Loss of shock attenuating capacity

Altered gait

Abnormal loading

Altered stress distribution

Injury

Figure 17: Injury model. Reproduced from “Basic Biomechanics of the Musculoskeletal System” Nordin, M & Frankel, V. H., 2001, p 41.

Summary

There are benefits of running to improve general fitness by inducing physiological stress and/or psychological well-being. Although the exact mechanism of overuse running injuries is not fully understood, this type of injury occurs when runners undergo repetitive forces generated between the foot and the ground. One hypothesis addressing overuse running injuries is that muscle fatigue is associated with injury since muscle dissipates the stress on bones by eccentric contraction during the foot-ground contact.

SA is a biomechanical measure used to understand how the impact initiated with each
foot strike is reduced through the body. The purpose of the present study was to examine the effects of local muscle fatigue on SA, $a_{\text{leg}}$, $a_{\text{head}}$, and stride characteristics. It was observed that leg impact acceleration and SA increased during running following the fatigue protocol of the ankle dorsiflexors but there was no change in head impact accelerations. It should be noted that there were some unique responses to fatigue by individual subjects, suggesting that individual subjects adjusted to local muscle fatigue differently. Nevertheless, as a group, SA and $a_{\text{leg}}$ were sensitive to ankle dorsiflexor muscle fatigue and more shock was attenuated through the body during fatigued running. It was concluded that local muscle (the ankle dorsiflexors) influenced leg impact and SA of the runners. Further research is needed to better understand the implications of changes in SA with local muscle fatigue on the risk of overuse running injuries.
TITLE OF STUDY: Effects of Local Muscle Fatigue on Shock Attenuation During Running on Treadmill

INVESTIGATOR(S): Kaori Teramoto (data analysis, data collection, processing)  
Dr. John Mercer (supervisor)

CONTACT PHONE NUMBER: If you have any questions or concerns about the study, please contact:

DR. JOHN MERCER 895-4672
KAORI TERAMOTO 895-3419

Purpose of the Study
You are invited to participate in a research study. The purpose of this study is to examine the effect of local muscle fatigue on shock attenuation and joint movements during the ground contact phase of running on a treadmill. The muscles that will be fatigued are the ones which pull the foot up toward the leg (i.e., the dorsiflexors).

Participants
You are being asked to participate in the study because you are between 18 and 45, and are not pregnant, are free from any injury or condition that would interfere with your ability to run. You will be asked to self-report or have any health condition that would interfere with your ability to run. The entire testing session should take less than two hours from the time you report to the laboratory.

Procedures
If you volunteer to participate in this study, you will be asked to do the following: a one time testing session that will last approximately two hours will be scheduled. All testing will be conducted in the Biomechanics Laboratory in the Sports Injury Research Center building, room 103.
Upon reporting to the laboratory, specific measurements will be recorded (e.g. height, weight, limb lengths). After sufficient time to warm-up (minimum of five minutes, maximum of 20 minutes), specific instruments will be placed on your skin to record your movements. These instruments will include accelerometers placed on your lower part of your leg and forehead as well as reflective markers placed on your feet, ankles, knees, hips and upper body. You will be asked to wear shorts and a sleeveless shirt so that reflective markers can be viewed by the 3D cameras. Following the data collection you will be given a cool down.

The experiment will consist of running on a treadmill at a "preferred speed" which will be like a moderate long distance run but not a sprint. You will not be shown or told what running speed you have selected. Each run will be conducted on the treadmill at the test speed. Each run will last a Total of 2 minutes. The first condition will always be non-fatigued running.

After running non-fatigued at a test speed, the muscles that pull up the foot will be fatigued by a repetitive contraction exercise using a strength training device. This device is designed to isolate the muscles in front of the lower leg. You will sit on a mat and perform as many repetitive ankle upward and downward movements that you can do. Once you are fatigued, you will be asked to run on the treadmill at the test speed. The strength training device will be positioned next to the treadmill that will allow you to transfer to the treadmill quickly. Prior to testing you will be given instructions and time to practice how to transfer from the exercise to running in a safe manner. During running, an experimenter will stand behind you in case you have difficulty running. If at any time you feel you cannot run or the experimenter determines that it is not safe for you to continue to run, the test will stop.

You will be encouraged to rest between conditions and we want you to tell us if you are getting tired in any way during the tests.

**Benefits of Participation**

There may or may not be direct benefits to you as a participant in this study. By participating you will be contributing to the body of human performance literature. The anticipated benefit of this study is to better understand how people attenuate shock during running with or without local muscle fatigue. Your data are an important part of the investigation and we hope you will receive satisfaction from participating in a research project.

**Risks of Participation**

There are risks involved in participating in research studies. This study may include only minimal risks. As in any running activity, there is always the possibility of lower extremity joint, muscle injury, and/or muscle soreness. There is also the risk of your slipping on the treadmill when starting running and dismounting the treadmill with fatigued muscles. We can help minimize these risks by: providing you with sufficient time to warm-up, providing instructions, and practice mounting and/or dismounting the treadmill.
Cost/Compensation
There will not be financial cost to you to participate in this study. The study will take 120 minutes 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 Kaori Teramoto 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 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.
Severity Scale

None: 1
Very mild: 2
Mild: 3
Moderate: 4
Severe: 5
Very severe: 6
### Biomechanics Laboratory Project Organization Form

<table>
<thead>
<tr>
<th>Project</th>
<th>Impact Attenuation Characteristics in Females</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Date of Consent</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Test Date(s)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Subject ID #</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Date of Birth/Age</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>cm</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>kg</td>
</tr>
<tr>
<td><strong>Location of Files</strong></td>
<td>Lab2\student stuff\Kaori\WCE</td>
</tr>
<tr>
<td><strong>Speed of Running</strong></td>
<td>C1: C2:</td>
</tr>
<tr>
<td><strong>Conditions</strong></td>
<td>C1: Non-fatigued running</td>
</tr>
<tr>
<td></td>
<td>C2: Fatigued running</td>
</tr>
<tr>
<td><strong>Fatigue Protocol:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Number of repetition</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>the subject completed</td>
</tr>
<tr>
<td></td>
<td>&amp; Severity Score</td>
</tr>
<tr>
<td><strong>Set #1:</strong></td>
<td>Severity Score:</td>
</tr>
<tr>
<td><strong>Set #2:</strong></td>
<td>Severity Score:</td>
</tr>
<tr>
<td><strong>Set #3:</strong></td>
<td>Severity Score:</td>
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<td><strong>Set #4:</strong></td>
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<tr>
<td><strong>Set #5:</strong></td>
<td>Severity Score:</td>
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<td><strong>Notes</strong></td>
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<td><strong>Range of Motion:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>_________°</td>
</tr>
<tr>
<td><strong>Tester</strong></td>
<td></td>
</tr>
</tbody>
</table>
MATLAB PROGRAMS

%identify leg peaks and time of occurrence
OGTMleg

%identify head peaks and time of occurrence
OGTMhead

%back accelerations
OGTMback

%calculate stride length and frequency
TMSL

%calculate shock attenuation for treadmill running
TMSA

wce2

%wce2.m
%
%Written to process WCE grant & Kay's thesis:
%
%Written Spring 2006
%

clc
clear;
close('all');
temporary_directory = pwd;
fprintf(1,'

Processing

');

% Change the following parameters prior to running program
startwithsubj = 16; % subject number to start with
startwithcond = 1;  % condition number to start with (there were 3 conditions)
startwithtrial = 1; % trial number to start with
directory = 'c:\biomech\KT\WCE'; %directory where data are located
outputfile = 'S29C1out2.txt';

runningspeed = 1.56; %in m/s
biofs = 1004;

searchwindow = 50; %number of points for searching max
headsearchwindow = 20;
backsearchwindow = 20;

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

precision = 4; %output precision
bioheaders = 14;
biocol = 4;

subjects = 1; %number of subjects to process
conditions = 1; %number of conditions per subject
trials = 1; %trials per condition

%variable locations
headacol = 2;
backcol = 3;
legacol = 4;
biotimecol = 1;

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
            [biodata, inputfile] = my_open2(s, c, t, directory, '.txt', '.out', biocol, inf, bioheaders);

            %assign variables from bioware
            heada = biodata(:,headacol);
lega = biodata(:,legacol);
backa = biodata(:,backcol);
biotime = biodata(:,biotimecol);
clear biodata;

%number of leg peaks (+1 of strides)
npeaks = 11;

%Identify leg, head and SA
OGTMSAe

%save SA, knee angle, impact accelerations per trial
for i = 1:length(headpeak)
    ss(i) = s;
    cc(i) = c;
    tt(i) = t;
end

%compile data for a treadmill running condition
alldata(:, :) = [ss' cc' tt' legpeak(1:npeaks-1)' peakpos(1:npeaks-1)'/biofs
    headpeak' headpeakpos'/biofs ...
    backpeak' backpeakpos'/biofs ...
    tmsa' tmsf' tmsl'];
clear ss cc tt;
end
end
end
end

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

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

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

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

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

my_open2

% function: my_open2
% this function will run the commonly used commands to open a file.
%
% called as:
% data = my_open2(s, c, t, 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] = my_open2(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];
fprintf(1,f_name); fprintf(1, '\n');
inputfileroot = f_name;

% create filenames
inputfile = [f_name datain];
grfout = [f_name dataout];

% my_dir = data directory
% inputfile = filename with extension
% columns = number of columns
% headers = number of headers to discard

% 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
');
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');

OGTMleg

%OGTMleg
%
%Identify leg peaks during running on treadmill
%
point1 = 20000;
point2 = 40000;

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

56
fprintf(1,'nIdentify leg peaks.
')

plot(biotime(1:point1),lega(1:point1), 'k');
hold on
ylabel('leg acceleration (g)')
xlabel('time (s)')
title('Leg Acceleration During Treadmill Running')

%find peaks
numberofpeaks = input(' How many peaks? ');
fprintf(1, 'n');
for i = 1:numberofpeaks

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

%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(lega))
    endsearch = length(lega);
end

legpeak(i) = max(lega(start:xpos+searchwindow));
temppeakpos = find(lega(start:xpos+searchwindow)==legpeak(i));
temppeakpos(2) = 0;
peakpos(i) = temppeakpos(1);
peakpos(i) = peakpos(i) + (start)-1
plot(biotime(peakpos(i)),lega(peakpos(i)), 'ro')
drawnow
end
pause(0.5)

%repeat if number of peaks was less than 10
if numberofpeaks < npeaks
    close(gcf)
end

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

plot(biotime(point1+1:point2),lega(point1+1:point2), 'b');
hold on
ylabel('leg acceleration (g)')
xlabel('time (s)')
title('Leg 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 * biofs);

  %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(lega))
    endsearch = length(lega);
  end

  legpeak(i) = max(lega(start:xpos+searchwindow));
  temppeakpos = find(lega(start:xpos+searchwindow)==legpeak(i));
  temppeakpos(2) = 0;
  peakpos(i) = temppeakpos(1);
  peakpos(i) = peakpos(i) + (start)-1;

  plot(biotime(peakpos(i)),lega(peakpos(i)), 'ro')
drawnow
end
end
pause(0.5)

clear tempeakpos i start endsearch numberofpeaks numberofpeaks2 xpos ypos;
Identify back peaks during running on treadmill

fprintf(1,"nIdentify back peak for first leg peak.")

figure('position', [100, 300, 500, 500])

for i = 1:npeaks-1
    startplot = peakpos(i)-100;
    endplot = peakpos(i+1)+100;

    subplot(2,1,1)
    plot(biotime(startplot:endplot),lega(startplot:endplot),'g')
    hold on
    plot(biotime(peakpos(i)),lega(peakpos(i)),'ro')
    plot(biotime(peakpos(i+1)),lega(peakpos(i+1)),'ro')
    hold off
    title('Leg Acceleration')
    ylabel('Acceleration (g)')

    subplot(2,1,2)
    plot(biotime(startplot:endplot),backa(startplot:endplot),'g')
    hold on
    title('Back Acceleration')
    ylabel('Acceleration (g)')
    xlabel('Time (s)')

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

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

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

backpeak(i) = max(backa(start:xpos+backsearchwindow));
tempreakpos = find(backa(start:xpos+backsearchwindow)==backpeak(i));
tempreakpos(2) = 0;
backpeakpos(i) = temppeakpos(1);
backpeakpos(i) = backpeakpos(i) + (start)-1;

plot(biotime(backpeakpos(i)),backa(backpeakpos(i)), 'ro')
drawnow
pause(0.1)
hold off
end

close(gcf)

OGTMhead

%OGTMhead
%
%Identify back peaks during running on treadmill
%
fprintf(1,'nIdentify back peak for first leg peak."

figure('position', [100, 300, 500, 500])

for i = 1:npeaks-1
    startplot = peakpos(i)-100;
    endplot = peakpos(i+1)+100;

    subplot(2,1,1)
    plot(biotime(startplot:endplot),lega(startplot:endplot), 'g')
    hold on
    plot(biotime(peakpos(i)),lega(peakpos(i)),'ro')
    plot(biotime(peakpos(i+1)),lega(peakpos(i+1)),'ro')
    hold off
    title('Leg Acceleration')
    ylabel('Acceleration (g)')
subplot(2,1,2)
plot(biotime(startplot:endplot),backa(startplot:endplot), 'g')
hold on
title('Back Acceleration')
ylabel('Acceleration (g)')
xlabel('Time (s)')

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

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

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

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

backpeak(i) = max(backa(start:xpos+backsearchwindow));
temppeakpos = find(backa(start:xpos+backsearchwindow)==backpeak(i));
temppeakpos(2) = 0;
backpeakpos(i) = temppeakpos(1);
backpeakpos(i) = backpeakpos(i) + (start)-1;

plot(biotime(backpeakpos(i)), backa(backpeakpos(i)), 'ro')
drawnow
pause(0.1)
hold off
end

close(gcf)

TMSL

% TMSL
%

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%Calculate stride length while running on treadmill
%
% v = SL*SF
%

% calculate stride frequency
fprintf(1,'nStride parameters (SL, SF) calculated.')

% transform position to time
for i = 1:npeaks-1
    stridetime(i) = peakpos(i+1)-peakpos(i);
end

stridetime = stridetime./biofs;
tmsf = 1./stridetime;

meantmsf = mean(tmsf);

sdtmsf = std(tmsf);

% calculate stride length
for i = 1:npeaks-1
    tmsl(i) = runningspeed/tmsf(i);
end

meantmsl = mean(tmsl);

clear stridetime;
APPENDIX B

RAW DATA
RAW DATA

Descriptive Data.

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Age</th>
<th>Mass (kg)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>28</td>
<td>59</td>
<td>160.5</td>
</tr>
<tr>
<td>14</td>
<td>23</td>
<td>61.5</td>
<td>170</td>
</tr>
<tr>
<td>15</td>
<td>19</td>
<td>66.5</td>
<td>166</td>
</tr>
<tr>
<td>37</td>
<td>24</td>
<td>68.4</td>
<td>167</td>
</tr>
<tr>
<td>38</td>
<td>28</td>
<td>66</td>
<td>164</td>
</tr>
<tr>
<td>39</td>
<td>26</td>
<td>67.3</td>
<td>168</td>
</tr>
<tr>
<td>50</td>
<td>27</td>
<td>59</td>
<td>163.5</td>
</tr>
<tr>
<td>19</td>
<td>34</td>
<td>59</td>
<td>160</td>
</tr>
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<td>20</td>
<td>27</td>
<td>42</td>
<td>165</td>
</tr>
<tr>
<td>22</td>
<td>26</td>
<td>81</td>
<td>161.5</td>
</tr>
<tr>
<td>23</td>
<td>22</td>
<td>58</td>
<td>161</td>
</tr>
<tr>
<td>24</td>
<td>25</td>
<td>70</td>
<td>166</td>
</tr>
<tr>
<td>40</td>
<td>21</td>
<td>64.5</td>
<td>163</td>
</tr>
<tr>
<td><strong>avg</strong></td>
<td><strong>25.4</strong></td>
<td><strong>63.2</strong></td>
<td><strong>164.3</strong></td>
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<tr>
<td><strong>std</strong></td>
<td><strong>3.8</strong></td>
<td><strong>8.9</strong></td>
<td><strong>3.1</strong></td>
</tr>
</tbody>
</table>

Running Speed and Range of Motion before the Fatigue Protocol.

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Speed (m/s)</th>
<th>ROM (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>2.59</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>2.95</td>
<td>25</td>
</tr>
<tr>
<td>15</td>
<td>3.26</td>
<td>20</td>
</tr>
<tr>
<td>37</td>
<td>3.58</td>
<td>35</td>
</tr>
<tr>
<td>38</td>
<td>2.91</td>
<td>27</td>
</tr>
<tr>
<td>39</td>
<td>2.59</td>
<td>30</td>
</tr>
<tr>
<td>50</td>
<td>3.50</td>
<td>30</td>
</tr>
<tr>
<td>19</td>
<td>3.71</td>
<td>35</td>
</tr>
<tr>
<td>20</td>
<td>2.21</td>
<td>20</td>
</tr>
<tr>
<td>22</td>
<td>2.37</td>
<td>40</td>
</tr>
<tr>
<td>23</td>
<td>2.73</td>
<td>38</td>
</tr>
<tr>
<td>24</td>
<td>2.46</td>
<td>38</td>
</tr>
<tr>
<td>40</td>
<td>2.95</td>
<td>30</td>
</tr>
<tr>
<td><strong>avg</strong></td>
<td><strong>2.91</strong></td>
<td><strong>30.6</strong></td>
</tr>
<tr>
<td><strong>std</strong></td>
<td><strong>0.48</strong></td>
<td><strong>6.5</strong></td>
</tr>
</tbody>
</table>
Time Domain Data

Shock Attenuation: The ratio of head and leg impact accelerations (means and standard deviation of 10 consecutive strides); units (%).

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Non-fatigued mean</th>
<th>std</th>
<th>Fatigued mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60.8</td>
<td>4.1</td>
<td>62.3</td>
<td>5.0</td>
</tr>
<tr>
<td>2</td>
<td>76.7</td>
<td>1.8</td>
<td>78.3</td>
<td>3.9</td>
</tr>
<tr>
<td>3</td>
<td>66.9</td>
<td>5.1</td>
<td>76.1</td>
<td>4.2</td>
</tr>
<tr>
<td>4</td>
<td>70.9</td>
<td>5.7</td>
<td>81.1</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>71.1</td>
<td>2.8</td>
<td>78.9</td>
<td>2.2</td>
</tr>
<tr>
<td>6</td>
<td>80.1</td>
<td>2.6</td>
<td>77.4</td>
<td>4.4</td>
</tr>
<tr>
<td>7</td>
<td>80.5</td>
<td>3.0</td>
<td>82.2</td>
<td>4.0</td>
</tr>
<tr>
<td>8</td>
<td>68.4</td>
<td>4.6</td>
<td>82.7</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>72.7</td>
<td>1.9</td>
<td>70.3</td>
<td>7.6</td>
</tr>
<tr>
<td>10</td>
<td>75.7</td>
<td>3.2</td>
<td>85.0</td>
<td>1.1</td>
</tr>
<tr>
<td>11</td>
<td>78.9</td>
<td>2.2</td>
<td>78.6</td>
<td>3.1</td>
</tr>
<tr>
<td>12</td>
<td>84.9</td>
<td>3.2</td>
<td>83.2</td>
<td>2.4</td>
</tr>
<tr>
<td>13</td>
<td>77.1</td>
<td>3.0</td>
<td>83.3</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Leg Impact Acceleration (means and standard deviation of 10 consecutive strides): Units (g).

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Non-fatigued mean</th>
<th>std</th>
<th>Fatigued mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.8</td>
<td>0.2</td>
<td>4.5</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>4.6</td>
<td>0.8</td>
<td>5.4</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>3.7</td>
<td>0.7</td>
<td>5.3</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>4.4</td>
<td>0.5</td>
<td>8.2</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>5.5</td>
<td>0.3</td>
<td>6.6</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td>3.7</td>
<td>0.6</td>
<td>4.2</td>
<td>0.4</td>
</tr>
<tr>
<td>7</td>
<td>4.4</td>
<td>0.3</td>
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Head Impact Acceleration (means and standard deviation of 10 consecutive strides): Units (g).

<table>
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Stride Frequency (means and standard deviation of 10 consecutive strides): Units (Hz).

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Stride Length (means and standard deviation of 10 consecutive strides): Units (m)

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Severity Scale: 1 – None, 2 – Very mild, 3 – Mild, 4 – Moderate, 5 – Severe, and 6 – Very severe.

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Differences in Shock Attenuation (paired t-test)

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Paired Samples Test

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Differences in Leg Impact Acceleration (paired t-test)

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<tbody>
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Paired Samples Test

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Differences in Head Impact Acceleration (paired t-test)

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Differences in Stride Frequency (paired t-test)

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Differences in Stride Length (paired t-test)

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REFERENCES


VITA

Graduate College
University of Nevada, Las Vegas

Kaori Teramoto

Local Address:
4200 Paradise Road #3114
Las Vegas, NV 89109

Home Address:
6-3-9, Matsuba-cho
Kashiwa, Chiba 277-0827, JAPAN

Degrees:
Bachelor of Science, Physical Education, 2003
Utah State University

Special Honors and Grants:
Graduate Assistantship, 2005-2006
UNLV Graduate and Professional Student Association Grant, 2005-2006

2006, Research Grant, Graduate and Professional Student Association, University of Nevada, Las Vegas (amount funded: $600)

2005, Research Grant, Graduate and Professional Student Association, University of Nevada, Las Vegas (amount funded: $450)

Abstracts:


Thesis Title:
The Effects of Local Muscle Fatigue on Shock Attenuation Characteristics during Running

Thesis Examination Committee:
Chairperson, Dr. John A. Mercer, Ph.D.
Committee Member, Dr. Janet S. Dufek, Ph.D.
Committee Member, Dr. Brent C. Mangus, Ed.D.
Graduate Faculty Representative, Dr. Edward S. Neumann, Ph.D.