A Single Session of Repeated Wingate Anaerobic Test Caused Alterations in Peak Ground Reaction Force during Drop Landings

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Lower extremity injury is prevalent in individuals participating in sports. Numerous variables have been reported as predisposing factors; however, the predisposing effects of muscle fatigue on landing kinetics are unclear.

The purpose of this study is to investigate the effects of a single session of repeated muscle fatigue on ground reaction forces (GRF) during drop landings. Ten female (22.5±0.85 yrs) and ten male (24.1±2.6 yrs), healthy recreational athletes performed five experimental conditions. The first condition consisted of five non-fatigue drop landings (60 cm), followed by four conditions of a fatigue protocol. Fatigue was induced by a 20 second Wingate Anaerobic Test. Following each fatigue condition, participants completed two drop landings (60 cm) onto a force platform with 5 minutes of active rest between each fatigue condition. Kinetic data were used to identify peak magnitude of force for forefoot force (F1), rearfoot force (F2), anterior/posterior (AP) and medial/lateral (ML) at both F1 and F2. A mixed effect factorial ANOVA with repeated measures for GRF variables was used to determine differences between gender and within fatigue. No significant main effect was observed between genders across all GRF variables. A significant main effect was observed within the non-fatigue and fatigue conditions in respect to peak F2 force, (0.003, $p \leq 0.05$, $\eta^2=0.634$). The greatest
significant difference was shown between the first fatigue drop landing condition (F2=7.15±2.68 bodyweights) compared to the last fatigue drop landing condition (F2=9.38±2.1 bodyweights) in respect to peak F2, (0.002, p≤0.05). No significant difference was observed between gender and peak F2 (0.671, p≤0.05) and no difference was observed across AP and ML at peak F1 and F2 across conditions. A single session of repeated conditions of anaerobic muscle fatigue induced by WAT caused an initial reduction in peak F2 followed by an increase in peak F2 across conditions. Muscle fatigue consequently alters landing kinetics, potentially increasing the risk for injury.

Approved: _____________________________________________________________

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CHAPTER ONE

Introduction

Lower extremity injuries are common in sports and are caused by the interaction of modifiable and non-modifiable risk factors (Cameron, 2010). Modifiable and non-modifiable risk factors that predispose individuals to injury and specifically to the anterior cruciate ligament (ACL) include: anatomical structure, neuromuscular response, hormonal, and environmental (Cameron, 2010). Conceptualizing modifiable and non-modifiable risk factors enables clinicians and injury researchers to understand and propose evidence base injury prevention interventions (Cameron, 2010; Finch, 2006).

High rates of lower extremity injuries have been documented with ACL knee injuries recorded as one of the highest (Kellis & Kouvelioti, 2007; Renstrom, et al. 2008; Cameron, 2010). Noncontact ACL tears are prevalent in the U.S. (Hewett, Schultz, & Griffin, 2007). According to the National Collegiate Athletics Association (NCAA), approximately 5,000 athletes injured their ACL over a 16 year period (Renstrom, et al. 2008) and the highest numbers of reported injuries occurred among females (Renstrom, et al. 2008; Hewett, Schultz, & Griffin, 2007). It has also been estimated that 1.4 million females tore their ACL between the years of 1997 and 2007 (Hewett et al., 2007). More alarming are estimates that one out of 100 high school girls and one out of 10 athletically active college women will tear their ACL (Hewett et al., 2007). The prevalence of ACL injuries has also been reported in Norway, Denmark, Sweden, and Germany that have national registration to gather information on operative ACL injuries (Renstrom, et al. 2008). According to Norwegian data, ACL injuries occur at a rate of 34 per 100,000
citizens and 85 per 100,000 citizens in the high risk age group of 16-39 years old. Females sustained the majority of these reported injuries (Renstrom, et al. 2008).

Sports medicine professionals have addressed the concern of noncontact ACL and lower extremity musculoskeletal injury risk, injury prevention, and management in a multi facet approach. A biomechanical approach provides quantifiable data on the force acting on the body that explain injury.

During ambulation and athletic performance, the body is subjected to great forces specifically from landing. Forces applied to the body are multidirectional resulting in forces in the vertical, horizontal (anterior/posterior), and from the side (medial/lateral direction (see figure 1 from author’s own data). Ground reaction force (GRF) has been reported to be approximately three times a person’s body weight during running and significantly higher from a vertical jump and landing (Devita & Skelly, 1992; Munro & Miller, 1987). The result of GRF is determined by landing style, joint positioning prior to and at initial contact, and during the landing influence the execution and the magnitude of GRF. Landing style affects the magnitude of stress applied on the body and how it will move.
Additional variables, such as muscle fatigue, add to the complexity of lower extremity injury and GRF. GRF has been shown to decrease with lower extremity muscle fatigue and increase in angular velocity of the hip and knee (Coventry, O’Connor, Hart, Earl, & Ebersole, 2006). This reduction in GRF results from changes in angular velocity and leads to concerns about landing strategies. Lower extremity muscle fatigue could result in undesirable movement patterns such as, increase knee valgus angle and increase internal rotation of the tibia and femur causing additional tissue stress to the ACL and surrounding tissue (Coventry et al., 2006; Kellis & Kouvelioti, 2007; Madigan & Pidcoe, 2003; Orishimo & Kremenic, 2006). Therefore, studies on landing are of great importance to investigate and address injury prevention and treatment concerns of the lower extremity. Muscle fatigue results in an inability to sustain muscle contractions at a given force production (Gandevia, Allen, Butler, & Taylor, 1996; Barry & Enoka, 2007; Enoka & Duchateau, 2008; Vøllestad, 1997). Fatigue can be both central and peripheral.
in nature. Central fatigue relates to decision making, memory, emotional status, chemical processes, and neural drive to the muscle (McComas, 1996; Latash, 2008; Lieber, 1992; Gandevia et al., 1996). Peripheral fatigue occurs distal of the neuromuscular junction and affects the physiological response of muscle contractions (Gandevia et al., 1996). Both types of fatigue affect landing mechanics by altering muscle stiffness and execution of landing due to inadequate force production. Therefore, adaptations in landing mechanics while fatigued predispose athletes to lower extremity musculoskeletal injuries. Recent research has focused on the effect of muscle fatigue on task specific skills and the interactions of exercise-induced fatigue (Enoka & Duchateau, 2008; Barry & Enoka, 2007; Hunter, 2009). This research has provided insight into injury prevention and management (Coventry et al., 2006; Kellis & Kouvelioti, 2007; Madigan & Pidcoe, 2003; Orishimo & Kremenic, 2006, McLean & Samorezov, 2009; McLean, Felin, Suedekum, Calabrese, Passerallo, 2007). Little is known about the interaction of muscle fatigue on kinetics and kinematics during landing.

Various protocols have been used to investigate exercise-induced fatigue responses on muscle force production and neuromuscular activation (Vøllestad, 1997; Barry & Enoka, 2007). A 30-sec Wingate Anaerobic Test (WAT) has been the standard modality to measure anaerobic responses, such as the fatigue index that measures a decline in peak power (Laurent, Meyers, Robinson, & Green, 2007). No search of the literature revealed that a WAT has been used as a fatigue protocol to induce muscle fatigue and the effect of this modality on landing mechanics. Therefore, a study using a valid exercise intervention to induce lower extremity muscle fatigue and to determine if changes in landing mechanics exist is warranted.
Statement of the Problem

Lower extremity injuries, specifically to the anterior cruciate ligament (ACL), are prevalent in individuals participating in sports. Numerous factors have been identified as predisposing factors; however, the effects of muscle fatigue on landing kinetics are unclear. Therefore, this research will specifically examine the following questions:

The vertical force is defined as peak force at forefoot (F1) and rearfoot (F2), horizontal force as anterior/posterior (AP), and side force as medial/lateral (ML).

1. Are there differences in the magnitude of GRF within the fatigue conditions?
2. Are there differences in the magnitude of GRF between gender?
3. Are there differences in magnitude between fatigue and gender of GRF?

Purpose of the Study

This dissertation compares the effect of WAT to induces fatigue on GRF during drop landings of 60-cm. Participants will serve as their own control to investigate differences in GRF within fatigue and non-fatigue conditions and between gender.

Null Hypotheses

Ho\textsubscript{1}: Are there significant differences observed within the fatigue conditions across each dependent variable?

Ho\textsubscript{2}: Are there significant differences observed between gender across each dependent variable?

Ho\textsubscript{3}: Are there significant interaction effects across each dependent variable?

Delimitations

This study was conducted with the following delimitations:

1. Only students from Ohio University participated.
2. Ten males and ten females with no lower extremity musculoskeletal injuries for at least six months prior to testing were included.

3. Participants performed drop landings from a height of 60-cm.

4. Each participant landed from the 60-cm height on their dominate foot on the force plate and their left foot adjacent to the force plate.

5. The WAT was used to induce lower extremity muscle fatigue for each participant.

6. All participants were classified as physically active and healthy from any significant lower extremity injury, cardiovascular, and pulmonary illness as determined by a health questionnaire and orthopedic examination assessing ankle and knee joint stability which was performed by a License Athletic Trainer (LAT).

7. Experimental protocol was explained to the participants at least one day prior to data collection and each participant was able to practice as many landing as desired to become familiar with the experimental protocol.

Limitations

The following limitations were observed during the research study.

1. Differences in landing styles between participants exist.

2. Trials included only the participant’s dominate limb.

3. Landing asymmetry was based on visual inspection of the landing.

4. Controlled experimental conditions were different from the participants’ actual sport or exercise program.

5. Landings from only one height were analyzed, precluding generalization for other heights.
6. All participants were volunteers and may not represent a true random sample.

Assumptions

The following assumptions were made regarding this study.

1. Participants reported injury, medical history, and perceived exertion honestly and accurately.
2. Participants performed the WAT with maximum effort for the duration of the test.
3. Participants refrained from exercise, alcohol, and caffeine at least 24 hours prior to performing in the study.
4. F1 is the peak of magnitude force for toe contact and F2 is the peak force of magnitude for heel contact established by Dufek & Bates (1991), as shown in Figure 1 (page 12).

Definitions of Terms

*Anterior/Posterior Force (AP).* Force that acts on a body from the front and back to maintain stability and provide movement.

*Central Fatigue.* Results in alterations in decision making, memory, interpretation of effort, emotions, and chemical processes of the brain that drives impulses to the muscle (McComas, 1996; Latash, 2008).

*Drop Landing.* Landing in which participants’ step from a 60-cm platform onto a force plate.

*Forefoot Force (F1).* The peak force the occurred right after initial contact.

*Ground Reaction Force (GRF).* The forces that are exerted on the body during ground contact in the perpendicular, AP, and ML planes as measured by a force plate.
**Kinematics.** A description of body motion in relation to movement.

**Kinetics.** The forces that act on a body that may or may not cause movement.

**Medial/Lateral Force (Ml).** Acts on a body away and towards the midline of a body to maintain stability and movement.

**Muscle Fatigue.** Any reduction in maximum force-generating capacity, regardless of the force required in any given situation (Madigan & Pidcoe, 2003).

**Peripheral Fatigue.** Results in alterations in impulse conduction and transmission of a nerve affecting muscle contractions in force production (McComas, 1996; Latash, 2008; Lieber, 1992).

**Rearfoot Force (F2):** The peak force the occurred right after heel contact also called peak force.
Quantifying ground reaction force (GRF) determines the magnitude of force applied to a body. The time application of the force is called impulse. When collecting GRF, data can be represented by a force-time curve graph that graphically presents peak magnitude and the time to peak magnitude in the vertical, medial/lateral (ML), and anterior/posterior (AP) directions (see figure1). Impulse, loading rate, and shock can also be determined with GRF data. Ground Reaction Force data provides valuable information for injury prevention and treatment.

Ground reaction force and kinematic analyses are used to study the relationship of forces and the angular velocity of certain joints that influence force. Researchers have used these components to study walking, running, landing, cutting, floor surface interaction, and footwear characteristics (Madigan & Pidcoe, 2003). One particular area of interest is drop landings. Landing is a functional movement pattern associated with all forms of ambulation. Therefore, studying landing has significant implications for further understanding injury, prevention, and treatment of injury because the forces applied to a body during landing are primary causative factors (Dufek & Bates, 1990).

Landing is a complex motor pattern that is influenced by many variables. These variables determine how the landing is executed and performed. Variables such as gender, age, mass, velocity, anatomical structure, strength, balance, injury and injury history, fatigue, landing strategy, landing height, landing surface, footwear, braces, and orthotic devices are all variables that influence GRF (Dufek & Bates, 1991; Hargrave,
Carcia, Gansneder, & Shultz, 2003; Hewett, Meyer, & Ford, 2006). Therefore, a study to investigate one of the variables, such as fatigue, is of great importance. Muscle fatigue is not well understood on how it influences landing mechanics. In order to investigate the effect of muscle fatigue during a landing task, a general understanding of the problem is essential. The literature review will consist of the following sections: landing, fatigue, gender differences during landing, muscle fatigue protocols, lower extremity injury, and chapter summary.

Landing

The complexity of a landing is such that it must be studied from various angles in attempt to understand injury. Powers (2003) indicated common lower extremity injuries include stress fractures of the tibia, and knee injuries with particular attention to the patellofemoral joint (PFJ) and the anterior cruciate ligament (ACL). These injuries can result from a cause-and-effect biomechanical and neuromuscular relationship. Mechanical stress results in either increased tissue strength or damage, which may lead to injury. The stress of landing is two-fold 1) either a high magnitude of stress occurring over a short or long duration or 2) a low magnitude of stress occurring over a short or long duration. When studying landings, the focus is on how landing mechanics are performed and the factors that influence these mechanics. Major factors associated with landing performance include muscle strength, muscle fatigue, range of motion, motor and neuromuscular control, gender, and landing strategies (Hewett, Myer, et al. 2006).

Landing research, specifically from a drop landing, has shown differences among participants (Seegmiller & McCaw, 2003; Cortes, Onate, Gagen, Dowling, & Van Lunen, 2007; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005). A toe to heel landing
pattern is typically seen during a landing task. Other landing patterns include heel to toe or flat foot style (Gross & Nelson, 1988). The toe to heel landing pattern is recommended to reduce peak GRF and increase the time in which GRF is absorbed (Devita & Skelly, 1992). In contrast, the flatfoot style decreases the time GRF is applied, resulting in a general increase in peak GRF values.

Landing style is also influenced by joint range of motion (ROM) of the upper and lower extremity. Research has shown that as range of motion (ROM) increases, peak GRF decreases (Devita & Skelly, 1992; Dufek & Bates, 1991; Noyes et al., 2005). Landing style mechanics are classified as either soft or hard. A soft landing is defined as knee flexion greater than 90 degrees, while hard landings have knee flexion less than 90 degrees after floor contact (Devita & Skelly, 1992). Increased ROM of the ankle and hip has been shown to significantly decrease GRF (Devita & Skelly, 1992; Gross & Nelson, 1988; Cortes et al., 2007). Dorsiflexion of the ankle has been reported to absorb 44% of the GRF when landing from a height of 60-cm, followed by the knee, then the hip (Devita & Skelly, 1992).

**Types of Landing**

The type of landing performed by the participant will influence both the landing style and kinetic and kinematic stress to the body. Landings are classified as single leg, double leg, side to side, or unexpected. Each type of landing is associated with athletic activity and occurs in combination with performing most skills, for example playing a game of soccer that combines jumping, landing, and cutting.

Single leg landings typically occur from landing on the dominate leg (Hewett, Meyer, et al., 2006). The dominate leg is classified as your preferred leg if the participant
kicked a ball. During a single leg landing, the GRF is placed across only one limb, resulting in a greater joint stiffness requirement of the lower extremity to maintain balance.

Double leg landing is the preferred method for landing but it is not always feasible based on the activity. Under normal conditions and in the absence of injury or muscle fatigue, GRF is dissipated throughout two legs and less muscle activity is required to maintain balance (Hewett, Meyer, et al., 2006; Coventry et al., 2006). Side to side or directional movement requires more of a single leg landing style. This landing style increases the kinetics and kinematics in different directions, such as in the medial, lateral, anterior, and posterior directions. Side to side landing also increases rotational forces on joints.

Unexpected landings are also a type of landing that is associated with movement. Unexpected landings can occur from an outside force induced by a second party while in the air affecting the execution of the landing and simply by not expecting alterations in joint positioning. The body’s response to landing during expected and unexpected landings undergoes different kinetic and kinematic changes. During an unexpected landing, an individual may not have sufficient time to prepare for the landing and might not utilize the landing style required to decrease GRF thus resulting in undesirable joint positioning (Brown, Palmieri-Smith, & McLean, 2008). The alteration adds to the unexpected landing and increases the body’s response to maintain balance.

Unexpected and expected landings while fatigued have also induced an additional component that has resulted in kinetic and kinematic alterations that are detrimental (Borotikar, Newcomer, Koppes, & McLean, 2007).
Fatigue

Fatigue is a major component that affects landing and how impact forces are dissipated. Muscle fatigue causes changes in muscle activation patterns which adversely affects landing strategies (Kellis & Kouvelioti, 2007).

Muscle fatigue can be defined simply as an inability to maintain a power output during repeated muscle contraction (McIntosh, Gardiner, & McComas, 2006; McComas, 1996). An alternative definition of fatigue is any reduction of a muscle in the maximum force generating capacity, regardless of the force required in any given situation (McIntosh et al., 2006). Muscle fatigue can be divided into two categories, depending on whether it is a central or peripheral response in the motor system. According to McComas (1996), central fatigue is mediated by the central nervous system (cerebral cortex, basal ganglia, cerebellum, and spinal nerves). Central fatigue relates to decision making, memory, interpretation, emotions (the sense of effort), and chemical processes of the brain and their role in muscle response (McComas, 1996; Latash, 2008). Peripheral fatigue is responsible for the physiological response to muscle contraction within the motor system. This includes the impulse conduction and transmissions of the nerves to illicit a muscle contraction (McComas, 1996; Latash, 2008; Lieber, 1992).

Both central and peripheral fatigue influences one another. Depletion of muscle glycogen in working muscles adversely affects force production and can limit the neurological drive from the brain to help illicit a muscle contraction (Blomstrand, 2006). Central and peripheral fatigue are both dependent on duration, intensity, and frequency of the muscle contraction. Therefore, muscle fatigue has been shown to adversely affect joint proprioception, neuromuscular control, movement coordination, and muscle
reaction control (Rozzi, Yuktandans, Pincivero, & Lephart, 2000; Madigan & Pidcoe, 2003).

**Muscle Fatigue and Ground Reaction Force**

Walking, running, and landing are standards used to quantify the parameters of peak force magnitude and the time force that is applied. Lower extremity muscle fatigue has been shown significantly to influence GRF. Muscle fatigue has been studied by targeting selective muscles for analysis using isokinetic resistance and other equipment, to more dynamic and functional related skills such as hopping, jumping, and running. A standard protocol for lower extremity muscle fatigue has not yet been established. The attempt to show differences in the amount of force a muscle can generate and sustain is the criteria to establish muscle fatigue (Madigan & Pidcoe, 2003).

Drop landing as a strength exercise is commonly used for strength and power development (Miyama & Nosaka, 2007). This form of exercise can be developed through plyometric exercises ranging from explosive repetitive jumps to drop landings focusing on eccentric loading. Eccentric loading increases stress on the musculoskeletal system, causing an increase in muscle soreness and reduced function in untrained participants (Miyama & Nosaka, 2007).

Miyama & Nosaka (2007) investigated drop landings by trained participants to establish if this sample related to the results of untrained participants. Results indicated that participants who performed a series of 10 consecutive drop landings from 60-cm had similar responses as the group that performed 50 consecutive drop landings (60-cm). The responses included increased muscle function recovery time, decreased lower extremity range of motion, decreased knee joint swelling due to the landing condition, and general
lower extremity muscle soreness. These results showed a predisposition to injury among untrained individuals, while trained individuals showed greater injury prevention responses.

*Fatigue and Landing Mechanics*

Muscle fatigue has been shown to adversely affect joint proprioception, neuromuscular and muscle reaction control, and movement coordination (Riemann & Lephart, 2002a; Riemann & Lephart, 2002b). There are two responses that fatigue has on landing mechanics in respect to kinetics and kinematics. Kinematics will either increase or decrease as a result of fatigue. Increased ROM tends to relate to a decrease in peak GRF and an increase in muscle activity. However, the decrease in peak GRF does not always correlate to desirable neuromuscular control and function. The landing style may be one that predisposes the body to additional mechanical stress to tissues because of inadequate joint stiffness and balance.

Joint positioning during a landing is therefore a main concern. Fatigue will directly impact the magnitude of joint stiffness caused by supporting muscles. A certain amount of stiffness is required to provide joint stability and attenuate GRF experienced by the body during landing. Studies have shown that participants who are unable to land with adequate joint stiffness decrease their spine flexion to assist in stiffening of the knee (Huston & Wojtys, 2000; Huston, 2007). This helps control deceleration of the landing and provide balance. Changes in trunk positioning place additional shearing force on the tibia and knee joint, increasing the potential for injury.

Muscle fatigue may lead to an increase in kinematic activity and altered landing mechanics. Kinematic changes directly affect the kinetic forces placed on the body.
There is a balance between the amount of joint stiffness needed for joint stability and the magnitude of GRF resulting from the landing style. Wolff’s Law indicates that bone will either increase or decrease in strength due to the level of mechanical stress that is imposed (McGinnis, 1999). Increased ROM at the ankle, knee, hip, and trunk, along with adequate joint stiffness are necessary for increased strength, injury prevention, and performance. This adequate ROM has been classified as knee flexion in the ranges of 90 degrees and greater after floor contact during a landing (Devita & Skelly, 1992).

**Fatigue and Neuromuscular Responses in Landing**

The neuromuscular response during voluntary muscle contractions is a complicated process where muscle contractions and neural responses control the sequence of movement. In order to investigate motor responses, the sensorimotor system should be examined.

The sensorimotor system incorporates and integrates information from the sensory, visual, and vestibular system to illicit a motor response (Riemann & Lephart, 2002a). Proprioception is directly related to the sensorimotor system and is responsible for information regarding joint position and motion. This information is then used to provide input and feedback for balance, orientation, and joint position sense (Rozzi et al., 2000). The sensorimotor system processes information from areas within the CNS. Areas that include the spine, brain stem, motor cortex, basal ganglia, and cerebellum are integrated to form motor control response (Rozzi et al., 2000). Muscle fatigue directly affects the contraction and capability mechanism of muscle, regardless if fatigue is a central and/or peripheral response. The decrease in force production of muscle correlates to changes in joint positioning often resulting in undesirable movement patterns.
Joint positioning is influenced by sensory information and results from activation of spinal and supraspinal reflexes that are essential in providing dynamic muscle stabilization (Rozzi et al., 2000; Latash, 2008). Muscle fatigue often creates inadequate responses from spinal reflexes. Afferent neural pathways provide information that results in undesirable joint position and inadequate response of muscle force, also modifies descending supraspinal drive that lead to undesirable responses in motor control. Due to the body’s interpretation of the sense of stability (kinesthesia), a response creates a conflict for joint stability. What the body perceives as stable joint positioning, may be incorrect.

*The Effects of Fatigue on Neural Activation and Force Production*

There are changes and adaptations that occur to muscle because of the decrease in force production as mediated by the Nervous System (NS). As a result, a decrease in force production and a decrease in conduction velocity occur as action potential slows (Latash, 2008). Changes in alpha motor neuron excitation, decreases in firing frequency of individual motor units, and slowing of the relaxation phase of muscle contractions also have been observed in fatigued muscles (Latash, 2008; Lieber, 1992). When fatigued muscles contract, the relaxation phase slows. This can create prolonged muscle contractions which generate irregular force output.

Reduction of sustainable force production is influenced by other variables occurring from spinal mechanisms within the CNS. One notable alteration is the change in recruitment and synchronization of motor units. Muscle fatigue causes a switch in the selection process of which motor unit is to be recruited. This switch results in recruiting smaller and slower motor units and the de-recruited larger motor units (Latash, 2008).
This switch causes the larger motor units to decrease in frequency and force production. The change in synchronization causes an increase in muscle force production during certain contractions and causes an influx of force in other contractions. This change creates irregular muscle contractions with a varying degree of force production resulting in a decrease in synchronization of motion.

A switch in motor unit recruitment directly impacts landing strategy. Larger muscles in the lower extremity are required to execute a landing that provides sufficient joint stiffness and reduced GRF. Activation of the hamstrings and quadriceps muscles are required to supply knee flexion and to control the deceleration of the body (Huston, 2007). Fatigue will alter the muscle contractions of the quadriceps and hamstrings, causing the body to rely on smaller muscles such as the plantarflexors of the foot to provide the required joint stiffness of the knee. This alteration may lead to injury of the knee joint, specifically to the ACL (Huston, 2007).

Alterations in stretch reflex responses have also been reported to change in response to muscle fatigue (Latash, 2008; Osterning, 2000). This alteration causes a change in the autogenic reflexes, decreasing the net magnitude of joint torque. This muscle response modification decreases overall joint stiffness, joint positioning, and the sense of joints stability. These variables may predispose the body to injury.

An additional CNS-mediated response occurs due to muscle fatigue and is manifested by an increase in cortical neuron activity within supraspinal tracts, such as in the motorcortex in the brain. This pathway has been shown to provide stability and joint stiffness, but is less understood and difficult to measure (Latash, 2008).
Neurological adaptive changes occur as a result of muscle fatigue. To increase joint stability as muscle fatigue increases, the body responds by activating antagonist muscles of the fatigue muscles groups, termed co-contractions (Latash, 2008; Hewett, Meyer, et al., 2006; Hewett, Ford, & Meyer, 2006). However, co-contractions could also be detrimental to joint stability. To control the degree of knee flexion during landing, the hamstrings muscles should be recruited first and with a greater magnitude of force than the quadriceps muscles. The hamstring muscles decrease the anterior translation of tibia, decreasing stress to the ACL and tibia. If the order of muscle recruitment is reversed, increased stress of the ACL and tibia, alterations in landing mechanics and changes in peak GRF will result.

Additional research has added to our understanding of neuromuscular responses that influence muscle fatigue and, in turn, affects neuromuscular control. These predisposing factors to neuromuscular control and stability include: anatomical design of muscle, lack of dynamic flexibility, and hormonal influence (Rozzi et al., 2000; Hewett, Meyer, et al., 2006).

*The Effects of Fatigue on Performing a Landing Task*

Muscle fatigue significantly affects how a landing task is performed. The CNS is directly responsible for the response of muscle and the integration of central and peripheral responses controls force production and joint positioning. Fatigue reduces force production, which is the primary mechanism to protect muscles and structures from injury.

The muscle response to fatigue may alter performance characteristics, prevent injury, or cause injury. Alterations in muscle force production, recruitment, timing,
sequence, quality, reflex responses, and adaptations are all the result from muscle fatigue. The reduction of force output during sustained and repeated contraction protects muscle and other structures. The neurological response due to fatigue alters neuromuscular control resulting in changes in joint positioning and stiffness. These changes may correlate to undesirable movement patterns which place unwanted stress to the body.

Central fatigue can lead to a decrease in motivation to perform and execute a landing (Parekh, Palmieri-Smith, & McLean, 2008). This response is less common in trained athletes and tends not to influence their performance (Lieber, 1992). However, this response may lead to injury because of their perception of the effort needed for repeated forceful contractions. An additional factor relating to central fatigue is degradation in central control resulting in a cross over effect to the non-fatigue contralateral side. This cross over effect is caused by to alterations in supraspinal and spinal control pathways (McLean & Samorezov, 2009). Central fatigue therefore may be the dominating factor that mediates muscle fatigue (McLean & Samorezov, 2009).

The threshold of muscle fatigue is highly variable and individual. This presents a challenge for controlled investigations, because what may fatigue one person might not fatigue the next, and each person recovers differently. A recent study indicated that muscle fatigue continued 40 minutes after inducing a fatigue protocol and kinetic and kinematics values were not restored to pre-fatigue levels until after 40 minutes of rest (Tsai, Sigward, Pollard, Fletcher, & Powers, 2008).

The effects of muscle fatigue on landing mechanics is relatively new in the literature. What is known are the physiological responses to muscle fatigue and the landing strategies that influence kinetic and kinematic variables. The principles of the
two are integrated in order to understand how muscle fatigue influences landing mechanics. Therefore, a training program that incorporates a fatigue protocol, trains the body to land with increased knee flexion, reduces kinematics in the anterior/posterior direction, and measures adequate joint stiffness is warranted to decrease the risk of lower extremity injury specifically to the knee joint (Hewett, Ford, et al., 2006).

Fatigue and Prevention of Injury

Muscle fatigue is considered a physiological adaption designed to prevent further damage to the muscle during movement. Central or peripheral fatigue is a protective response. This response may decrease performance, but also limits the amount of force the body can produce or absorb. Central commands respond by increasing the perceived effort and altering the perception of the force needed for the muscle contraction. Central responses are activated in preparation of a landing skill and influence peripheral response during the completion of a landing. All responses will directly affect the execution of the landing and influence GRF.

Therefore, to enhance the prevention and performance of a landing, regardless of the type, a muscle fatiguing protocol should be implemented in training to illicit a motor response to reduce GRF. This motor response can be used to adopt a landing style that places decreased stress to the body and decreases GRF.

Gender Differences During Landing

Gender differences have been reported among participants who performed landings under the same conditions. When compared with females, males tend to land with more knee flexion and an overall increase in lower extremity ROM. The increase in ROM influences a more toe to heel landing strategy and results in decreased GRF.
Gender can be an influential variable causing differences in landing performance. Females, regardless of age, demonstrate different landing strategies and different neuromuscular responses than males (Hewett, Ford, et al., 2006; Hewett, Meyer, et al., 2006; Kernozek, Torry, & Iwasaki, 2008; McLean, et al., 2007). The female neuromuscular response has been shown to be a predisposing factor to lower extremity injuries, including stress fractures and ACL tears (Hewett, Meyer, et al., 2006; Moran & Marshall, 2006).

Regardless of the drop jump height, mass of the participant, and type of landing, significant gender differences in GRF and joint moments have been reported (Devita & Skelly, 1992; Gross & Nelson, 1988; Huston, 2007). Joint positioning during landing is a variable that influences GRF and joint moment forces.

A landing that has reduced ROM at the ankle, knee, and hip at contact and throughout the absorption phase will result in an increase in GRF. This is not a gender-specific variable, but as a group, females tend to land with less knee flexion at contact, causing an increase in force at the knee, hip, and other joints. The reduction of knee flexion creates a decrease in the time the force is applied throughout the entire sequence of the landing.

Upper body posture influences lower extremity kinematics during landing. Females demonstrate a more erect posture during landing which causes a decrease in knee flexion and increase in joint stiffness (Coventry et al., 2006; Huston, 2007; Hewett, Meyer, et al., 2006). This landing strategy provides joint stiffness; but also increases tibial translation, placing high loads of stress on the ACL and knee joint. This response may be adaptive in nature to assist and provide joint stability. This comes at the expense
of increased GRF and joint moments at the ankle, knee, and hip. Therefore, landing with an adequate flexion of the trunk, decreases GRF and quadriceps muscle activity by increasing flexion of the knee and hip and should be encouraged as a desired landing style (Blackburn & Padua, 2009). An additional study also concluded, landing with increase trunk flexion decreases knee extensor moments and increases hamstring co-contraction thereby decrease stress to the ACL (Shimokochi, Lee, Shultz, & Schmitz, 2009).

One of the most significant differences seen in females, when compared with males during all types of landing and heights, is the increase in knee valgus moments (Powers, 2003; Huston, 2007; Hewett, Meyers, et al., 2006; Hewett, Ford, et al., 2006; Kernozek et al., 2008). The increase in knee valgus angle creates large moments of force at the knee and is a strong predictor in ACL injuries (Hewett, Meyer, et al., 2006; Hewett, Ford, et al., 2006). Increases in valgus knee angles create lower extremity excursions in the medial/lateral direction generating the moments that occur at the knee. Knee valgus joint positioning in females occurs at both initial contact and continues as the knee reaches maximal flexion.

The increase in knee valgus observed during bilateral drop landings has also been demonstrated in single-leg landings from drop jumps, sidesteps, and cutting maneuvers. This type of landing is associated with most forms of athletic activity and creates additional moments of force at the joints of the lower extremity. Females continue to demonstrate increased knee valgus angles, along with increased inversion and eversion moments at the ankle during all types of landing (Huston, 2007).
Overall, the increase in knee valgus moment causes the tibia to externally rotate and the femur to internally rotate. These responses create larger moments of force at the ankle, hip, and spine. Females have demonstrated significantly larger kinematic activity for ER of the tibia and IR of the femur when compared to males during all forms of landing, regardless of the height (Huston, 2007; Madigan & Pidcoe, 2003; Kellis & Kouvelioti, 2007).

Females tend to land with decreased knee flexion at both initial contact and at the point of maximal knee flexion during the landing (Devita & Skelly, 1992; Huston, 2007). This landing strategy increases joint stiffness and reduced knee valgus angles. However, this response creates greater quadriceps muscle activity adding to lower extremity joint moments in the anterior direction stressing the ACL once again.

One positive adaptation among females resulting from a decrease in knee flexion is an increase in ankle ROM. Plantarflexion and dorsiflexion have been shown to decrease peak GRF (Devita & Skelly, 1992). This adaptive response from the plantarflexors may cause more rapid fatigue than the muscles involved with controlling knee flexion.

**Gender Differences in Muscle Activation**

Gender differences have also been identified in muscle activation patterns during a landing task (Hewett, Meyer, et al., 2006; Huston, 2007; Houston, 2000; Osterning, 2000). In the absence of lower extremity muscle fatigue, significant neuromuscular responses occur in the muscles around the knee joint in females. Females tend to be more quadriceps and leg dominant (Hewett, Meyer, et al., 2005; Shelburne, Torry, Yanagawa, & Pandy, 2003). The increase in quadriceps activity and the longer sequence
of activation creates increases in knee joint moments stressing the ACL and supporting structures (Osterning, 2000; Hewett, Meyer, et al., 2006). In addition, females are inclined to land on the same leg repeatedly causing additional stress and predisposing that leg to early fatigue (Houston, 2007).

The neuromuscular responses of females during landing resemble that of muscle fatigue. Females have demonstrated changes in motor unit recruitment effecting overall force production. The conduction velocity of the knee flexor muscles has been shown to be significantly slower in females during a landing task increasing anterior translation of the tibia (Huston et al., 2000; Madigan & Pidcoe, 2003).

Inadequate joint stiffness during landing results from muscle imbalances, reduction in dynamic flexibility, increases in quadriceps activation, insufficient co-contractions of knee flexors and extensors, leg dominance landing, and joint positioning during landing (Huston, 2007; Hewett, Meyer, et al., 2006; Riemann et al., 2002a; Riemann et al., 2002b). All of these variables decrease overall balance sense and resistance to dynamic stretching of the knee joint.

Joint positioning is the variable that affects kinetics and kinematics during landing, regardless of gender, mass, landing height, or muscle fatigue. Joint positioning before, during initial contact, and throughout the landing will determine the magnitude of the force applied to the body and how body segments move. Joint moment force and GRF can be significantly different between participants based on the joint position of the ankle, knee, and hip both at initial contact and at the completion of the landing. Greater significance is placed on the landing at initial contact and the time of peak magnitude of the heel at heel strike. Participants could have the same ending ROM but have
completely different GRF at initial contact and heel contact. These differences are due to joint positioning during the landing task.

Individuals can manipulate the force applied to the body during landing by adapting landing strategies so that force is applied over a longer period of time, thereby decreasing peak GRF values. This can be accomplished by increasing joint ROM during the landing and may decrease joint stiffness and increase forces in other planes of motion.

Ending ROM has little influence on overall GRF and joint moment forces. After heel contact, peak GRF continues to decrease and the overall ROM of the ankle, knee, and hip also decrease. In cases of insufficient joint stiffness and muscle fatigue, ROM increases and causes an increase in joint moments of force.

Muscle Fatigue Protocols

Various studies have investigated the effect of muscle fatigue using exercise protocols to induce decreases in force production. Protocols have included the use of strength exercises, drop landings, weight machines, functional exercises, and agility drills. The fatigue exercise protocols are designed to induce either anaerobic or aerobic muscle fatigue. The majorities of the protocols are anaerobic in nature and involve a series of jumping activity. Aerobic protocols, also called endurance, involve activity such as running for a longer period of time until a fatigue state is achieved. Both types, either anaerobic or aerobic, do not occur in isolation. All protocols use both types; the selection is based on what the researcher is investigating.

Researchers have induced muscle fatigue in selected muscle groups by using weight machines for concentric and eccentric contractions followed by drop landings (Kernozek, Tory, & Iwasaki, 2008; Rodacki, Fowler, & Bennett, 2002). Both studies
found differences in landing strategies due to fatigue. Kernozek et al. (2008) induced lower extremity muscle fatigue by having participants perform parallel squats of 5-8 repetitions on a Smith weight machine for a minimum of four sets at 60% of their one-repetition maximum. Fatigue was established if the participant was unable to maintain a constant speed based on a metronome. Following the fatigue protocol, participant’s were instructed to perform six single-leg drop landings of 50-cm from a hanging suspended bar. Results indicated that males and females were affected by the fatigue protocol and the protocol caused each group to land with more hip flexion. Differences were noted among males and females in joint positions for the knee. Females demonstrated an increase valgus angle at the knee where as males showed an increase in varus angle at the knee. The authors postulated that this knee joint position predisposes females to knee injuries and other lower extremity injury.

Rodacki et al. (2002) examined the effect of lower extremity muscle fatigue by measuring changes in maximal vertical jump and peak torque from isokinetic testing. The fatigue protocol consisted of knee extension and knee flexion exercises on a weight machine. Fatigue was determined if the participants could lift approximately 50% of their body mass during knee extension and 40% for knee flexion. After the fatigue protocol, participants were tested for peak torque for knee extension and knee flexion. This was followed by performing countermovement jumps onto a force plate. GRF, kinematics analysis, and EMG analysis were conducted. Results showed that fatigue of the knee flexor muscles did not cause any significant changes in GRF, kinematics, or EMG profiles. However significant changes occurred with muscle fatigue for the knee extension variable.
A study by Kellis & Kouvelioti (2007) continued with an isolated muscle group fatigue protocol and tested muscle fatigue during drop landings while measuring GRF variables. Knee extension and knee flexion exercises were used as the fatigue protocol using isokinetic concentric efforts. Participants performed two sets of repeated maximal contraction until 30% of maximal torque could not be continued. Ten single-leg drop landings from 30-cm were performed before, in the middle, and at the end of the fatigue protocol. Results indicated knee extension fatigued, showing an increase in knee and hip flexion and a decrease in peak GRF. Knee flexion presented no changes in peak GRF.

Weight Machines & Functional Skills Exercises

A study by Augustsson et al. (2006) used a single leg hop test and knee extension exercise for their fatigue protocol and compared the results to the non fatigue to determine kinetic and kinematic parameters. Eleven participants performed two trials of a single leg hop before and after fatigue. The fatigue protocol consisted of leg extension exercises on a weight machine at 80% and 50% of their one-repetition max. A second group of eight male participants performed a single-leg hop test at a given distance for the second fatigue protocol. Fatigue was determined when the single-leg hop distance did not reach 80% of their baseline distance. Kinetic and kinematic data were recorded for the second group. Results showed a decrease in GRF for the fatigued hop condition and participants generally landed with an adapted hop strategy caused by less knee and hip flexion.

An additional study compared dynamic stabilization time after isokinetic and functional fatigue (Wikstrom, Powers, & Tillman, 2004). Six male participants completed a series of two-legged jumps at 50% of their maximal jump height, single leg
landings to measure stabilization time, and a series of functional test. The functional test included the Southeast Missouri Agility Drill (three series of forward sprints, diagonal back pedaling, and side shuffling), plyometrics box jumps (31, 46, and 61-cm), side to side bounds, mini-tramp jumps (30 small jumps on and off a trampoline), co-contraction arc side shuffling (ten 180° arcs performed by side shuffling with tension from an elastic cord), and two-legged hop sequence exercises. Another six participants performed isokinetic concentric exercises of plantarflexion and dorsiflexion at 30°/s and 120°/s. Fatigue was determined when the participant torques dropped under 50% of their pre-fatigue state during isokinetic testing and no set standard was used to classify fatigue from the functional exercise condition. Results revealed no significant differences in time to stabilization during drop landing testing and no protocol main effect was shown.

**Functional Skills**

Orishimo & Kremenic (2006) studied the effects of fatigue on a single-leg hop landing. Thirteen male participants performed at least two sets of 50 step-ups of 30-cm and single leg hops of 80% of their maximal distance onto a force plate until fatigued. Fatigue was determined when each participant was unable to achieve at least 80% of the distance for the single-leg hop. Results showed that fatigue increased knee flexion and shifted the ankle into a more dorsiflexed position at contact, while hip flexion decreased. The authors indicated that the compensatory increase in ankle motion was important to maintaining lower extremity stability.

Coventry et al. (2006) compared the effect of lower extremity fatigue on shock attenuation during a single-leg landing. This study focused on single-leg drop landings rather than bilateral landings. Research has indicated most ACL injuries occur from a
noncontact single-leg landing (Hewett et al., 2007). The authors report that single-leg landings are far stiffer than double-leg landings. The study used cycles of drop landings, countermovement jumps, and five single leg squats all on their dominant leg. Results indicated that the ankle extensor muscles became fatigued, and that knee and hip flexion increased at contact in order to maintain shock attenuation. The single leg landings resulted in greater stiffness to decrease additional movement in the anterior and posterior direction and maintain balance in the drop landings. This landing strategy altered body position and shifted the stress distribution of the lower extremity. The level of stress that may be placed to other areas of the knee joint is an area in which further study is warranted.

Madigan & Pidcoe (2003) continued with a functional fatigue protocol involving a series of two 25-cm single-leg landings onto a force plate followed by three single-leg squats for both legs. Data were recorded on their right leg and each participant continued the fatigue protocol until they felt their knee would collapse on the next trial. Results indicated that participants landed with increased lower extremity ROM and decrease GRF while fatigued. The authors suggested that the results could be due to adjustments made by each participant to reduce the impact during landing while fatigued.

Mclean et al. (2007) investigated the impact of fatigue on gender-based high risk landing strategies. The functional fatigue protocol consisted of 20 step ups and step downs of 20-cm, bounding for six meters with a direction change, and repeating the process until four minutes elapsed. Before and after the fatigue protocol, each participant performed ten drop landings from a 50-cm platform. The focus of this study was on the kinematic variables with additional information on joint moment force of the lower
extremity. Results showed females landed with more ankle plantarflexion, ankle supination, knee abduction, and knee internal rotation at contact with both models. The addition of fatigue caused a significant increase in ROM and female outcome measures were more pronounced than males. The kinetic variables showed increased knee joint moments in both groups resulting in a posterior sheer force of the tibia. However, the posterior sheer force of the tibia occurred earlier for females than males. This response has been shown to increase the risk of anterior cruciate ligament injuries in females (Hewett, Meyer, et al., 2006; Hewett et al., 2007).

Other functional muscle fatigue protocols included a series of vertical jumps; followed by a 30-m sprint until volitional exhaustion was achieved (Chappell, Herman, Knight, Kirkendall, Garrett, & Yu, 2005). A study by Pappas, Sheikhzadeh, Hagins, and Nordin (2007), followed the model of Chappell and associates with 100 consecutive jumps over short obstacles followed by 50 maximal vertical jumps. Pappas, et al. (2007) justify their fatigue protocol by indicating the movement patterns are similar to athletes participating in sports such as soccer that involve concentric and eccentric loading of the muscles.

Muscle Fatigue Induced by Treadmill Running

Lower extremity muscle fatigue induced by running on a treadmill has been shown to influence VGRF and kinematics during drop landings. Cerullo (2000) investigated the effects of lower extremity muscle fatigue during drop landings by comparing EMG activity, kinetics, and kinematics during soft and hard drop landings of 60-cm. Soft landings were defined as maximal knee flexion and hard landings as minimal knee flexion after initial contact. A running fatigue protocol was applied to
measure the effect of muscle fatigue. Each participant (10 males and 10 females) performed five acceptable trials of soft and hard landings, followed by the running fatigue protocol, and ending with five additional soft and hard landings. Landings were randomized for each participant. The running fatigue protocol consisted of a five minute warm-up run on a treadmill starting at five miles per hour (mph) and 0% grade. Every two minutes, the treadmill settings were increased by one mph and 5% grade until each participant established a heart rate 75% of their maximal heart rate (MHR). Once the participant reached 75% of their MHR they were asked their Rating of Perceived Exertion (RPE). After RPE was established, each participant was asked every 30 seconds if the treadmill speed had to be adjusted to maintain the target heart rate and RPE level. The fatigue test was terminated when participants reached a 50% reduction in treadmill speed compared with the speed which was established to reach 75% MHR. Participants repeated the testing 72 hours later for fatigue and non-fatigue conditions using isokinetic testing. Results indicated a significant increase in muscle activity after fatigue, significant increase in peak magnitude of F1 in the hard and control condition, and a significant increase in peak magnitude of F2 in soft landings after fatigue.

In an additional study, participants performed a fatigue protocol of running at a speed of five-eight mph for three minutes, increasing by 2.5% grade every two minutes until the participants could not continue at maximal effort or until exhaustion (Benjaminse et al., 2008). The fatigue protocol was used to represent an overall body fatigue model and examine lower extremity kinematics. Each participant (15 males and 15 females) performed five acceptable trials of a single-leg hop onto a force plate followed by a vertical jump pre and post running fatigue protocol. Trials were
considered acceptable when the single-leg hop was equal to 40% of their height, landing with their preferred leg on the force plate, and landed without losing balance. After the fatigue protocol, each participant performed the single-leg hop test. Results indicated all participants were affected by the fatigue protocol. The participants revealed significantly less maximal knee valgus and knee flexion at contact following the fatigue condition. A gender difference was not found in the single-leg hop test or during fatigue. The authors concluded that participants may land with a stiffer landing strategy in a protective effort to increase knee stability and activate more static muscle structures.

Similar findings were reported by Moran and Marshall (2006) investigating the effect of fatigue on tibial impact accelerations and knee kinematics during drop landings. Fifteen male participants performed a treadmill running protocol, running at 6-mph with a 3% grade. The grade increased 1.5% every minute until each participant achieved a RPE of 17 (very hard). The 17 score on the RPE was used to determine a fatigue state. Participant’s performed drop landings of 30-cm and 50-cm (five in each) followed by a vertical jump as soon as landings occurred before and after the fatigue protocol. Results are consistent and similar with the other studies using treadmill running and drop landings. Findings indicated that fatigue significantly increased tibial acceleration and peak angular velocity from 30-cm, but not from the 50-cm drop landings. Drop landings occurring from lower heights of 30-cm decreases the capacity to attenuate the force and can be associated with increase injury risk (Moran & Marshall, 2006).

Wingate Anaerobic Test

One modality that has been used extensively to measure anaerobic power is the Wingate Anaerobic Test (WAT). The WAT can be used to assess anaerobic performance
and as an exercise to investigate responses to supramaximal exercise (Bar-Or, 1987).

Anaerobic performance is determined by measuring peak power, mean power, and the fatigue index. Peak power typically is seen within the first five seconds of the test and then a significant decline in power occurs. The fatigue index, also called the percentage of power drop, is peak power minus the minimal power, divided by peak power. The WAT is performed for 20 or 30 sec at maximal effort. The standard protocol is typically 30 sec, however 20 sec is also used and has been shown to be a valid alternative to the 30 sec test (Laurent et al., 2007). The WAT results in both central and peripheral fatigue due to the maximal effort required to perform the test. During maximal anaerobic exercise, a accumulation of $[\text{H}^+]$ and lactate acid occurs and results in impair enzyme activity in energy metabolism affecting muscle function, along with an initial increase in blood glucose that can lead to hypoglycemia (Laurent et al., 2007). Symptoms for hypoglycemia include fatigue, headaches, dizziness, and nausea (Laurent et al., 2007).

The WAT is considered mainly an anaerobic test. However, it is evident that during short duration of maximal effort, some aerobic metabolism occurs (Smith & Hill, 1991). The overall conscious is that the WAT is highly anaerobic (Meldbo & Tabata, 1993) resulting in 80% of the energy metabolism from anaerobic pathways (Beneke, Pollmann, Bleif, Leithäuser, Hüttler, 2002). Understanding the energy system contributions of an exercise test and fatigue protocol is therefore imperative in order to accurately measure muscle force (Smith et al., 1991; Bar-Or, 1987).

The vast majority of sports require a combination of both aerobic and anaerobic metabolism to complete the skill. Sports like soccer, basketball, and baseball entail short
burst of maximal effort repeated countless number of times. The WAT resembles that effort seen in those popular sports, specifically repeated bouts of the Wingate.

In order to accurately measure anaerobic performance, there are a variety of factors that affect the validity of the WAT. Factors include: learning effect, motivation, seated vs. standing during cycle, straps or no straps on pedals, time of day the test is conducted, humidity and temperature, caffeine in diet, dietary intake, and should be controlled for as much as possible.

Although the WAT is a standard test and exercise modality, the test has not been used in isolation as fatigue protocol and implemented into drop landing studies to measure its effect. Therefore using a WAT for a fatigue protocol to investigate overall lower extremity muscle fatigue and how fatigue affects landing mechanics, is warranted.

Assessing Fatigue

One way to assess muscle fatigue is based on metabolites measured in muscle to the accumulated of O2 deficit and how it affects adenosine triphosphate (ATP) turnover rate (Medbo & Tabata, 1993). The ATP in muscle is responsible for fueling muscle contractions and is used to shuttle all energy system pathways regardless of the work performed (Shulman & Rothman, 2001). In order to investigate metabolites, blood samples and muscle biopsies are needed (Medbo & Tabata, 1993). In addition, maximum oxygen consumption (VO² Max) testing is necessary to calculate ATP levels thus calculating the amount of fatigue in a given muscle (Medbo & Tabata, 1993). However, when muscle biopsies are conducted, they are usually taken only from one muscle and indicate muscle fatigue in only one area. When examining muscle metabolites, diet should be controlled among participants, along with fitness levels. Measuring
metabolites and performing muscle biopsies helps to determine the nature and extent of muscle fatigue. This methodology is not commonly used because of the invasive procedure, time and cost constraints.

Electric stimulation has also been used to assess muscle fatigue by measuring the electrical potential generated by muscle by quantifying amplitude, latency, and conduction velocity. By measuring those variables, valuable information can be ascertained on muscle function. The use of electric stimulation is often limited because of the stimulation needed to illicit a muscle contraction is not well tolerated by subjects (Kremenic, Glace, Ben-Avi, Nicholas, & Mchugh, 2008).

The use of magnetic stimulation, in addition, has been used to assess muscle fatigue (Kremenic et al., 2009). Magnetic stimulation is designed to excite neurons in muscle or brain by using a magnetic field to pass current through insulating tissues (Loo, Sachdev, Mitchell, Gandevia, Malhi, Todd, et al., 2008). Transcranial (central) magnetic stimulation can be used to measure the connection between the primary motor cortex and a muscle to determine the conduction velocity. Measuring the conduction velocity is useful for studying brain function and for evaluation and treatment of certain brain disorders. Transcranial magnetic stimulation recently has gained approval by the Food and Drug Administration in the United States (2008) for use but is limited to certain conditions and disorders. Overall magnetic stimulation devices are less invasive and does not cause discomfort usually associated with electric stimulation.

Although there is not a standard methodology to assess muscle fatigue, the standard methodology is to determine a reduction of work performed in a given muscle action. Assessments are based on power output, percentage of work performed by weight
lifting, running performance base on time, and reduction of performance on agility and balance drills, and investigations on concentric and eccentric work. Overall, selecting a fatigue protocol is supported by what the researcher is investigating.

Lower Extremity Injuries

Stress fractures resulting from landings are common and an area of interest for researchers and clinicians who seek to understand lower extremity injury. The injury is common among athletes and military recruits because of repetitive loading to bone and other soft tissues (Edwards, Wright, & Hartman, 2005; Milgrom et al., 2006). GRF applied during landing can be defined as active loading and impact loading (high frequency). Active loading refers to low frequency stress influenced by neuromuscular feedback. Impact loading stress results in preplanned neuromuscular and mechanical activity (Nigg, 1986).

High magnitude of GRF attenuated while running has been linked to stress fractures in runners (James, Dufek, & Bates, 2006). High impact exercises such as jumping may cause more impact forces and stress to bone and other connective tissue than running (Milgrom et al., 2000). James et al. (2006) reported drop landing strategies and indicated that participants who landed with increased ROM of the hip, knee, and ankle, experienced less tibial stress. James et al. (2006) implemented a fatigue protocol before drop landings were performed and concluded that, in addition to landing with increased lower extremity range of motion, participants had greater GRF peaks, increased loading rate, and less muscle EMG activity. James and associates implicated the results as high risk factors for stress fractures.
Attention in the literature has focused on the knee specifically to patellofemoral syndrome and ACL injuries. The complexity of these injuries is such that they are associated with many factors. Patellofemoral Syndrome has 68 causes documented in the literature (Powers, 2003). Anterior cruciate ligament injuries occur among the active population at an alarming rate, with an approximate 250,000 injuries per year in the U.S. (Hewett et al., 2007). The majority of these injuries are sustained by females, reported as one in 100 high school girls and one out 10 college women participating in sports (Hewett et al., 2007). Various factors have been associated with ACL injury including: contact collisions, noncontact (70% of all ACL injuries), abnormal motion perturbation, shoe-surface interaction, anatomical characteristics, hamstring flexibility, foot pronation, body mass index, age, hormonal responses, diet, injury history, neuromuscular and biomechanical relationships (Hewett, Meyer, et al., 2006).

Activities requiring landings and previous ACL injury have been identified as high risk factors for ACL injuries, with the majority of these re-injuries occurring among females. Researchers have established that females land with less ROM, greater impact forces, increased knee valgus moments, delayed muscle co-activation, and incorrect muscle activation timing as common predisposing factors (Hewett, Meyer, et al., 2006; Hewett et al., 2007). As a result, research has focused on landing in order to address concerns of injury, to help educate and train athletes to land appropriately and potentially to decrease the risk of ACL and other lower extremity injuries. Efforts to reduce this injury rate have included jumping and landing training, which has been shown to decrease the risk and severity of injury by given landing instructions (verbally and by visual inspection), strength and balance training, neuromuscular training and reeducation
to promote correct movement patterns (Hewett, Meyer, et al., 2006; Hewett, Ford, et al., 2006; Noyes et al., 2005; Onate et al., 2005).

Summary

Landing is an important component for understanding lower extremity injury and functional performance. Landings are complex and multifaceted in nature. Numerous variables are associated when studying how athletes land and the stress which is placed on the body. Lower extremity muscle fatigue is a new perspective with which to investigate injury prevalence and specifically, injury to the knee (see Table 1, focused review summary).

Muscle fatigue can be briefly described as a reduction in muscular work. One of the limitations of studying muscle fatigue is establishing a protocol to accomplish fatigue. Studies that focused on muscle fatigue and biomechanics have defined their fatigue protocols as some arbitrary number in reduction of muscular work. Protocols have ranged from running, drop landings, functional skill exercises such as jumping and hopping, and isolated muscle selection fatigued by weight machine exercises.

Previous research has shown that females have the highest knee injury rate because of selected landing strategy, and biomechanical and neuromuscular factors (Hewett et al., 2007). Additional research examining the landing strategies of male and female athletes under fatigue conditions is warranted.
Table 1. Focused Review Summary

<table>
<thead>
<tr>
<th>Author</th>
<th>Title</th>
<th>Year</th>
<th>Purpose of Investigation</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>McLean</td>
<td>Fatigue-induced ACL Injury Risk Stems from a degradation in central control</td>
<td>2009</td>
<td>To determine whether fatigue-induced landing mechanics were governed by central fatiguing mechanisms.</td>
<td>Unilateral fatigue induces a fatigue crossover effect to the contralateral limb during single-leg landings.</td>
</tr>
<tr>
<td>Kernozek et al.</td>
<td>Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue</td>
<td>2008</td>
<td>To determine and describe the lower extremity kinematics and kinetics differences caused by neuromuscular fatigue during drop landings and compare changes between age and skilled match among females.</td>
<td>Neuromuscular fatigue caused men and women to land with more hip flexion. Men exhibited larger peak knee varus angles regardless of fatigue. Women demonstrated larger peak valgus angles. No changes with fatigue or a different response due to gender. Women exhibited greater knee anterior shear force post-fatigue.</td>
</tr>
<tr>
<td>Benjaminse et al.</td>
<td>Fatigue alters lower extremity kinematics during a single leg stop jump task</td>
<td>2008</td>
<td>To examine the kinematic characteristics of the hip and knee during a single-leg stop-jump task before and after exercise-to-fatigue, and to determine if the fatigue response is gender-dependent.</td>
<td>Males and females demonstrated significantly less maximal knee valgus and decreased knee flexion at initial contact post-fatigue. Fatigue developed from exhaustive running alters lower extremity kinematics.</td>
</tr>
<tr>
<td>McLean et al.</td>
<td>Impact of fatigue on gender bases high risk landing strategies</td>
<td>2007</td>
<td>Examine the potential contribution of neuromuscular fatigue to noncontact Anterior Cruciate Ligament injuries.</td>
<td>Females landed with more initial ankle plantar flexion and peak stance ankle supination, knee abduction, and knee internal rotation compared with men. Fatigue increased initial and peak abduction and internal rotation motions and peak knee internal rotation, adduction, and abduction moments and pronounced more in females.</td>
</tr>
<tr>
<td>Study</td>
<td>Title</td>
<td>Year</td>
<td>Objective</td>
<td>Findings</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>------</td>
<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td>Kellis et al.</td>
<td>Agonist versus antagonist muscle fatigue effects on thigh muscle activity and vertical ground reaction during drop landings</td>
<td>2007</td>
<td>To investigate if knee extension fatigue would have a higher influence on landing biomechanics compared with a knee flexion protocol.</td>
<td>Knee extension fatigue resulted in significantly lower ground reaction force and higher knee flexion angles at initial contact while maximum hip and knee flexion also increased and an increased in quadriceps to hamstring muscle activation. Knee flexion fatigue had no effect on ground reaction force and the quadriceps to hamstring muscle activation increased before landing and decreased after impact.</td>
</tr>
<tr>
<td>Augustsson et al.</td>
<td>Single leg hop testing following fatiguing exercise: Reliability and biomechanical analysis</td>
<td>2006</td>
<td>To improve the possibilities of evaluating the effects of training or rehabilitation interventions.</td>
<td>During the take off for the single leg hops, hip and knee flexion angles generated power for the knee and ankle joints, and ground reaction forces decreased for the fatigued hop conditions compared with the non fatigued condition. Hip moments and ground reaction forces were lowered for the fatigued hop condition. The negative joint power was 2-3 times greater for the knee than for the hip and 5-10 times greater for the knee for the ankle during landing for all conditions.</td>
</tr>
<tr>
<td>Moran et al.</td>
<td>Effect of fatigue on tibial impact acceleration and knee kinematics in drop jumps</td>
<td>2006</td>
<td>To determine if whole body fatigue increased peak impact acceleration on the proximal tibia during plyometric drop jumps and produced associated changes in knee joint kinematics during landing.</td>
<td>Fatigue caused a significant increase in tibial impact acceleration and peak angular velocity in drop jumps from 30 cm but not from 50 cm. Drop jumps from 50 cm resulted in larger impact accelerations.</td>
</tr>
<tr>
<td>Orishimo et al.</td>
<td>Effect of fatigue on single leg hop landing biomechanics</td>
<td>2006</td>
<td>To measure adaptations in landing strategy during single leg hops following thigh muscle fatigue.</td>
<td>Fatigue significantly increased knee motion and shifted the ankle into a more dorsiflexed position. Hip flexion was reduced following fatigue. Peak extension moment tended to decrease at the knee and increased at the ankle and hip. Ankle plantar flexion moment at the time of peak total support moment also increased. Performance at the ankle increased to compensate for weakness in the knee musculature and to maintain lower extremity stability during landing.</td>
</tr>
<tr>
<td>Authors</td>
<td>Title</td>
<td>Year</td>
<td>Objective</td>
<td>Findings</td>
</tr>
<tr>
<td>------------------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
<td>---------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Coventry et al.</td>
<td>The effect of lower extremity fatigue on shock attenuation during single leg landing</td>
<td>2006</td>
<td>To determine the effect of lower extremity fatigue on shock attenuation and joint mechanics during a single leg drop landing.</td>
<td>No significant change in shock attenuation throughout the body. Hip and knee flexion increased and ankle plantar flexion decreased at touchdown with fatigue. Hip joint work increased and ankle work decreased. The lower extremity is able to adapt to fatigue though altering kinematics and redistributing work to larger proximal muscles.</td>
</tr>
<tr>
<td>Chappell et al.</td>
<td>Effect of fatigue on knee kinetics and kinematics in stop-jump tasks</td>
<td>2005</td>
<td>To determine the effect of lower extremity fatigue on knee kinetics and kinematics on stop-jump task.</td>
<td>Fatigued athletes demonstrated altered motor control strategies that may increase the risk of injury for both males and females.</td>
</tr>
<tr>
<td>Wikstrom et al.</td>
<td>Stabilization time after isokinetic and functional fatigue</td>
<td>2004</td>
<td>To compare the effects of an isokinetic fatigue protocol and a functional fatigue protocol on time to stabilization, ground reaction force and joint kinematics during a jump landing.</td>
<td>No significant differences when comparing time to stabilization, ground reaction force, and joint kinematics after isokinetic and functional fatigue protocols. No difference was noted between isokinetic and functional fatigue protocols relative to dynamic stability when landing from a jump.</td>
</tr>
<tr>
<td>Madigan et al.</td>
<td>Changes in landing biomechanics during a fatiguing landing activity</td>
<td>2003</td>
<td>To investigate the effects of lower extremity fatigue on ground impact force, lower extremity kinematics and lower extremity kinetics during landing.</td>
<td>A decrease in ground impact force and an increase in maximum joint flexion during landing with fatigue were observed. Trend reversals in hip and ankle impulse during the activity suggest a change in landing strategy as fatigue progressed.</td>
</tr>
<tr>
<td>Cerullo, J.F.</td>
<td>The effects of lower extremity muscle fatigue on vertical ground reactions and muscle activation patterns during landing</td>
<td>2000</td>
<td>To determine the effects of dynamic lower extremity muscle fatigue on vertical ground force data and muscle activation patterns during consciously controlled drop landings.</td>
<td>Results indicated a significant increase in muscle activity after fatigue, significant increase in peak F1 in the hard and control condition, and a significant increase in F2 in soft landings after fatigue.</td>
</tr>
<tr>
<td>Ben-Or</td>
<td>The wingate anaerobic test an updates on methodology, reliability and validity</td>
<td>1987</td>
<td>To review most aspects of the wingate anaerobic test.</td>
<td>Ample evidence exist that the wingate anaerobic test is a reliable and valid test to access.</td>
</tr>
</tbody>
</table>
CHAPTER THREE

Methods

Design

This study investigated the effects of a single session of repeated muscle fatigue on ground reaction force (GRF) during drop landings. The independent variables included: fatigue conditions and gender. The dependent variables included the GRF variables: forefoot (F1), rearfoot (F2), anterior/posterior (AP) peak force at F1, AP peak force at F2, medial/lateral (ML) peak force at F1, and ML peak force at F2. The maximum F1 and F2 were scaled to the number of body weights (bw) for each participant for practical relevance.

Null Hypothesis

Ho1: Are there significant differences observed within the fatigue conditions across each dependent variable?

Ho2: Are there significant differences observed between gender across each dependent variable?

Ho3: Are there significant interaction effects across each dependent variable?

Participants

Ten female (22.5 yrs.±0.85) and 10 male (24.1 yrs.±2.6) recreational athletes from Ohio University volunteered and were recruited by announcement posters located throughout Ohio University. A complete demographic breakdown can be found in Table 2 (in Chapter 4). The number of participants and drop landing trials used is this study was determined by Bates, Dufek, and Davis (1992) whose research in drop
landings indicating for statistical power the number of trials that are required for each subject for a subject sample size of 20.

Participants attended an information session at least one week prior to data collection in order to orient them to the experimental protocol, answer all questions and review the informed consent.

The experimental session included the collection of the signed consent form, administration of the medical history injury form, and completion of the lower extremity orthopedic physical examination to assess joint integrity (see Appendix A-C).

Participants were required to be free of lower extremity injury for at least six months prior to data collection and with no history of cardiovascular/pulmonary illness, as screened by the health questionnaire and an orthopedic physical exam performed by an athletic trainer (AT) (see Appendix C). Participant information regarding demographics of age, weight, and height was recorded. A complete breakdown can be found in Table 2 (p. 62).

Each subject was asked not to participate in any form of exercise 24 hours prior to data collection and to refrain from any alcohol and caffeine consumption. Data collection and analysis was performed in the Exercise Science laboratory located in Grover Center (E116) at Ohio University. The study was approved by the Institutional Review Board of Ohio University. Prior to participation all participants read and signed an informed consent form (see Appendix A).

Experimental Condition

Participants performed five experimental conditions. The first condition consisted of five non-fatigue drop landings (control) from a 60 cm platform, followed by four fatigue
conditions that consisted of a 20 sec Wingate Anaerobic Test (WAT). Each fatigue condition was followed by two drop landings (60-cm) onto a force platform with five minutes of active rest. The means and standard deviations were calculated for the drop landings for each experimental condition.

The WAT consisted of pedaling an ergometer bicycle using both legs, in a seated position, and with the use of toe straps on the pedals. Before the experimental condition was administered, a five minutes warm up on the cycle was performed between 50-60 watts for each participant. After the warm up, the participant performed five non-fatigue drop landings.

Drop Landings

Each participant was given landing instruction and shown a demonstration by the primary investigator. Participants were allowed to practice the drop landing as many times as needed to feel comfortable with the protocol. Participants performed drop landings from a 60-cm platform onto a force plate installed flush with the floor surface (see Figure 2). The force plate was located 20-cm from the front of the 60-cm platform. Each participant landed with their dominate foot on the force plate and the other foot beside the force plate (see Figure 3). Leg dominance was determined by asking each participant with which leg they would prefer to kick a soccer ball. Participants landed with their bare feet on the force plate and floor to eliminate shoe interaction and changes in GRF due to cushioning of shoes.
To avoid any coaching effect, participants were instructed to land how they would normally land if they had to drop from any given height to ensure their normal landing mechanics. Participants dropped when given the instructions, “ready and drop”. The ready command was given once participants had their arms crossed in front of their body and their dominant foot was hanging off of the platform. Each participant performed two drop landing after each fatigue condition with 30 sec of rest after each drop landing to reduce muscle fatigue recovery. A stop watch was used to control for time.

A spotter was present for each participant while performing the drop landings and padding was placed behind each participant to ensure safety. Drop landings were deemed acceptable if the entire foot was in contact with the force plate, balance was maintained, and the participant remained on the force plate for a minimum of two seconds.
Unacceptable trials were repeated. Participants were able to discontinue the study at any time.

*Figure 3. Drop landing.*

**Fatigue Condition**

Fatigue was induced by a 20 sec WAT (see Figure 4). Before the test was administered, participants practiced the protocol for several seconds to ensure the test was performed correctly. The fatigue protocol included pedaling as hard as possible with no resistance until each subject reached a cadence that approximately took several seconds to achieve. Once the participants reached a high cadence, the participants pushed a button on the handlebars that instantly added a resistance of 0.075 kg per their body weight for 20 seconds as verbal encouragement was given to promote maximal effort. Immediately following participants were instructed promptly to remove their
shoes and prepare for the drop landings. This process was repeated four times with five minutes of active rest between each fatigue condition. Active rest included each participant cycling one minute after the drop landings with resistance between 50-60 watts. The rest period between fatigue bouts provided sufficient time for full recovery to replenish adenosine triphosphate (ATP) and phosphocreatine (PC) energy pathways used to supply fuel to the muscle during anaerobic maximum work (Shulman & Rothman, 2001). The fatigue protocol is similar in intensity to maximal performance and training experienced by athletes. Peak power, average power, and power drop (fatigue index) was collected to monitor fatigue and effort (see Table 3, p. 62).

Each participant was asked to rate their perceived rate of exertion using the Borg scale immediately following the WAT to determine their rate of effort. The Borg scale ranges from 1-20, where 10 indicates light, 15 hard, 17 very hard, and 20 maximal exertion (found in Table 4, p. 62). Participants were also asked to report any possible side effects that may have occurred during the experimental protocol (see Appendix C). Participants were asked during their five minute active rest if they experienced a headache, dizziness, and/or other adverse symptoms (see Appendix C). Each participant’s physical reaction was monitored because the high intensity work output necessary to assess maximum power in the WAT could result in a drop in blood pH leading to hypoglycemia (Laurent et al., 2007).

Instrumentation

Ground reaction force was collected by using a 9281C Kistler force plate (Kistler Instruments Corporation, USA) and amplified with an external 8-channel 9865B change amplifier (Kistler Instruments Corporation, USA). The GRF data were synchronized
with an Event Synchronization Unit (Peak Performance Technologies Inc., USA) and analyzed with Peak Motus Software 8.0 (Peak Performance Technologies Inc., USA).

Anaerobic data were collected by using a Monark Ergomedic 894E Peak bike (Monark, Sweden) with Windows-based Monark Anaerobic software (Monark, Sweden) to determine muscle fatigue characteristics.

Figure 4. WAT to induce lower extremity muscle fatigue.

Statistical Analysis

A mixed effect factorial analysis of variance (ANOVA) with repeated measures for the dependent variables was used to analyze the equality of means under a number of dependent variables treated separately to test within, in between and interactions of the independent variables set at an a priori alpha of 0.05. Data were analyzed using SPSS statistical software, version 17.0 for windows (SPSS Inc., Chicago, IL).
Operational Definitions

For this study, terms were operationally defined as follows:

*Non-fatigue Condition*: Consisted of five non-fatigue drop landings that served as the control for each participant.

*Fatigue Condition*: Consisted of a Wingate Anaerobic Test, followed by two drop landings and was performed a total of four times.

*Number of body weights (bw)*: The magnitude of force applied to the body expressed in multiples of its own weight. Newton (N) was the unit of measure used to calculate the force acting on the body. The force was scaled using N force/ body weight in kg. Each participant’s body weight was converted to kg.

*Recreational athlete*: A participant with previous involvement in organized sport or training program that included jumping activities such as basketball, volleyball, and running (Dufek et al., 1990).

*Trial*: Consisted of two drop landings that were averaged for each condition.
CHAPTER FOUR

Results

The participants used for this study consisted of ten female (22.5±0.85 yrs) and 10 male (24.1±2.6 yrs) healthy recreational athletes that were free from lower extremity injury and cardiovascular/pulmonary illness (Table 2).

Table 2

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Age</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>10</td>
<td>24.1 ± 2.6</td>
<td>174.15 ± 11.38</td>
<td>71.36 ± 11.01</td>
</tr>
<tr>
<td>Female</td>
<td>10</td>
<td>22.5 ± 0.85</td>
<td>166.85 ± 9.25</td>
<td>62.57 ± 6.27</td>
</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>23.3 ± 2.11</td>
<td>170.50 ± 10.50</td>
<td>66.97 ± 9.82</td>
</tr>
</tbody>
</table>

Note. Cm=centimeters; kg = kilograms

Descriptive information was collected for the WAT for all participants to monitor fatigue. Male participants revealed an overall percent power drop similar to the female participants, despite differences observed in peak power. Peak power was significantly greater in males compared to the females (Table 3).
Table 3

 Means and Standard Deviations for Peak Power (W), Mean Power (W), and Power Drop (%) of Participants

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Peak Power (W)</th>
<th>Mean Power (W)</th>
<th>Power Drop (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>10</td>
<td>633.34 ± 120.30</td>
<td>504.68 ± 106.09</td>
<td>45.36 ± 8.29</td>
</tr>
<tr>
<td>Female</td>
<td>10</td>
<td>373.23 ± 80.58</td>
<td>303.35 ± 67.24</td>
<td>43.00 ± 10.21</td>
</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>503.29 ± 100.29</td>
<td>404.02 ± 86.67</td>
<td>44.18 ± 9.23</td>
</tr>
</tbody>
</table>

Note. W=watts

The mean rating of perceived exertion (RPE) was identical between participants and was reported as hard and very hard across all conditions (Table 4). The RPE was used to monitor fatigue and effort during the fatigue conditions.

Table 4

 Means and Standard Deviations for Rate of Perceived Exertion (RPE) of Participants

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>RPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>10</td>
<td>16.23 ± 1.73</td>
</tr>
<tr>
<td>Female</td>
<td>10</td>
<td>16.23 ± 2.38</td>
</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>16.23 ± 2.06</td>
</tr>
</tbody>
</table>

Note. 12=moderate; 13=somewhat hard; 15=hard; 17=very hard; 20=maximal exertion
A mixed effect factorial analysis of variance (ANOVA) with repeated measures was conducted. The independent variables included gender and fatigue condition. Fatigue was treated as the repeated measure. The dependent variables included: peak magnitude of forefoot force (F1), peak magnitude of rearfoot force (F2), anterior/posterior (AP) force at forefoot peak force (F1), anterior/posterior (AP) force at rearfoot peak force (F2), medial/lateral (ML) at forefoot peak force (F1), and medial/lateral (ML) at rearfoot peak force (F2). In each analysis only one dependent variable was included.

No significant main effect was observed between gender across all dependent variables, p>0.05. A significant main effect was observed within the fatigue conditions at F2, F(4,15)=6.508, Wilks lambda=0.366, p<0.05, partial $\eta^2=0.634$. No significant interaction effect was observed, p>0.05. A Mauchy’s test was conducted to test the assumption of sphericity (p>0.05). Sphericity assumption was held and the Greenhouse-Geisser test reported, $\varepsilon=0.780$ and the Huynh-Feldt=1. Raw data for all dependent variables can be found in Appendices E-J.

Pairwise comparisons were conducted to identify differences within the fatigue conditions using a Bonferroni adjustment (see Table 5). Differences were observed between condition one and condition five, p=0.021, p<0.05. Significant differences were observed within all fatigue conditions except for the first fatigue condition compared to the second fatigue condition, p<0.05.
Table 5

Pairwise Comparisons for F2

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Significant Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 5</td>
<td>.021</td>
</tr>
<tr>
<td>2 &amp; 4</td>
<td>.017</td>
</tr>
<tr>
<td>2 &amp; 5</td>
<td>.002</td>
</tr>
<tr>
<td>3 &amp; 4</td>
<td>.022</td>
</tr>
</tbody>
</table>

Note. p<0.05.

Research Question 1

Are there significant differences observed within the fatigue conditions across each dependent variable?

Analysis. No significant differences observed within the non-fatigue condition and the fatigue conditions for AP force at F1, AP force at F2, ML force at F1, ML force at F2, and F1 force, p>0.05 (see Table 6).
Table 6

*Statistical Analysis for all Dependent Variables across all Conditions and between Gender*

<table>
<thead>
<tr>
<th></th>
<th>M</th>
<th>SD</th>
<th>P</th>
<th>(\eta^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-F1</td>
<td>3.51</td>
<td>0.90</td>
<td>0.314</td>
<td>0.257</td>
</tr>
<tr>
<td>F2</td>
<td>8.35</td>
<td>2.35</td>
<td>0.003*</td>
<td>0.634</td>
</tr>
<tr>
<td>AP at F1</td>
<td>-416.12</td>
<td>135.77</td>
<td>0.172</td>
<td>0.330</td>
</tr>
<tr>
<td>AP at F2</td>
<td>101.03</td>
<td>159.17</td>
<td>0.427</td>
<td>0.214</td>
</tr>
<tr>
<td>ML at F1</td>
<td>0.14</td>
<td>69.62</td>
<td>0.942</td>
<td>0.047</td>
</tr>
<tr>
<td>ML at F2</td>
<td>309.31</td>
<td>666.44</td>
<td>0.305</td>
<td>0.261</td>
</tr>
</tbody>
</table>

Note. F1 (forefoot force), F2 (rearfoot force), AP (anterior/posterior), and ML (medial/lateral)

*Analysis.* There is a significant differences observed within the non-fatigue condition and the fatigue conditions for only F2 force, F(4,15)=0.003, p<0.05, partial \(\eta^2=0.634\) (see Figure 5).
Research Question 2

Are there significant differences observed between gender across each dependent variable?

*Analysis.* No significant main effect was observed between gender across all dependent variables, \( p > 0.05 \) (see Figure 6).

*Figure 5.* Condition differences for F2.

Note. 1 and 2 not significantly different, \( p < 0.05 \).
Research Question 3

Are there significant interaction effects across each dependent variable?

Analysis. No significant interaction effect was observed, p>0.05.
CHAPTER FIVE

Discussion

This study investigated the effects of a single session of repeated Wingate Anaerobic Test (WAT). The WAT was used to produce exercise-induce fatigue and to identify alterations on ground reaction force during drop landings. The independent variables in this study included levels of fatigue, and gender. The dependent variables included ground reaction force (GRF) variables: forefoot (F1), rearfoot (F2), anterior/posterior (AP) peak force at F1, AP peak force at F2, and medial/lateral (ML) peak force at F1 and F2.

Gender and Ground Reaction Force

Data revealed significant differences in GRF for F2, following the fatigue conditions, regardless of gender. Gender did not influence peak force magnitudes for any levels of fatigue during drop landings. Values for peak GRF for males (7.84±1.5bw) and females (7.82±2.2bw) were nearly identical in the non-fatigue condition (see Appendix F), where gender differences were not revealed in respect to peak force. This result is atypical and is a contrast to the literature. Research has shown there are landing differences between males and females (Devita & Skelly, 1992; Gross & Nelson, 1988; Huston, 2007). Ground reaction force variables determine magnitude of force, but do not quantify the joint positioning that created those forces. Kinematic analyses are required to quantify and explain changes in GRF. Gender differences in landing may have been identified with kinematic analyses and explained the changes that were reported in GRF while performing repeated conditions of fatigue.
Participants across each fatigue condition demonstrated higher peak force for the second drop landing compared to the first, 76% of the time. This result was interesting and might have occurred due to an increase in fatigue. This result may indicate that subjects continued to increase levels of fatigue through repeated conditions of exercise-induce fatigue. Traditionally the mean and standard deviation are collected for all trials in a condition. The participants’ during the second trial was observed to be much higher than the first trial. Therefore if duplicated, reporting the second trial value instead of averaging the trails within each condition might be a better way to report the data to indicate greater fatigue results. Additional analyses investigating the mean differences between each individual post fatigue is warranted for future research.

Landing differences typically seen between genders can be attributed to neuromuscular responses (Renstrom, et al. 2008; Hewett et al., 2007). These neuromuscular responses usually are altered immediately following muscular fatigue. Neuromuscular exercise-induced fatigue is the integration of central and peripheral processing of the nervous system and skeletal muscle resulting in a reduction of muscular work. In this study muscle function following fatigue was equally altered for both genders. Although, differences in landing strategies have been reported between gender, muscle fatigue affected GRF the same by initially reducing GRF, followed by an increase in GRF as fatigue steadily progressed.

Data indicated that with the onset of muscle fatigue, participants increased the time over which the force was applied from initial contact to heel contact. This interpretation was based on the measured time between forefoot (F1) and rearfoot (F2) that was used to quantify the initial reduction identified in peak GRF. The initial
reduction of peak forces is advantageous in reducing lower extremity impact injuries. Kinematic analysis has shown that untrained females land with an increased valgus angle at the knees that result in increased time between initial contact and heel contact with inadequate joint positioning (Renstrom, et al. 2008; Powers, 2003; Huston, 2007; Hewett, 2007). Even though this landing strategy accomplishes this force reduction, it may predispose or even cause additional lower extremity injuries than high impact forces alone. These landing strategies usually resulted in a decrease in peak force after their first condition of the fatigue protocol, followed by a general progression of increased force in subsequent conditions. The overall increase of peak force (F2) occurring after continued conditions of the fatigue protocol can be attributed to increased landing stiffness.

Stiff landings results in altered joint positioning of the trunk and lower extremity, and is generally caused by reduced flexion of the trunk and knees (Coventry et al., 2006). This neuromuscular adaptation allows for the performance of fatigue landings even when muscles are incapable of producing maximal contraction or power out-put to perform a task (Enoka & Duchateau, 2008). Fatigued muscle responds by recruiting smaller motorneurons, and recruiting different muscles, which thereby influences nerves synaptic transmission, firing rate and frequency, conduction velocity, and sequence of muscle contractions (Latash, 2008; MacIntosh et al., 2006; Lieber, 1992). This neuromuscular alteration accommodates the demand of repeated muscle contractions. Without this adaptation, fatigued participants would collapse during landing. Therefore, a certain magnitude of joint stiffness is expected during fatigued landings and is a neuromuscular requirement. The question still exists of how it is possible for participants land while
fatigued to provide needed joint stiffness. The extent to which fatigued landing strategies influence lower extremity injury is not well defined.

This study demonstrated that peak ground reaction force increases as participants become more fatigued. Changes in joint positioning (kinematics) affect the magnitude and direction of force and offer a theoretical explanation of the changes observed in peak force. Unfortunately, kinematic analysis was not possible due to instrumentation and equipment constraints. An investigation to quantify how joint positioning affects landing mechanics in a fatigued state is the next step for this line of inquiry.

Anterior/Posterior and Medial/Lateral Force

Results of this study revealed no significant differences between gender for AP and ML force at F1 and F2 for the non-fatigue and fatigue conditions. Anterior/posterior and ML forces were measured to determine the relationship of changes in peak force. Medial/lateral force at F1 was not statistically significant, $F(4,15)=0.067, p \geq 0.05$, partial $\eta^2=0.424$; however the number of participants used in this study might not have been sufficient to detect these changes. Increases in ML force at F1 indicated movement in the frontal plane at contact that affected overall joint positioning and increases in lower extremity muscle activity (Shimokochi et al., 2009; Orishimo, 2006). These alterations affected landing performance and increased stress to the lower extremity, specifically to the ACL (Hewett et al., 2007). Changes were noted within these variables; however, the changes occurred in multiple planes of motion and this study was not equipped to analyze three dimensional movements. Therefore, it can be theorized that significant AP and ML force at the knee and hip may have occurred to provide the necessary stiffness required to
execute a landing while fatigued (Benjaminse et al., 2008; Coventry et al., 2007; Hewett, 2007).

Fatigue Protocols

The Wingate Anaerobic Test (WAT) was used for exercise-induced fatigue. There are various fatigue protocols, but all have limitations. Some protocols are deemed more functional than others and are more readily generalized to an active athlete population (Chappell et al., 2005; Pappas et al., 2005). Jumping and running protocols encompass the elastic component of tissue, and although the WAT does not, both involve concentric and eccentric work. The major limitation of using a jumping and running fatigue protocol is that it introduces a greater degree of variability due to individual skill performance of the task. To quantify fatigue occurrence, a reduction in individual work is noted, such as 50% of a participant’s maximal vertical jump. Utility of a jumping protocol is limited if a participant has trouble with the actual task of jumping.

Establishing fatigue criteria is difficult regardless of the protocol. The criterion is a measure expressed as a percentage of work capacity, such as 50% or 80% of maximal force output, which is then compared to a certain skill, such as ground reaction force to determine if differences occurred based on fatigue. Observed changes are accounted as fatigue effects. Therefore, in any fatigue protocol, the question of whether the protocol effectively induced fatigue remains open to interpretation since other factors may influence performance.

The WAT is a well-established exercise test that measures anaerobic capacity and produces a significant degree of fatigue during test performance, as evidenced by the percentage decrease of peak power at the end of the test. Although no standard for
percent of power drop has been established to indicate fatigue, participants recorded a 44% decrease in power across gender (see Table 3). These results are consistent with subsequent WAT performed with 3 minutes and 20 seconds of recovery (Wilson, Snyder, & Dorman, 2009). Wilson and associates reported a power decline of 48-56% across participants that performed repeated conditions of the WAT on different days and cycling positions. The results are also comparable to normative data reported for men (47±7.6) and women (42±7.9) in NCAA division I sports (Zupan, Arata, Dawson, Wile, Payn, Hannon, 2009).

An additional measure of fatigue can be accessed by determining the subjects’ levels of exertion. Participants rated their average exertion level at 16, which indicated ‘very hard’ exertion. When the WAT was performed with maximal effort, a significant degree of fatigue resulted. To ensure fatigue, four conditions of the WAT were administered with five minutes of active rest. Theoretically, participants could have recovered within five minutes of rest; however fatigue effects have been shown to last more than 40 minutes (Tsai et al., 2008). Therefore, it was assumed that participants were fatigued during the drop landing protocol and that changes in peak ground reaction force were the result of fatigue.

Clinical Relevance

Noncontact anterior cruciate ligament (ACL) and lower extremity injuries occur at high rates in sports with the highest percentage of those injuries occurring among females (Renstrom, et al. 2008; Hewett et al., 2007). The prevalence of ACL injuries occurring in sports for females has reached near-epidemic proportions. This concern has stimulated a surge in research to investigate the causes and provide possible prevention
strategies. Within the literature, it is generally accepted that females’ landing strategies predispose them to noncontact ACL injuries. The complexity exists in creating a research environment where athletes are exposed to the same stress and level of performance as their particular sport without causing injury. Research has identified modifiable and non-modifiable risk factors that are associated with ACL injury (Cameron, 2010; Finch, 2006). Recently, attention has focused on modifiable risk factors such as neuromuscular control, biomechanical factors, and fatigue during landing and cutting (Griffin, et al. 2006; Cameron, 2010; Renstrom, 2008).

Understanding how the body responds to landing in a fatigued state is vital since athletes participate in sports while fatigued. “Even in everyday life, a low degree of fatigue occurs and has been shown to be a precursor to many overuse injuries” (Hunter, 2009). The adaptation that occurs during all forms of fatigue, regardless of the magnitude, is a necessary neural adaptation. It is known that fatigue is caused by many different mechanisms occurring simultaneously that result in decreased power outputs and causes alterations in task performance (Enoka & Duchateau, 2008). These alterations demonstrated in specific functional tasks are of great importance. Alterations seen during landing may be the result of task failure caused by fatigue, and can still be performed though physiological and neuromuscular adjustments. Adjustments can be counterproductive and predispose the body to injury. Identifying what neuromuscular factors influenced specific task failure, rather than quantifying force output to establish fatigue, is the desired direction for understanding functional task performance and fatigue (Enoka & Duchateau, 2008).
Overall functional strength and neuromuscular control delays muscle fatigue. Therefore, functional strength along with proper education on how to land is critical for the reduction of overuse injuries. Education and landing coaching has been effective in reducing injury and risk (Hewett et al., 2006; Hewett, 2007; Noyes et al., 2005; Onate et al., 2005). Prevention programs have implemented landing and jump training to encourage a landing strategy that decreases force and maintains adequate joint stiffness by increased knee and hip flexion at initial contact and throughout the absorption phase. A goal of any prevention program is based on altering dynamic loading through neuromuscular training (Griffin, et al. 2005; Cameron, 2010; Hewett et al., 2006b; Hewett et al., 2007; Noyes et al., 2005; Onate et al., 2005; Renstrom et al., 2008).

Neuromuscular training focuses on plyometrics, balance training, and biomechanic injury awareness to cause positive alterations of modifiable neuromuscular risk factors (Griffin, et al. 2005; Cameron, 2010). Prevention programs are designed to enhance neuromuscular alterations and do so by improving balance, strength, and neuromuscular coordination that facilitate joint stabilization (Griffin, et al. 2005; Hewett et al., 2006b; Hewett et al., 2007; Renstrom et al., 2008). The effectiveness of neuromuscular prevention programs are difficult to measure. While performing these prevention programs, fatigue occurs and detrimental neuromuscular alterations develop (Griffin, et al. 2005). This is the point during the prevention program where neuromuscular training should be performed while encouraging correct neuromuscular control. The fatigue state is where the undesirable neuromuscular alterations are significantly seen and are most applicable to understand what occurs during real-time athletic participation. Neuromuscular training during different magnitudes of fatigue should be considered to
train the correct responses for functional movement in sports and for daily living specific task.

Conclusion

A single session of repeated WAT induced fatigue and caused an initial reduction in peak F2 followed by an increase in peak F2. This research design offered a novel way to induce fatigue and to investigate the effects of fatigue on landing kinetics. This study offers the following conclusions from the data:

1. No significant main effect was observed between genders across all GRF variables.
2. Differences exist between non-fatigue and fatigue conditions in respect to peak F2 force.
3. The greatest significant difference was observed for peak F2 within the first fatigue condition and the last fatigue condition.
4. No significant difference was observed between gender.
5. No significant difference was observed across AP and ML at peak F1 and F2.

This dissertation demonstrated a significant difference between non-fatigue and fatigue conditions in peak force. Increases in peak force predispose participants to lower extremity injury. Injuries associated with increased peak force and landing alterations are stress fractures and knee injuries, specifically to the ACL. Fatigue consequently affected landing mechanics by initial reducing GRF, followed by an increase joint stiffness resulting in higher ground reaction force.

The results of this study are similar to past research, indicating muscle fatigue decreases GRF by changes in landing strategies (Augustsson et al., 2006; Madigan et al.,
What is novel about this study, is when repeated conditions of fatigue were performed, GRF increased. This adaptation has been identified in single-leg landings (Coventry et al., 2006). Muscle fatigue resulted in altering landing strategies by increasing joint stiffness and redistributing muscle work (Coventry et al., 2006). Therefore, single-leg landings while fatigued have similar responses to landing with both legs.

Recommendations

Further research is warranted to investigate the effects of fatigue on landing mechanics. Future methodology should focus on ways to quantify fatigue, differentiate fatigue that is central or peripheral in nature, and identify the cause and effect relationship associated with both forms of fatigue. Neuromuscular training during various levels of fatigue, along with the integration of kinematic and kinetic analyses are also recommended to understand the relationship of joint positioning and ground reaction force. Implementing a sufficient amount of participants to detect changes in kinetic and kinematic variables is necessary and has been a limitation in the literature that should be put into practice. This supplemental information provides additional understanding into the complexity of preventing, and treating lower extremity and noncontact ACL injuries.
REFERENCES


Title of Research: The effect of lower extremity muscle fatigue on ground reaction force during drop landing

Researchers: David J. Dominguese

You are being asked to participate in research. For you to be able to decide whether you want to participate in this project, you should understand what the project is about, as well as the possible risks and benefits in order to make an informed decision. This process is known as informed consent. This form describes the purpose, procedures, possible benefits, and risks. It also explains how your personal information will be used and protected. Once you have read this form and your questions about the study are answered, you will be asked to sign it. This will allow your participation in this study. You should receive a copy of this document to take with you.

Explanation of Study

Participating in this study requires you to be between the ages of 18-35, a student at Ohio University, and involved in recreational activity that involve jumping, such as basketball or running at least twice a week. You should be free of any history of cardiovascular/pulmonary illness that impairs your ability to perform strenuous exercise and without any injury to your foot, ankle, knee, hip, or back in the last six months, such as an ankle sprain and back pain. If you meet the requirements, you will be asked to refrain from any exercise, alcohol or caffeine consumption at least 24 hours prior to participating in this study. You will be asked to attend one orientation session (20 minutes) and one experiment session (60 minutes).

This study was designed to investigate how muscle fatigue may alter how you position your foot, knee, and hip when you drop to a force plate from a 60 cm high platform (24 inches) placed approximately 8 inches from the force plate. This study will contribute valuable information concerning injury-risk, and prevention of foot, knee and hip injury.

Testing will take place in the Grover Center Exercise/Biomechanics Laboratory, E116, at Ohio University. You should wear exercise clothing such as a t-shirt and shorts. When you arrive you will complete a medical evaluation sheet detailing your injury history over the last six months. An Athletic Trainer (AT) will evaluate the joint stability of your ankles and knees. If you are deemed eligible to participate in the study, you will be instructed on the use of the ergometer bicycle, how to perform the twenty-second Wingate Anaerobic Test (WAT) on the ergometer bicycle, and instructions for the drop landings. You will alternate pedaling on the bicycle, performing drop landings, and resting for five minutes.
The WAT is used as an assessment tool to measure your anaerobic performance capacity and as an exercise protocol. The bicycling test will consist of cycling for 20 seconds with a resistance of approximately seven-fourteen pounds (depending on your body weight) with maximal effort. You will cycle using both legs, in a seated position, with the use of toe straps located on the pedals for safety and to ensure maximum effort.

The testing will take approximately one hour and during that period you will have completed four cycling periods, 13 drop landings, and four rest periods. During each rest period you will be asked to answer a few questions on how you fell and report any possible signs of dizziness, headache, and or nausea.

**Risks and Discomforts**

During the study you may experience soreness initially or after your participation. Soreness may be delayed (soreness can arises 24-72 hours after activity has ended). Additionally, it is possible, however very unlikely, to sustain a sprain, strain, or even fracture as a result of the drop landings. After the fatigue protocol you may become fatigued enough that you may lose your balance during the drop landings. To reduce the possible effects from the fatigue protocol, a spotter will be present during all drop landings to assist each subject in maintaining balance. In addition, padding will be placed around the landing surface to ensure safety during the drop landings. There may be additional risks that are unknown to the investigators.

**Benefits**

There will be no direct benefit to you from participating in this study.

The results of this experiment will help researchers and clinicians develop assessments, screening, and training tools to prevent injuries and improve the current knowledge on injury prevention and treatment.

**Confidentiality and Records**

The information obtained during this study will be shared and available only to the investigators involved with the study. Data files collected in this study will be placed in a locked cabinet in the Exercise Science/Biomechanic laboratory located in Grover Center (E116) and stored for the duration outlined by Ohio University IRB. Subjects will have an individually assigned ID number that will remain confidential. Information will be kept for four years following data analysis. David Dominguese will keep the code key of the subjects of the study and the code key will be destroyed following data analysis. The consent form will be kept separately from the other data that will be collected.
Additionally, while every effort will be made to keep your study-related information confidential, there may be circumstances where this information must be shared with:
* Federal agencies, for example the Office of Human Research Protections, whose responsibility is to protect human subjects in research;
* Representatives of Ohio University (OU), including the Institutional Review Board, a committee that oversees the research at OU

**Contact Information**

If you have any questions, please contact:
David Dominguese (262) 880-9261, dd131506@ohio.edu or Dr. Andrew Krause (740) 593-4648, krausea@ohio.edu

Regarding your rights as a research Subject, please contact Jo Ellen Sherow, Director of Research Compliance, Ohio University, (740) 593-0664.

By signing below, you are agreeing that:
- you have read this consent form (or it has been read to you) and have been given the opportunity to ask questions
- known risks to you have been explained to your satisfaction.
- you understand Ohio University has no policy or plan to pay for any injuries you might receive as a result of participating in this research protocol
- you are 18 years of age or older
- your participation in this research is given voluntarily
- you may change your mind and stop participation at any time without penalty or loss of any benefits to which you may otherwise be entitled.

Signature__________________________________________ Date____________

Printed Name__________________________________________

Version Date: 06/03/09
APPENDIX B: MEDICAL EVALUATION SHEET

Date:

Subject ID:

Section 1 (to be completed by subject):

Injury History

Please list any injuries that you have sustained in the last six months to your knowledge for your foot, ankle, leg, knee, thigh, hip, and back. Leave blank if no injuries have occurred.

Right Foot:
Left Foot:
Right Ankle:
Left Ankle:
Right Leg:
Left Leg:
Right Knee:
Left Knee:
Right Thigh:
Left Thigh:
Right Hip:
Left Hip:
Spine:

Medical History

Please answer yes or no to the following questions. If you answer yes to any of the questions, please provide an explanation to your response.

1. Have you ever been diagnose by a physician for any related cardiovascular illness or condition, such as high blood pressure or chest pains.

2. Have you ever been diagnose by a physician for any related pulmonary illness or conditions, such as asthma or chronic bronchitis.
Section 2 (to be filled out by AT):

Joint Stability Assessment
Ligament Laxity Screening (N=negative, no abnormal joint instability and P=Positive test, abnormal laxity). Positive values on any of the ligament screening test will result in exclusion of the study.

<table>
<thead>
<tr>
<th>Ankle</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
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<td></td>
</tr>
<tr>
<td>Drawer Test</td>
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<table>
<thead>
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<th>Knee</th>
<th>Right</th>
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<tr>
<td>Valgus Stress Test</td>
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<tr>
<td>Lachman Test</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C: SUBJECTS QUESTIONNAIRE

Date

Subject ID

Directions: Please answer the following questions with a *Yes or No* response and provide additional comments as need.

After each session of the experimental protocol (two non-fatigue drop landings, a 20 s fatigue protocol, followed by two fatigue drop landings), did you experience any of the following symptoms:

1. Headaches: 

2. Dizziness: 

3. Nausea: 

Please list any other symptoms that you may have experience:

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________
### APPENDIX D: RATEING of PERCEIVED EXERTION

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<thead>
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<th>RPE</th>
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<td>8</td>
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<td>Very Light</td>
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<tr>
<td></td>
<td>10</td>
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<tr>
<td>Light</td>
<td>11</td>
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<tr>
<td>Moderate</td>
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</tr>
<tr>
<td></td>
<td>13</td>
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<td>Hard</td>
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<td>Very Hard</td>
<td>16</td>
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<tr>
<td></td>
<td>17</td>
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<tr>
<td>Very, Very, Hard</td>
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<tr>
<td></td>
<td>19</td>
</tr>
<tr>
<td>Maximal Exertion</td>
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</table>
APPENDIX E: FOREFOOT FORCE (F1) in BW

<table>
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<th>Male</th>
<th>Female</th>
</tr>
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<tbody>
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<td>3.38±0.87</td>
<td>3.41±0.91</td>
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<tr>
<td>2</td>
<td>10</td>
<td>3.56±1.07</td>
<td>3.56±0.75</td>
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<td>3</td>
<td>10</td>
<td>3.55±1.08</td>
<td>3.6±0.81</td>
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<td>10</td>
<td>3.38±1.13</td>
<td>3.5±0.69</td>
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<td>5</td>
<td>10</td>
<td>3.43±0.98</td>
<td>3.68±0.78</td>
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Note. BW
APPENDIX F: REARFOOT FORCE (F2) in BW

<table>
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<th>Condition</th>
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<th>Female</th>
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<tbody>
<tr>
<td>1</td>
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<td>7.84±1.49</td>
<td>7.81±2.22</td>
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<td>2</td>
<td>10</td>
<td>7.39±2.31</td>
<td>6.92±3.11</td>
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<td>3</td>
<td>10</td>
<td>8.73±2.31</td>
<td>7.59±2.93</td>
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<tr>
<td>4</td>
<td>10</td>
<td>9.48±2.79</td>
<td>9±2.65</td>
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<tr>
<td>5</td>
<td>10</td>
<td>9.32±2.2</td>
<td>9.42±2.29</td>
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</table>

Note. BW
## APPENDIX G: ANTERIOR/POSTERIOR (A/P) AT FOREFOOT FORCE (F1) in N

<table>
<thead>
<tr>
<th>Condition</th>
<th>N</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-390.08±165.92</td>
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<td>10</td>
<td>-444.39±154.67</td>
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<td>4</td>
<td>10</td>
<td>-390.21±170.92</td>
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<td>5</td>
<td>10</td>
<td>-384.36±187.53</td>
<td>-455.28±86.22</td>
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Note. Newtons
APPENDIX H: ANTERIOR/POSTERIOR (A/P) AT REARFOOT FORCE (F2) in N

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<th>Condition</th>
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<td>10</td>
<td>131.53±107.35</td>
<td>63.66±130.1</td>
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<td>2</td>
<td>10</td>
<td>129±211.02</td>
<td>80.6±171.74</td>
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<td>3</td>
<td>10</td>
<td>140.07±144.72</td>
<td>37.89±156.25</td>
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<td>4</td>
<td>10</td>
<td>167.83±163.81</td>
<td>95.74±177.35</td>
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<td>5</td>
<td>10</td>
<td>143.78±192.68</td>
<td>110.11±127.23</td>
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Note. Newtons
APPENDIX I: MEDIAL/LATERAL (M/L) AT FOREFOOT FORCE (F1) in N

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<th>Condition</th>
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<th>Female</th>
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</thead>
<tbody>
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<td>10</td>
<td>6.6±53.75</td>
<td>-8.66±54.14</td>
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<td>10</td>
<td>18.96±79.22</td>
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<td>-27.59±69.51</td>
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<td>4</td>
<td>10</td>
<td>22.07±78.17</td>
<td>-18.78±67.33</td>
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<td>5</td>
<td>10</td>
<td>32.86±65.24</td>
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Note. Newtons
APPENDIX J: MEDIAL/LATERAL (M/L) AT REARFOOT FORCE (F2) IN N

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<th>Condition</th>
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<tbody>
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<td>170.5±77.48</td>
<td>552.9±1060.33</td>
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<tr>
<td>2</td>
<td>10</td>
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<td>110.26±101.13</td>
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<tr>
<td>3</td>
<td>10</td>
<td>197.72±113.46</td>
<td>290.19±536.06</td>
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<tr>
<td>4</td>
<td>10</td>
<td>237.93±143.95</td>
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<tr>
<td>5</td>
<td>10</td>
<td>1068.62±2687.61</td>
<td>120±98.22</td>
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Note. Newtons
APPENDIX K: MEAN POWER (W)

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<tr>
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<td>10</td>
<td>532.22±96.24</td>
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<td>478.23±116.43</td>
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<td>280.07±64.5</td>
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Note. Watts
## APPENDIX L: PEAK POWER (W)

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<td>380.72±82.9</td>
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<td>10</td>
<td>594.53±135.04</td>
<td>352.59±79.73</td>
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<td>10</td>
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<td>340.62±74.67</td>
</tr>
</tbody>
</table>

Note. Watts
APPENDIX M: POWER DROP (%)

<table>
<thead>
<tr>
<th>Condition</th>
<th>N</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>47.34±8.41</td>
<td>41.47±4.39</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>45.82±6.79</td>
<td>39.96±4.42</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>42.41±8.7</td>
<td>42.35±10.01</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>45.87±9.04</td>
<td>48.2±21.98</td>
</tr>
</tbody>
</table>

Note. Percentage