ANALYSIS OF KNEE MECHANICS DURING THE SQUAT EXERCISE: DIFFERENCES BETWEEN FEMALES AND MALES

By

FRANCIS ARLINGTON FORDE

A THESIS PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2005

ACKNOWLEDGEMENTS

I would like to thank Dr. John Chow, Dr. Mark Tillman and Dr. James Cauraugh for their support and help with my research. I would also like to thank my family for their support. I must also extend special thanks to Dr. John Chow and Dr. Tillman for without their guidance during this endeavor success would not have been attainable and for that I am deeply grateful.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements of the Degree of Master of Science.

ANALYSIS OF KNEE MECHANICS DURING THE SQUAT EXERCISE: DIFFERENCES BETWEEN FEMALES AND MALES

By

Francis Arlington Forde

May 2005

Chairman: John Chow
Major Department: Applied Physiology and Kinesiology

The purpose of this study was to analyze the differences in tibiofemoral joint mechanics between males and females during squatting using the Trapezoid bar (TB) and Straight bar (SB). Twenty-two subjects were recruited from the University of Florida. Each subject performed two randomly assigned squat tests, one using a straight bar and the other using a trapezoid bar. Each test consisted of two trials with each trial consisting of three repetitions. Video, force platform and EMG were used to collect kinetic, kinematic and muscle activity data.

MANOVA results for the EMG data found significant differences for Quadriceps activity between the TB and SB squat conditions with the TB resulting in higher quadriceps muscle activation. Significant differences were also found between the ascending and descending phases of the squat for gluteal and hamstring muscle activity. The ascending phase resulted in higher muscle activation than the descending phase. The MANOVA also revealed significant interactions between phase and gender for gluteal

and hamstring muscle activity as well as significant interactions between phase and bar type for quadriceps muscle activity. An ANOVA revealed significant differences between bar types for compressive force, anteriorly directed shear force and extension moment at the tibiofemoral joint with the TB squat resulting in the higher values for compressive force, shear force and extension torque. T-tests were performed to determine differences in normalized hip width, Q-angle, and maximum knee angle during each SB and TB squat trial. There were significant differences detected for all of these measures. Women had a larger Q-angle and normalized hip width as compared to the males of this study. There were no differences between maximum knee angle during the TB and SB squats.

This study identified differences between phases and bar types for knee joint mechanics and muscle activity. Despite significant differences between genders for normalized hip width and Q-angle there was no observable difference between males and females of this study for joint kinetics, joint kinematics or muscle activation. This suggests that Q-angle and hip width do not have an effect on tibiofemoral joint kinetics or lower extremity muscle activity during squatting which may be as a result of the non-ballistic nature or the squat.

CHAPTER 1
INTRODUCTION

The number of females participating in sports has surged in recent years. With this surge has come an increased incidence of lower extremity injuries which include various non-contact and contact sprains to the joints of the legs, one of the more devastating type of injury being an anterior cruciate ligament (ACL) sprain.

A contact injury occurs when there is physical contact between players (Huston & Wojtys, 1996). It can be more specifically defined as an injury resulting from a collision between multiple players and injuries that occur in the absence of a player-to-player collision are considered non-contact injuries. Non-contact injury mechanisms also include overuse injuries such as patellar tendonitis, stress fractures and any injury which occurs without direct physical contact between players.

The prevention of contact injuries in athletics is an insurmountable task due to the infinite number of intrinsic and extrinsic factors that can cause these injuries, however contact injuries are not the primary cause of ACL sprains among competitors. Non-contact ACL injuries account for approximately 78% of all ACL sprains with many occurring during landing (Noyes, Mooar, Matthews & Butler, 1983). It has been suggested that these injuries may result from over training or a lack of training (Hahn & Foldspang, 1997).

Female athletes are eight times more likely to suffer an ACL sprain (Huston, Greenfield, & Wojtys, 2000) suggesting that there may exist a gender predisposition to injury (Toth & Cordasco, 2001). The speculation of Toth and Cordasco (2001) requires further investigation before being accepted as truth. Female athletes may suffer more severe and frequent ACL sprains owing largely to inadequate training rather than causes solely due to intrinsic gender differences.

Regardless of gender an ACL rupture can be career ending and is considered a catastrophic knee ligament injury. The ACL provides stability to the knee joint by limiting the tibia from sliding anteriorly on the femur hence, an injured ACL can reduce tibiofemoral joint stability and limit an athlete's ability to perform. Rehabilitation techniques used to increase tibiofemoral joint stability post ACL rupture have been used to aid joint sprain prevention and in effect build injury resistance. Still, as females continue to experience a higher rate of injury than males it is of special interest to investigate the reasons for this phenomenon. The evidence to support the suggestion that there is a gender predisposition to injury comes from a disproportionately higher rate of injuries among female competitors as compared to male competitors participating in the same sports, where females often suffer injuries that are more frequent and severe in nature (Arendt, Agel, & Dick, 1999; Ireland, 1999).

Despite higher injury rates among female competitors, there are common factors which can cause non-contact injuries in both males and females. These non-contact injury mechanisms include cutting maneuvers, changing direction, landing mechanics and sudden acceleration. Females, however have additional intrinsic and extrinsic factors influencing non-contact lower extremity injuries such as joint laxity, joint flexibility, various structural mal-alignments and hormonal influence (Shambaugh, Klein, & Herbert, 1991; Hutchinson & Ireland, 1995; Liu et al., 1997; Hewett et al., 1999), as well as muscle strength and landing characteristics (Dufek & Bates, 1991; Hewett et al., 1999).

Men have dominated athletics for some time and the training methods employed for athletic preparation seem to be sport specific rather than gender specific. Non-contact injuries appear to occur as a result of poor movement mechanics resulting from either a previous injury or other intrinsic factors that may be partly due to poor preparation for the explosive movements inherent in most sports.

The external forces and stresses placed on the body during competition cannot be altered, though the body's ability to withstand these loads can be improved through proper physical preparation. Treating the symptoms of injuries rather than preparing an individual for the stresses present during the activity may lead to repetitive injuries. Identifying the factors responsible for injury is essential in preparing an athlete for participation and improving his or her injury resistance. Once the causes of injury are identified conditioning programs can be modeled to help to prevent the onset of injury.

An increased time in rehabilitation results in loss of playing time and in some cases loss of revenues to a competitor. For this reason it is most desirable to have a competitor on the field as much as possible and therefore taking a preventative approach to training is possibly the most effective path.

Reducing and treating injuries falls squarely on the shoulders of those responsible for an athlete's well being. The first link in the chain of prevention is the strength and conditioning specialist (SCS). Prior to competition the SCS has to design the conditioning program to improve the physical health of the athlete over the course of the season at any level of competition.

Strengthening and conditioning, however has been split into two distinct approaches. Some SCSs consider absolute increases in strength regardless of exercise modality to be the best route, where single joint open kinetic chain muscle building activities are often used as the primary source of conditioning. Other SCSs believe that increases in strength through functional multi-joint closed kinetic chain exercises such as the dynamic squat provide greater physical benefits.

The focus of the research on the dynamic squat thus far has been on its benefits ranging from rehabilitation to strengthening and conditioning, and athletics (Chandler, Wilson, & Stone, 1989; Isear, Erickson, & Worrell, 1997; Zheng, Fleisig, Escamilla, & Barrentine, 1998; Toutoungi, Lu, Leardini, Catani, & O'Connor, 2000). Gender considerations have been overlooked. There have been studies investigating the risks of injury among women in athletics (Haycock & Gillette, 1976) but little research has been conducted on the benefits that squatting may have in helping to prevent injuries in women.

Certain intrinsic factors that may lead to injury such as skeletal mal-alignments cannot be altered without surgical intervention. However, improving movement mechanics may lead to a reduction in injury. Research sometimes follows the practice. It is easier for a SCS to speculate and implement new ideas before there is sound research to validate any claims made about the benefits or risks of a new training technique or apparatus. Thus manipulated variables of the dynamic squat such as stance width, foot position, bar loading position, cadence, and surface of execution (i.e., surfaces of different rigidity on which the exercise can be performed safely, for instance the use of a Dyna-disc or Airex mat) are thought to have positive effects on strength and coordination in the athlete.

The dynamic squat is commonly performed using a standard straight bar (also known as the Olympic bar) placed across the back of the shoulders when performing a back squat (Figure 1-1) or across the front of the shoulders when performing a front squat.

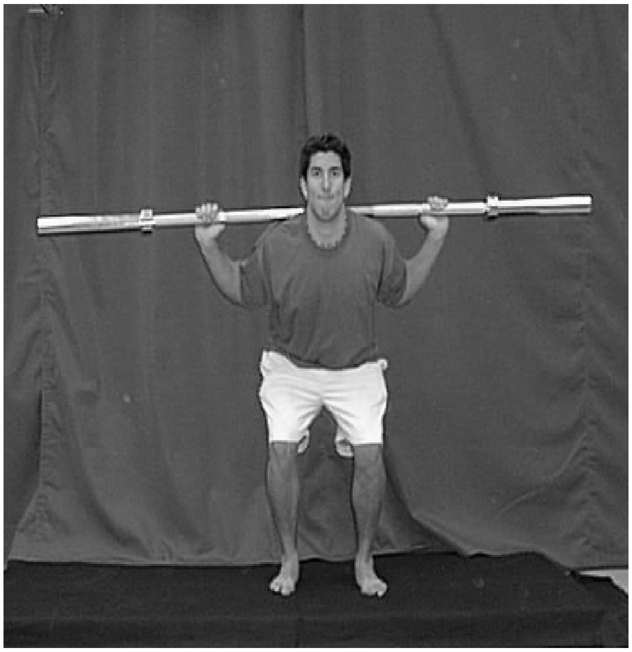

Figure 1-1. Squat using a straight bar.

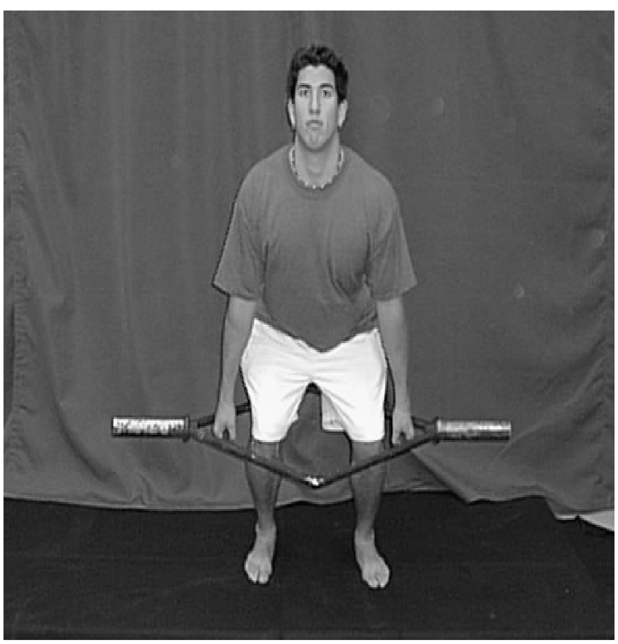

Figure 1-2. Squat using a trapezoid bar.

Different types of bars have been developed to increase the number of exercises that can be performed and reduce the risks of injury associated with the straight bar placement during the squat. The trapezoid bar (TB) is one type of bar that can be used as a conditioning tool for athletes to increase lower body strength (Figure 1-2). Previous studies have investigated differences in knee mechanics resulting from changes in the type of squat, for instance, front squat and back squat (Russell & Phillips, 1989), the effect of varying foot position (Ninos, Irrgang, Burdett, & Weiss, 1997), and the effect of stance width (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). While a number of these studies had a sample consisting of males and females, differences between genders were seldom reported.

The straight bar is placed across the rear of the shoulders while performing the dynamic squat and cannot move independently of the trunk while TB is placed at the hands using handle grips with the arms extended. The TB is free to move independently of the trunk in all directions and may present added balance requirements. Movements occur through sequential coordinated muscle contractions, a closed kinetic chain exercise that has increased balance and coordination requirements should be an essential training tool for SCS is worthy of further investigation. The TB squat is one such training tool because it can move independently of the trunk.

The tibiofemoral joint is the middle joint of the lower limb kinetic chain which consists of three major joints: the hip, knee and ankle. When the foot is internally or externally rotated, the rotation at the tibia could have an effect on tibiofemoral joint mechanics.

The most effective and efficient system of moving an object is to apply a force in the direction the object is to be moved. For instance to move an object vertically, the best means is a vertically applied force. For this reason it is thought that the most biomechanically sound squat position is with the feet placed hip width apart. Although biomechanically sound, a hip width stance is not sport specific as the legs are seldom directly under the hips during many sports, this is best seen during the push off in hockey.

Increased participation of females in high school, collegiate, and professional sports has been followed by increased incidence of severe non-contact knee injuries. Prior to the women's sports explosion strength and conditioning was focused on the needs of male athletes. This is reflected in the literature. Additional research is needed to investigate the effectiveness of preventative training and other accepted strengthening and conditioning techniques for the female athlete.

Statement of Purpose

Despite many training modalities utilized in SC the squat remains the most widely used and accepted functional multi-joint strength builder for the lower extremity. There have been publications investigating the effects of the dynamic squat but these investigations have focused on the training effects of the dynamic squat on the quadriceps and hamstring muscle groups without emphasis on gender differences. Comprehensive research studies that investigate synergistic muscle activity and gender differences such as, bony morphology and their relations to locomotion are now needed to compliment the existing literature.

Tibiofemoral joint kinetics and functional knee stability may be affected by muscles acting solely on the femur and or tibia without direct attachment to the tibiofemoral joint. This idea is further understood through the theory of the lower extremity closed kinetic chain (Stuart et al., 1996).

The purpose of this study was to investigate the relationships among gender and type of squat bar on tibiofemoral joint kinetics and kinematics during the performance of the dynamic squat. Specifically, this investigation attempted to identify the differences between joint kinetics, and muscle activity at the tibiofemoral joint between males and females during TB squat and straight bar back squat.

Research Hypotheses

This thesis investigated the following hypotheses.

1. Mean gastrocnemius, quadriceps and hamstring level would be greater during the trap bar squat.
2. Mean gluteal, quadriceps, hamstrings and gastrocnemius muscle activation level would be greater during the ascent phases.
3. Maximum compressive knee joint forces would be greater in female subjects.
4. Maximum anterior shear knee joint forces would be greater during the trapezoid bar squat.
5. Maximum extension moment would be greater in the trapezoid bar condition as compared to the straight bar condition.
6. There would be a significant difference between genders for normalized hip width.
7. There would be a significant difference between genders for Quadriceps angle.

Definition of Terms

1. <u>Stability:</u> The joint steadiness needed to carry out a functional activity.
2. <u>Closed Kinetic Chain:</u> Exercises for the lower extremity executed when the foot is fixed and the knee motion is accompanied by motion at the hip and ankle.
3. <u>Open Kinetic Chain:</u> Exercises for the lower extremity performed when the foot is mobile and the knee is free to move independently of the hip and ankle.
4. <u>Surface Electromyography (EMG):</u> The measure of electrical activity generated by a muscle in response to a nervous stimulation.

5. Range of Motion: The angular distance through which a joint moves from the anatomical position to the end point of a segment motion in a particular direction during an activity.

6. Kinematics: The study of movement described in terms of position, velocity and acceleration of the body or its individual segments without regard for the causes of those motions.

7. Kinetics: The study of motion with regard to the forces that cause movement.

8. Joint Resultants: The combined mechanical effects due to muscle, ligament and contact forces.

Assumptions

1. All subjects provided accurate information regarding eligibility requirements.
2. All subjects were volunteers.
3. All instrumentation were functioning correctly and properly calibrated.
4. Reflective marker placement was accurate and precise.

Limitations

1. Trapezoid bar dimensions may have limited the lower extremity motion of taller subjects.

2. Loading limitations for subjects with low grip strength may have affected TB squat performance.

3. All subjects were recruited from the sport and fitness classes offered at the University of Florida.

Significance

This study was undertaken to evaluate the uses of various squatting styles in the training of athletes with an appreciation for the anatomical differences between genders. It was the intent of the investigator to further the understanding of the varying needs and differences between genders and assess the effectiveness of the current training techniques employed in strength and conditioning and related exercise science disciplines.

There are several variations of conventional exercise training techniques and protocols that are extensively employed throughout SC to facilitate positive physiological, strength and flexibility changes in the athlete. Understanding the purpose for these modifications and their implications will aid practitioners in developing more effective exercise protocols and training sequences for athletes based on gender and type of sport.

CHAPTER 2
REVIEW OF LITERATURE

Tibiofemoral Joint Anatomy

The tibiofemoral joint (TFJ) (Figure 2-1) is the articulation of the femoral condyles on the tibial plateau with a cartilage cushion between the femur and tibia called the meniscus. The menisci are cartilage connected anteriorly by the transverse ligament and anteriorly and posteriorly attached to the anterior and posterior intercondylar area, respectively, of the tibia.

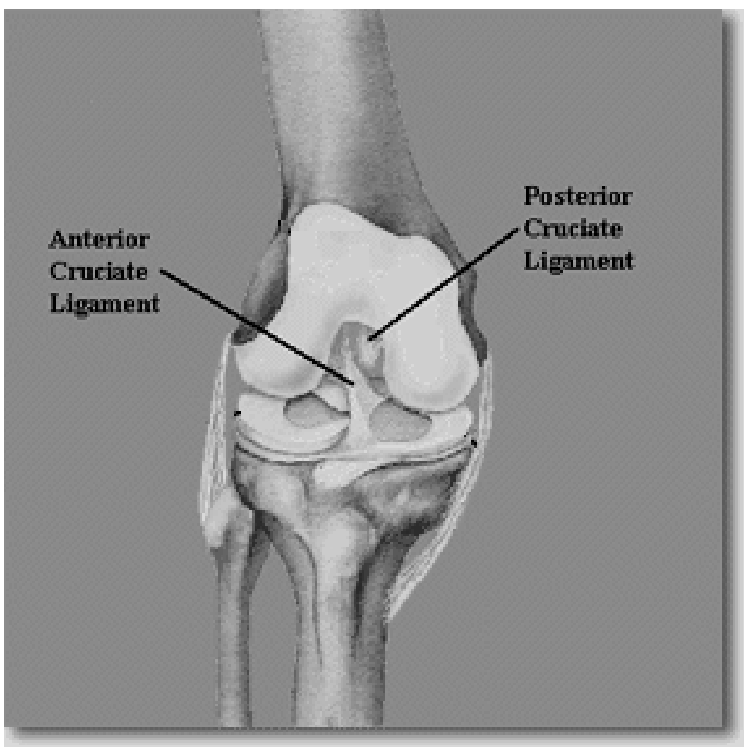

Figure 2-1. View of ACL and PCL.

The ligaments of the knee include the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) (Figure 2-1), lateral collateral ligament (LCL), and medial collateral ligament (MCL) (Figure 2-2). The (ACL restrains anteriorly directed forces and the PCL restrains posteriorly directed forces acting on the tibia. The cruciate ligaments also provide stability during internal and external rotation of the TFJ and provide minimal restraint to medio-lateral force which is the primary role of the medial and lateral collateral ligaments.

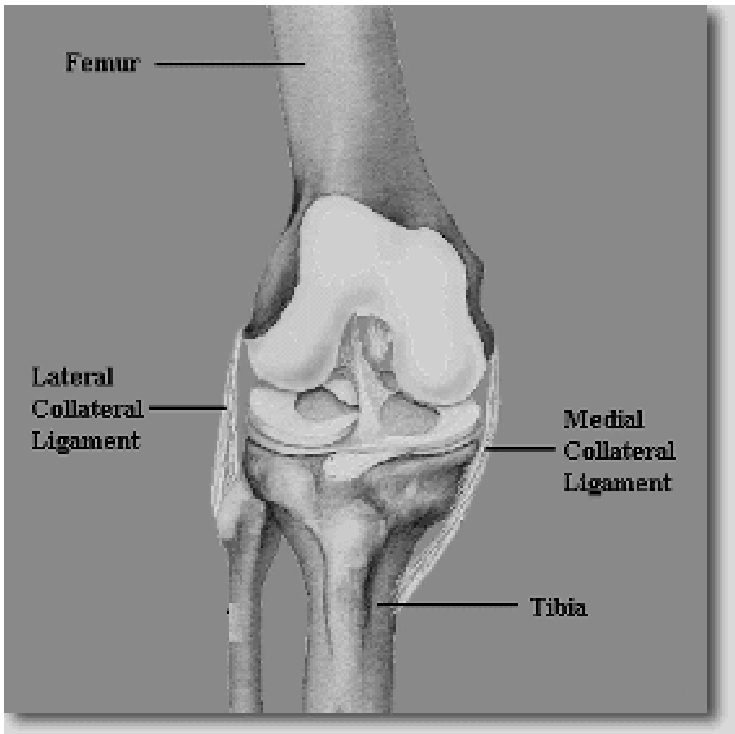

Figure 2-2. View of MCL and PCL.

The MCL restrains knee abduction and the LCL restrains the adduction of the knee. Therefore the collateral ligaments are the primary ligaments responsible for medio-lateral stability of the knee.

The surrounding muscles of the TFJ provide added stability depending on their insertions and action at the knee joint. The anterior and posterior muscles acting at the TFJ are the main stabilizers. The anterior muscles acting at the knee joint include the vastus medialis, vastus lateralis, vastus intermedius, rectus femoris, sartorius, and gracilis. The posterior muscles acting at the knee joint include the semitendinosus, semimembranosus, biceps femoris, and gastrocnemius.

Quadriceps Angle

Quadriceps angle (Figure 2-3) is the angle measured between a line connecting the anterior superior iliac spine (ASIS) and the midpoint of patella and tibial tubercle (Guerra, Arnold, & Gajdosik, 1994). Increased quadriceps angle (QA) can lead to various musculotendinous malconditions and stress the medial compartment of the knee due to excessive valgus force (Hutchinson & Ireland, 1995). Excessive QA presents a structural problem which may hinder movement mechanics at any level. With the aggressive nature of contact sports the risk of injury increases disproportionately with those suffering from a high QA. Evidence presented in the literature suggests a relationship between QA and injury among female athletes (Bergstrom, Brandseth, Fretheim, Tvilde, & Ekeland, 2001). Thus it is not surprising that female athletes are eight times more likely then male athletes to suffer an ACL sprain (Huston, Greenfield, & Wojtys, 2000).

Resultant Knee Joint Force and Tibiofemoral Joint Stability

The literature suggests that increased compressive forces at the tibiofemoral joint will decrease the forces acting against the ACL and PCL (Chandler & Stone, 1991). During a dynamic squat (DS), the compressive forces present at the TFJ vary according to the external load and subject's body mass thus, TFJ compressive forces can reach high values with peak readings reported as high as 7928 N (Escamilla, 2001). The magnitude at which compressive forces become deleterious to other knee joint structures such as the meniscus and articular cartilage has not yet been reported (Escamilla, 2001). However, it is assumed that compressive forces up to this magnitude are beneficial for knee joint stability and serve as a restraint against anterior and posterior shear forces.

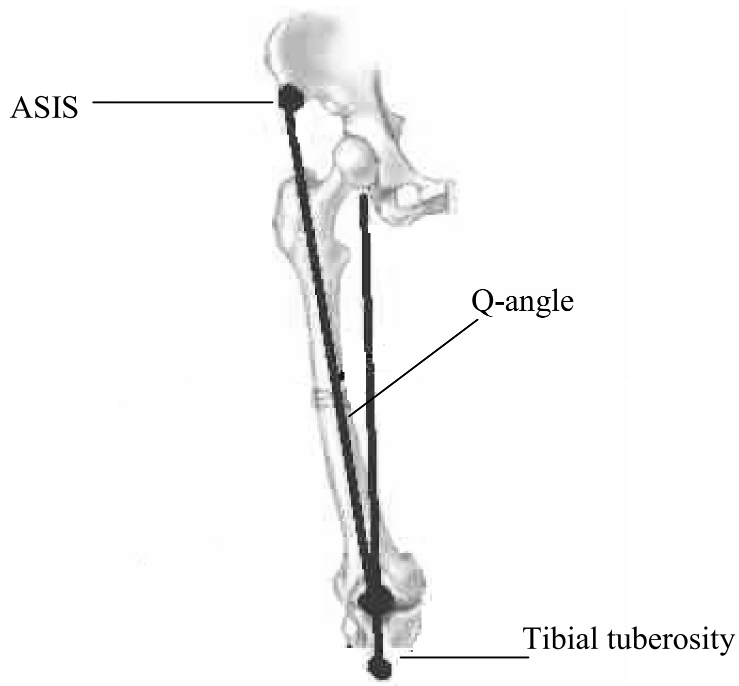

Figure 2-3. Illustration of Q-angle.

The ACL and PCL resist anterior and posterior shear forces. Butler et al. (1980) reported that the ACL provides 86% of the restraining force during an anterior draw test and the PCL provides 95% of the restraining force during a posterior draw test. The difference in percentage reported for each ligament is reasonable because this was a cadaver study hence, there was no muscle involvement during the posterior or anterior draw tests and the cross sectional area of the PCL is approximately 20-50% greater than the cross sectional area of the ACL (Harner et al., 1995).

Myers (1971) reported no significant difference in medio-lateral force at the tibiofemoral joint during the squat exercise. It is important to note that in this study gender was not considered and stance width was not reported. This is important to consider as stance width variations can change TFJ kinetics (Escamilla et al., 2001). Meyers (1971) however, did find that there was a significant interaction between deep squat exercise and medial collateral ligament stretch. Other studies investigating medio-lateral forces at the knee during the squat published forces of magnitudes ranging from 2.5-10% of the subject's body weight (Hattin, Pierrynowski, & Ball, 1989).

Resultant Knee Joint Torque and Tibiofemoral Joint Stability

The ligaments which restrain abduction and adduction torque at the TFJ are the MCL and LCL. The excessive valgus force present in people with an abnormal QA compromises medio-lateral TFJ stability and the function of the collateral ligaments. Abduction and adduction moments tend to induce an internal or external moment at the knee (Hewett et al., 1996). Hewett et al. (1996) found that post a jump and landing technique training program the adduction and abduction moment present at the knee at landing was significantly reduced in female volleyball players. The findings of Hewett et al. (1996) suggest that training can reduce the onset of internal and external moments at the knee by controlling the abduction and adduction torque present. Thus supporting their idea that tibiofemoral adduction and abduction torque may be one of the factors which induce internal and external moments at the TFJ.

The ACL is injured when there is an excessive posterior translation of the femur on the tibia. An excessive internal moment does not have to be present as the ACL is primarily active in the sagittal plane, however, an excessive internal moment coupled with an anteriorly directed force at the tibia can also cause an ACL sprain.

The tibia internally rotates during knee flexion and externally rotates during knee extension in an open kinetic chain environment (Escamilla, 2001) however, in a closed kinetic chain environment the tibia becomes semi fixed because the foot is fixed. Under these conditions the femur tends to rotate externally about the longitudinal axis of the tibia during knee flexion and internally rotates during knee extension. Unlike cadaver studies, one can expect muscular contribution to stabilize the knee and therefore the strength of the muscles surrounding the knee will make a difference on the rotation and linear movement allowed in studies using live human subjects.

The hamstrings also provide internal and external rotation restraint at the knee joint. The lateral hamstring (biceps femoris) inserts on the lateral side of the knee and when contracting solely can cause knee flexion and external rotation of the tibia. The medial hamstring (semimembranosus and semitendonosus) inserts on the medial side of the TFJ and thus when contracting singly causes knee flexion and internal rotation of the tibia. The muscles which provide extension and flexion torques at the tibiofemoral joint and thus resist external flexion and extension torques are the quadriceps muscle group and hamstrings respectively.

Muscle Co-contraction

Studies have investigated muscle activity during squatting; sit to stand, step-ups and other closed kinetic chain exercises (Isear, Erickson, & Worrell, 1997; Signorile et al., 1995). These studies have placed little emphasis on gastrocnemius contribution to the squat although 98% of the total cross sectional area of all knee musculature is made up of the gastrocnemius, quadriceps and hamstrings (Wickiewicz, Roy, Powell, & Edgerton, 1983).

According to Wilk et al. (1996) the quadriceps is an ACL antagonist and the hamstrings are an ACL agonist (More, Karras, Neiman, Fritschy, Woo, & Daniel, 1993). The exact action of the hamstrings -eccentric or concentric- during the squat has not yet been fully determined (Escamilla, 2001). From a biomechanics standpoint however, regardless of the type of contraction during a squat the hamstrings will provide a posteriorly directed force which along with the quadriceps act to stabilize the knee as well as facilitate movement. It is this interaction of the hamstrings and quadriceps contractions that serves as a protective mechanism (Isear et al., 1997). Loaded closed kinetic chain exercises such as the dynamic squat produce compressive forces and muscle co-contractions that protect the cruciate ligaments of the knee (More et al, 1993; Stuart et al., 1996).

The hamstrings muscle group and gastrocnemius are the primary and secondary flexors of the knee and assist cruciate ligament stabilization. Hamstring co-contraction during a squat is considered an aid in TFJ anterior load reduction (Fleming et al., 2001). Fleming et al. (2001) found that the gastrocnemius and quadriceps co-contraction with hamstring activity absent is an ACL antagonist. This investigation determined that the ACL strain increased as knee flexion angle decreased during isolated gastrocnemius contraction. The decreased PCL loading experienced when performing a squat in a plantar flexed position (Toutoungi, Lu, Leardini, Catani, & O'Connor, 2000) implicitly corroborates this finding.

The gastrocnemius is a secondary knee flexor and plantar flexes he foot during walking. Posterior cruciate ligament loading was reduced by 17% during squatting by having the subjects raise their heels off the ground thus eliciting a gastrocnemius contraction to perform plantar flexion (Toutoungi, Lu, Leardini, Catani & O'Connor, 2000). Like the hamstrings, the gastrocnemius flexes the shank, though it pulls downwards on the femur, whereas the hamstrings pull upward on the tibia. The downward pull of the gastrocnemius creates a force similar to the force created by the quadriceps. This suggests that a gastrocnemius hamstring co-contraction could increase compressive force at the knee joint, which may work as an ACL protective mechanism similar to a quadriceps and hamstrings co-contraction.

During the DS the gastrocnemius provides a plantar flexion torque, which prevents tipping forward and steadies the tibia on the foot. It is anticipated that muscle activity of the gastrocnemius during the trapezoid bar squat will be similar to values seen during walking or running.

Squat Biomechanics

Studies have shown that deep knee bending (knee angle less than 90˚) may produce excessive and injurious knee joint forces (Nagura, Dyrby, Alexander, & Andriacchi, 2002). Chandler, Wilson and Stone (1989) however found no significant difference in anterior or posterior knee stability after an 8-week training protocol using deep and half squat techniques. Evidence to support the findings of Nagura et al. (2002) may require a longitudinal study lasting longer than the 8-week protocol used by Chandler et al. (1989).

Varying stance width during the squat changes the angle of push during the exercise. The vertical force required to lift any given load is then increased or decreased depending on the change in stance width. Zhang and Wang (2001) investigated dynamic and static control of the knee joint. This study performed testing in an open kinetic chain environment and concluded that knee control can be maintained through co-contraction of medial and lateral musculature crossing the knee joint. Stance width and foot position will affect knee movement in the sagittal, frontal and transverse planes; however closed kinetic chain movements were not investigated in this study. It is not clearly understood how medial and lateral musculature co-contraction at the knee will be affected in a closed kinetic chain environment.

Exercises such as squatting have been done as a functional modality to stabilize and strengthen surrounding musculature of the knee. Ninos, Irrang, Burdett and Weiss (1997) investigated the effects of foot position on electromyography measures during the squat and found that muscle activity patterns were unaffected by lower extremity axial rotation.

Furthermore, additional studies investigating foot position on electromyographic activity of the lower limb muscles have not reported stance width (Boyden, Kingman, & Dyson 2000). The absence of certain variables in this analysis may have skewed the results of this study.

CHAPTER 3
METHODS AND MATERIALS

This chapter describes the methods used to collect and analyze the data for all subjects of this study. All tests and subsequent analyses were conducted under strict guidelines to insure validity of data and avoid extraneous factors that may have skewed the data collected.

Subjects

Twenty-two students (11 males and 11 females) were recruited from the Sport and Fitness classes offered by the Department of Exercise and Sport Sciences of the University of Florida. The sample size was determined using Gpower statistical software for sample size calculations. The a-priori α level was set at 0.05. Using these values, the calculated statistical power and sample size were 0.6 and 22, respectively.

According to Escamilla (2001) trained subjects have more consistent kinematics during testing, hence all subjects of this study were physically active; participating in resistance training programs approximately 3-5 times per week and frequently incorporated squatting into their exercise regimen. Those who qualified for this investigation were lower limb injury free and reported no prior history of injury to the lower extremities. Additionally a brief question and answer session on the exercise techniques required for this study was held prior to testing at which time subjects were given verbal instruction on how to perform each exercise and the same investigator gave instructions to all subjects.

Prior to participating, subjects were required to read and sign an informed consent form detailing the risks, benefits and procedures of this experiment approved by the Institutional Review Board of the University of Florida. Morphology measurements including: hip width, quadriceps angle, height, mass, selected anthropometric measurements (Tables 3-1 and 3-2) and structural alignment measures (Table 3-2) were also recorded at this time.

Table 3-1. Anthropometric measurement guidelines:

Parameter	Description
Body mass	Measurement of the mass of participant with shoes removed.
ASIS breadth	Using a sliding caliper, the horizontal distance between the anterior superior iliac spines was measured.
Thigh length	Using a sliding caliper, the vertical distance between the superior margin of the lateral tibia and superior point of the greater trochanter was measured.
Mid-Thigh circumference	The circumference of the thigh was measured using a tape placed perpendicular to the long axis of the leg and at a level midway between trochanteric and tibial landmarks.
Calf length	With a sliding caliper, the maximum vertical distance between the superior margin of the lateral tibia and lateral malleolus was measured.
Calf circumference	Using a tape the maximum circumference of the calf perpendicular to the long axis of the shank was measured.
Knee diameter	Using a sliding caliper, the maximum breadth of the knee across the femoral epicondyles was measured.
Foot length	Using a sliding caliper, the distance from the posterior margin of the heel and the tip of the longest toe was measured.
Malleolus height	Using a sliding caliper the vertical distance between the standing surface and lateral malleolus was measured.
Malleolus width	Using a sliding caliper, the distance between the lateral and medial malleolus was measured.
Foot breadth	Using a sliding caliper, the breadth across the distal ends of metatarsal I and V were measured.

Table 3-2. Morphology measurement guidelines:

Structural Alignment Measure	Procedure
Quadriceps Angle	Using a single axis goniometer the angle measured at the femur between the line intersecting the center of the patella and tibial tubercle and longitudinal axis of the femur was measured.
Hip Width	The distance between the left and right anterior superior iliac crests using a sliding callipers was measured.

Instrumentation

Trapezoid and Straight bars

The Trapezoid bar (TB) (Figure 3-1) is a trapezoid shaped bar. The TB is designed to allow a person to stand within its frame and perform exercises. There are handles located on the side of the bar situated perpendicular to the loading poles. The bar mass of the TB is 20.45 kilograms (45 lb) and the weight-plates are loaded on each end.

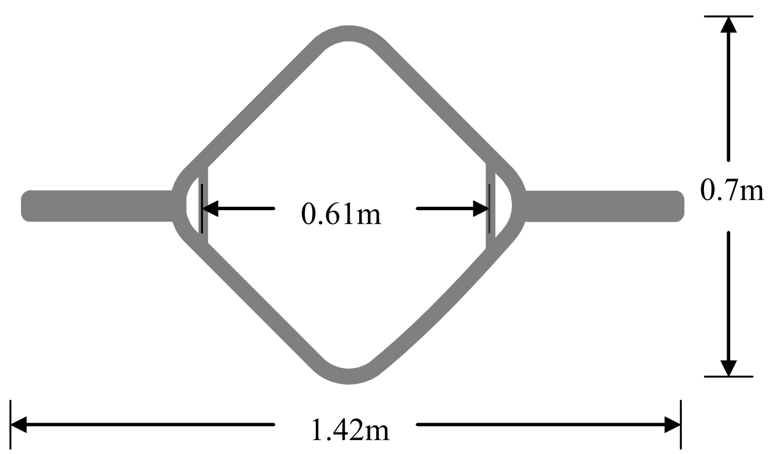

Figure 3-1. Trapezoid bar.

The straight bar (SB) (Figure 3-2) is a straight bar with a mass of 20.45 kg and bilateral loading poles designed to fit standard weight-plates. The bar is designed with grips to ensure good handling during exercises.

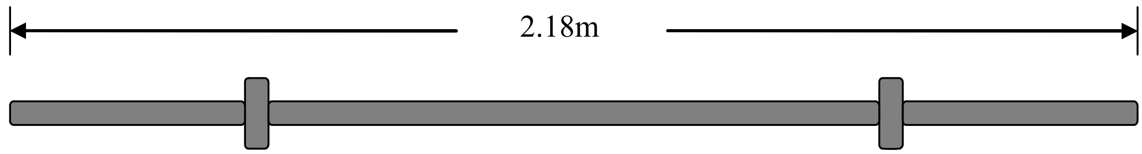

Figure 3-2. Straight bar.

Force Platform

A Bertec force platform (Type 4060-10, Bertec Corporation, Columbus, OH) sampling at 900 Hz was used to collect ground reaction force (GRF) data. The size of the top surface of the force platform is 0.6 m **x** 0.4 m. Before each testing session the force platform amplifier was balanced and on for approximately 30 minutes prior to testing.

Videography

Three JVC video cameras (Model # TK C1380) with a sampling rate of 60 Hz were used to collect all analog video data. Each camera was strategically positioned along the walls of the Biomechanics laboratory to allow for full view of all passive reflective markers. This eliminated any error due to estimation of reflective marker location during the execution of a trial. A three dimensional analysis was used to increase the accuracy of the data collected and all views were taken from the left side of the subject. Camera 1 was placed directly in front of the subject, and camera 2 and camera 3 were placed at diagonal views (Figure 3-3).

Muscle Activity

A MESPEC 4000 (Mega Electronics, Ltd., Finland) telemetric electromyography unit sampling at 900 Hz was used to record muscle activity for all trials. The MESPEC 4000 uses a transmitter which was attached to the subject to broadcast the muscle activity data of the subject during each trial to the Peak Motus system.

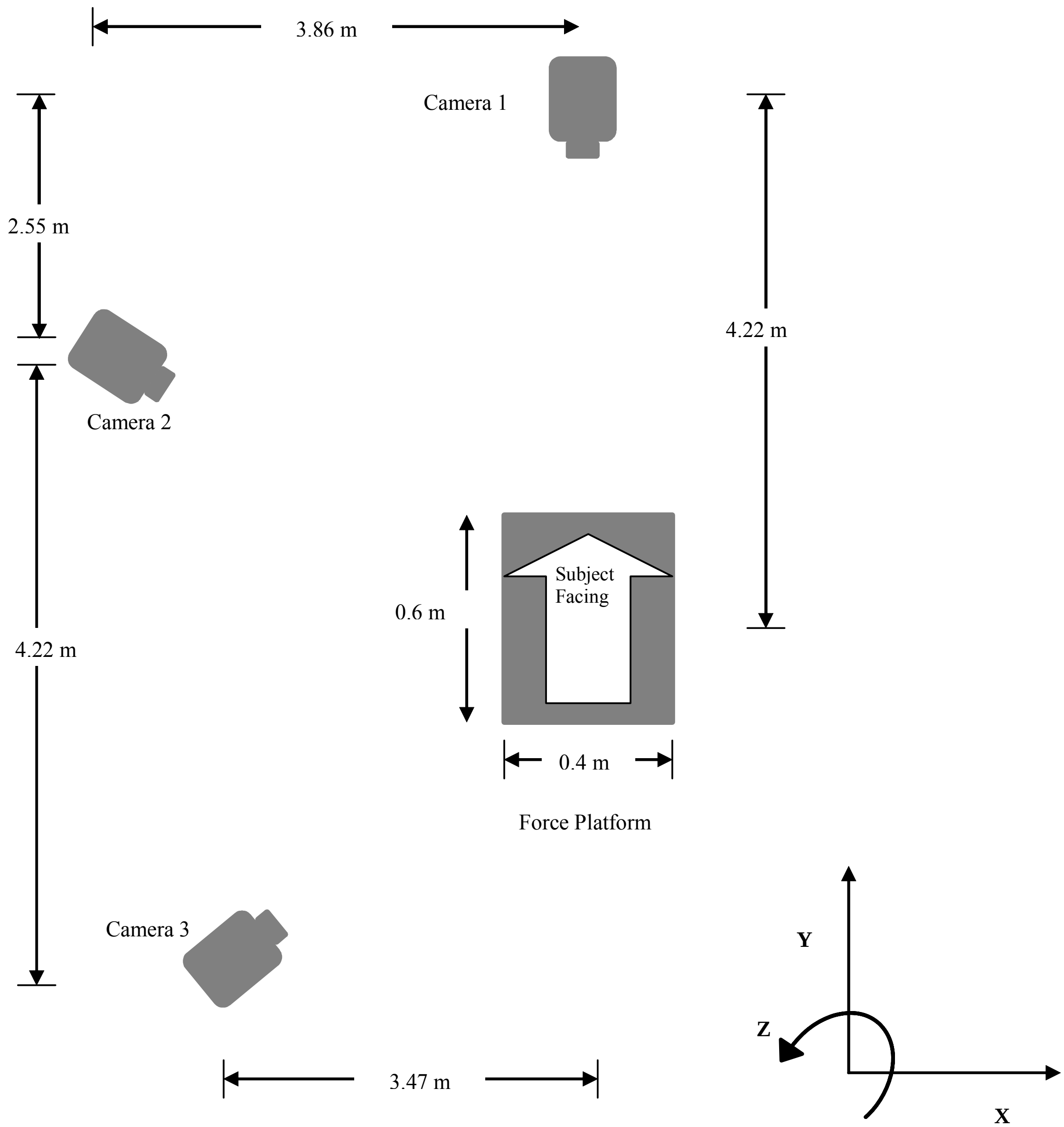

Figure 3-3. Overhead view of experimental set-up.

Peak Motus System

The Peak Motus® 2000 (Peak performance Technologies, Englewood, CO) software system was used to collect, synchronize and digitize all video data. This allowed the complete matching of all analog and video data.

Procedures

Subjects performed all testing protocols while supervised by the investigator in the Biomechanics Laboratory at the College of Health and Human Performance of the University of Florida. Each subject attended one testing session.

Video Calibration

A 16-point calibration frame (1.25 m x 1.1 m x 0.9 m) calibration frame (PEAK® Performance Technologies, Inc., USA) (Figure 3-4) was video taped while placed over a force platform prior to each testing session. Camera orientations were adjusted to ensure clear view of all calibration points. Each calibration point from all camera views was manually digitized. A calibration frame recording with an object space calibration error of greater than 0.5 % was rejected and the calibration frame was re-recorded and re-digitized. Force platform calibration was done manually prior to each testing session. Furthermore, testing was done only after the force platform has been turned on for a minimum of 30 minutes.

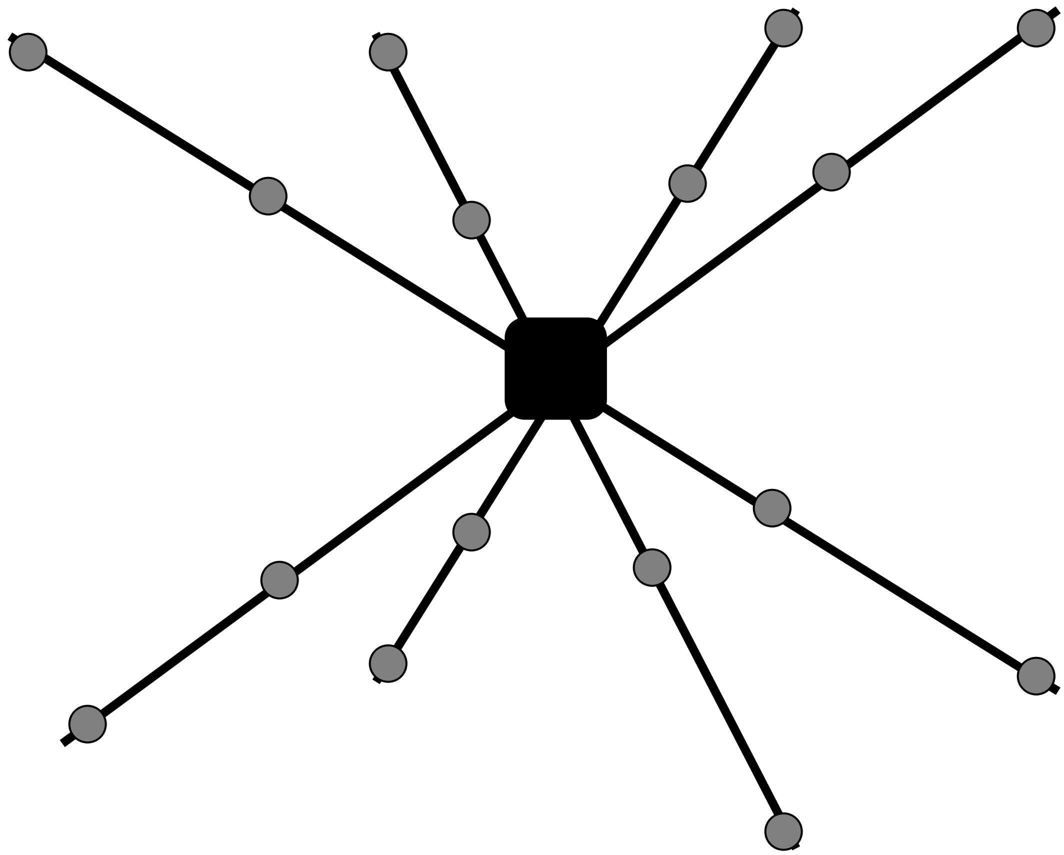

Figure 3-4. Schematic of the 16-point calibration frame.

Warm-up and Practice

Immediately following the pre-participation screening and before testing, each subject was instructed on the technique of each lift. Subjects were allowed to perform a self selected warm-up.

When the warm-up was completed, all subjects were required to complete a practice set of three repetitions of the squat using an unloaded OB and TB bar. An unloaded bar was used during each practice trial to avoid the onset of muscle fatigue during testing and to confirm that the subjects are using proper technique.

Testing and Subject Preparation

Upon the completion of the practice set, subjects began the testing protocol with a randomly assigned trial sequence. In previous literature a percentage of body weight was used to determine the load lifted by the study subjects (Caterisano et al., 2002). For this study 75% of the subject's body weight was used as the external resistance for all conditions. Caterisano et al. (2002) used 100 - 125% of body weight to determine the load in their experiment, however this investigation required the subjects to hold the load with their hands and across the shoulders, so, to avoid complications due to poor grip strength 75% of each subject's body weight was chosen as the appropriate load.

Subjects were prepared for each testing session by placing two surface electromyography (EMG) electrodes over each of the following muscles or muscle groups: the gastrocnemius, quadriceps, gluteus maximus, and hamstrings (Table 3-3).

Table 3-3. Electrode placement:

Muscle	Electrode Location
Gastrocnemius	Each placed on the belly of the medial and lateral gastrocnemius.
Gluteus maximus	Spaced approx. 3 cm apart ½ the distance between the trochanter and sacral vertebrae in the middle of the muscle on an oblique angle and in line with the muscle fibers at the level of the trochanter.
Quadriceps	Center of the anterior surface of the thigh and approximately (approx) ½ the distance between the knee and the iliac spine. Electrodes placed approximately 2 cm apart and parallel to the muscle fibers.
Hamstrings	Spaced 2 cm apart parallel to the muscle fibers on the lateral aspect of the posterior thigh 67% the distance between the trochanter and the back of the knee.

Prior to the electrode application the skin was shaved and cleaned with alcohol to reduce skin impedance allowing for a clearer signal (Brask, Lueke, & Soderberg 1984; Ninos, Irrang, Burdett, & Weiss 1997; Isear, Erickson, & Worrell 1997; Hung & Gross 1999).

Following EMG electrode placement subjects performed a Maximum Voluntary Isometric Contraction (MVIC) lasting approximately five seconds for each muscle that was monitored (Table 3-4). The EMG values were recorded for all MVIC trials and

Table 3-4. MVIC collection guidelines:

Muscle	Action	Body Position
Gastrocnemius	Plantar flexion	Lying with the ankle extended approx. 45°
Gluteus maximus	Hip extension	Standing with the hip flexed approx. 45° subjects forcefully extends hip
Quadricep	Knee extension	Seated knee flexed at approx. 90° posteiorly directed force applied at ankle.
Hamstring	Knee flexion	Seated knee flexed at approx. 90° anteriorly directed force applied at ankle.

reflective markers were placed on various landmarks of each subject.

These landmarks were the second metatarsal head, lateral malleolus, heel, femoral epicondyle, and greater trochanter of the left leg. There were two additional markers placed at mid-shank and mid-thigh locations of each subject (Figure 3-5).

Following the marker and electrode placement each subject was given further demonstration on the performance of each exercise of the testing session. After the participant felt comfortable with the performance of each exercise the testing session began.

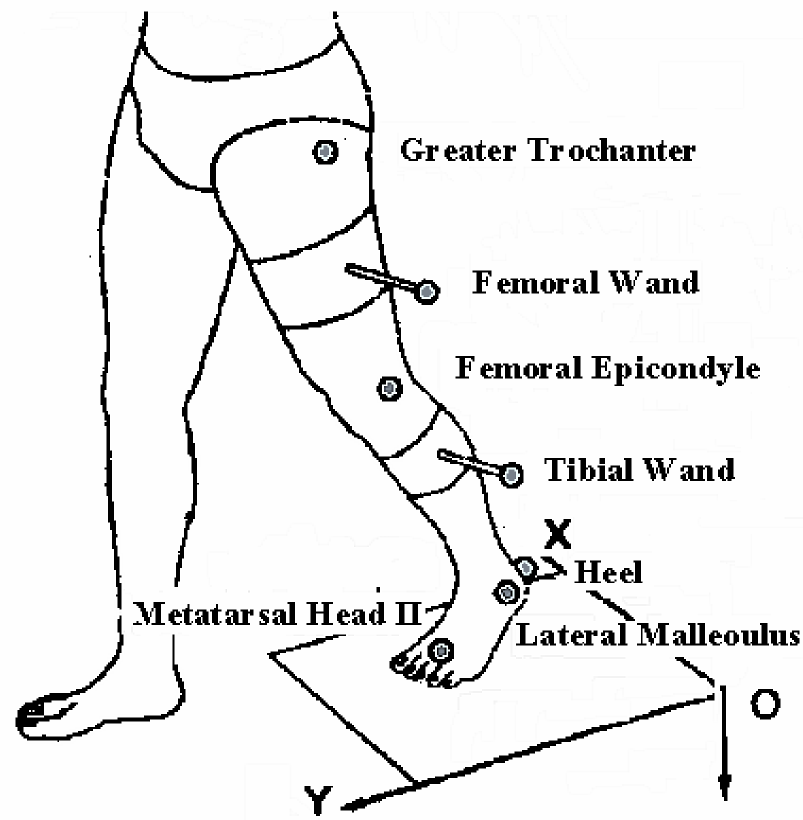

Figure 3-5. Marker placement.

The SB squat was performed with the standard SB superior to the middle trapezius muscle and in horizontal alignment but not in contact with any cervical vertebra. The TB squat was performed with the bar suspended from the hands of each participant. Stance width was manipulated for each TB and SB squat. In previous literature a percentage of shoulder width or hip width was used to determine stance width (McCaw & Melrose, 1998; Escamilla et al., 2000). For this investigation a percentage of femur length was used to determine stance length. The femur and tibia make up the length of the leg. When trying to control for stance width, using a percentage of femur length allowed a more consistent measure among the subjects of this investigation.

Femur length is proportional to lower extremity length and therefore a more appropriate measure of stance width can be made using a percentage of femur length rather than hip or shoulder width. The approximate location of the femur was defined as the distance between the greater trochanter and the lateral condyle of the tibia and measured with a calliper while the subject was standing still. Stance width was defined as 75% of the length of the femur and measured from heel to heel. Subjects used a self selected foot position during each trial.

Proper execution of each trial is important to ensure reduced risk of acute injury and to eliminate other extraneous variables that may skew the collected data. Each participant was instructed to maintain an erect posture and avoid the knee projecting in front of the toes. Subjects were required to execute a parallel squat for each trial taken while standing with their left foot on a force platform. A parallel squat was defined as the approximate location of the femur (midway between the top and bottom of the thigh) being parallel to the floor. Trials were discarded if a participant's feet do not remain flat on the force platform or if they fail to reach parallel. Each repetition for each trial was executed at a self-selected pace.

Session Protocol

All subjects performed two trials per bar condition. There were three repetitions per trial followed by a self-selected rest period. The values of the middle repetitions of the two trials for each condition were averaged and taken for subsequent analysis.

Data Reduction

Electromyography and Ground Reaction Force

All EMG data recorded were filtered using a band pass filter with a high pass cut-off frequency of 10 Hz and a Low pass cut-off frequency of 450 Hz. The low pass cut-off frequency was based on the Nyquist theorem. The signals were then rectified, and normalized to a MVIC value collected pre-exercise. The MVIC value used for normalization was the average value over the middle 2 seconds of the trial. A Butterworth low pass filter was used to condition the GRF data using a cut-off frequency of 6 Hz. Also, a 12-bit analog to digital (A/D) converter was used to convert all data from analog to digital form.

Kinematics

Each reflective marker of the middle trial was digitized using a the Peak Motus® 2000 Motion Measurement System. Two critical instants were identified for each trial: (1) the beginning of the downward phase of the squat and (2) the beginning of the upward phase of the squat.

The Peak Motus® 2000 was used to calculate joint kinematics and digitize (two frames before the start of and two frames after the completion) of the middle repetition of each set. The beginning and end of each digitized trial were identified as the initial eccentric movement from maximum vertical hip marker value and the final concentric movement from maximum vertical hip marker value respectively.

Knee joint angles were calculated using estimated joint centers of the ankle, knee, and hip. Ankle, and hip angles were not calculated. Inverse dynamics was utilized to calculate joint kinetics (Figure 3-7).

Joint Reaction Forces and Joint Moment

The knee joint resultants force (F_K) and moment (T_K) were determined using the equations listed below.

$$F_K + W_{FS} + F_G = 0 \qquad [1]$$

$$r_{FS} \times W_{FS} + r_G \times F_G + T_K = 0 \qquad [2]$$

where r_{FS} and r_G are moment arm vectors of W_{FS} (weight of foot and shank) and F_G (force due to gravity) about T_K (torque at the knee) respectively, and × denotes a vector (cross) product.

Statistical Analysis

The three factors examined in this investigation were gender (male and female), type of bar (straight bar or trapezoid bar), and phase (ascending and descending).

To assess the relations among gender, bar types and phases the following dependent variables were measured:

- Mean EMG values during the descent and ascent phases
- Maximum extension moment at the knee during the descent and ascent phases
- Maximum anteroposterior force at the knee during the descent and ascent phases
- Maximum compressive force at the knee during the descent and ascent phases
- Quadriceps Angle
- Hip width
- Maximum knee flexion angle during each squat.

Due to subject attrition, loss of data and the exploratory nature of this investigation three tests for significance were used. The a-priori level of significance for all statistical tests performed was $\alpha = 0.05$. To analyze the EMG data a 2x2x2 repeated measures MANOVA (Gender*Bar type*Phase) was used. A test of significance for the kinetic data was done using three 2x2x2 (Gender*Bar type*Phase) repeated measures ANOVAs with a Bonferroni adjustment for multiple comparisons which resulted in an adjusted level of significance of $p = .0167$ ($.05/3 = .0167$). To analyze maximum knee flexion angle during the straight bar and trapezoid bar squats, Quadriceps angle and normalized hip width data, four t-tests were used with a Bonferroni adjustment for multiple comparisons of four which resulted in an adjusted level of significance of $p = .0125$ ($.05/4 = .0125$).

In accordance with Schutz and Gessaroli (1987) a 2x2x2 MANOVA was used to analyse and compare electromyography data collected. The MANOVA was the more robust statistical test for the electromyography data however the kinetic and kinematic data required different statistical tests.

CHAPTER 4
RESULTS

This study revealed significant differences in Q-angle between males and females with no significant differences between genders for the average EMG, maximum net anterior and compressive force, maximum net knee extension moment, maximum knee flexion angle and maximum knee flexion angle for each squat type. However, significant main effects were found between bar types for the average EMG of the quadriceps, gluteals and hamstring muscle groups. Significant main effects were found between bar types for the maximum compressive force at the knee, maximum anteriorly directed shear force and maximum knee extension moment. The ratio or compressive to anterior shear force was also measured but there was no significant differences found with this measure. There were also significant interactions for the following: phase*group for gluteal and hamstring muscle activity, and bar*phase for quadriceps muscle activity.

There were significant differences between the trapezoid bar and straight bar types and between phases. However, gender main effects were not significant. Hence muscle activity was collapsed among gender groups and a comparison was made between straight and trapezoid bar types or phases where applicable. Quadriceps muscle activity was significantly different between bar types with the trapezoid bar yielding higher EMG activity than the straight bar. Activity of the gluteal and hamstring muscle groups showed significant differences between phases with ascending phase resulting in the higher percentage of MVIC in both the gluteals and hamstrings. There were no significant differences found with gastrocnemius activity and thus gastrocnemius activity or implications thereof were not addressed.

Average EMG Activity

The MANOVA revealed a significant main effect for bar type on muscle activity (F = 3.398, p< .05) (Figures 4-1, 4-2, & 4-3, Tables 4-2 & 4-3). Further analysis of muscle activity revealed significant differences between the descending and ascending phases in gluteals, and hamstring muscle activity (Figures 4-2 & 4-3, Tables 4-1, 4-2, & 4-3). Significant interactions were also found between muscle activity and phases (Figures 4-4, 4-5, & 4-6).

Table 4-1. Normalized EMG (mean average ± SD) of different muscle.

	Male				Female			
Muscle	Trapezoid Bar		Straight Bar		Trapezoid Bar		Straight Bar	
	Desc	Asc	Desc	Asc	Desc	Asc	Desc	Asc
Gluteals	3.92 (1.98)	13.12 (7.78)	5.40 (5.11)	13.12 (7.45)	5.25 (3.19)	8.67 (5.87)	4.30 (5.97)	5.07 (4.22)
Hamstring	5.03 (1.87)	11.03 (5.35)	5.48 (3.51)	10.05 (7.66)	5.99 (2.91)	8.06 (4.06)	5.03 (4.16)	4.96 (2.73)
Quadriceps	28.46 -16.53	50.82 (24.26)	32.80 (22.58)	32.61 (18.34)	24.61 (10.41)	33.38 (21.99)	22.14 (15.75)	15.91 (10.85)
Gastroc	4.82 (2.73)	3.41 (1.96)	8.18 (9.25)	9.60 (13.49)	5.94 (6.37)	9.6 (10.40)	5.81 (6.36)	9.33 (9.93)

Table 4-2. 2 x 2 x 2 MANOVA comparing the vectors of muscle activity between genders, bar types and phases.

	Wilks' Lambda	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Observed Power
Group	0.761	1.181	4	15	0.359	0.239	0.282
Bar	0.525	3.398	4	15	0.036	0.475	0.715
Phase	0.367	6.458	4	15	0.003	0.633	0.952
Bar * Group	0.812	0.867	4	15	0.506	0.188	0.213

Table 4-2. Continued

	Wilks' Lambda	F	Hypothesis df	Error df	Sig.	Partial Eta	Observed Power
Phase * Group	0.505	3.677	4	15	0.028	0.495	0.753
Bar * Phase	0.531	3.307	4	15	0.039	0.469	0.701
Bar * Phase * Group	0.893	0.448	4	15	0.772	0.107	0.127

Table 4-3. Univariate statistics for different EMG dependent measures (between subjects)

Muscle	Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
Gluteals	Phase (P)	557.04	1	557.04	26.386	0	0.594	0.998
	Bar (B)	11.781	1	11.781	0.555	0.466	0.03	0.109
	P * Group (G)	202.566	1	202.566	9.595	0.006	0.348	0.834
	B * G	45.451	1	45.451	2.141	0.161	0.106	0.283
	B * P	21.321	1	21.321	0.975	0.337	0.051	0.155
	B * P * G	1.711	1	1.711	0.078	0.783	0.004	0.058
	Error(P)	380.001	18	21.111				
	Error(B)	382.055	18	21.225				
	Error(B*P)	393.675	18	21.871				
Hamstrings	Phase (P)	197.506	1	197.506	17.33	0.001	0.491	0.976
	Bar (B)	26.335	1	26.335	1.936	0.181	0.097	0.261
	P * Group (G)	91.806	1	91.806	8.056	0.011	0.309	0.766
	B * G	15.576	1	15.576	1.145	2.99	0.06	0.173
	B * P	15.931	1	15.931	2.174	0.158	0.108	0.287
	B * P * G	0.63	1	0.63	0.086	0.773	0.005	0.059
	Error(P)	205.14	18	11.397				

Table 4-3. Continued

Muscle	Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta	Observed Power
	Error(B)	244.851	18	13.603				
	Error(B*P)	131.921	18	7.329				
Quadriceps	Phase (P)	763.23	1	763.23	2.603	0.124	0.126	0.333
	Bar (B)	1428.9	1	1428.9	5.634	0.029	0.238	0.613
	P * Group (G)	481.671	1	481.671	1.643	0.216	0.084	0.229
	B * G	46.056	1	46.056	0.182	0.675	0.01	0.069
	B * P	1762.5	1	1762.5	6.77	0.018	0.273	0.692
	B * P * G	71.253	1	71.253	0.274	0.607	0.015	0.079
	Error(P)	5277.61	18	293.201				
	Error(B)	4565.34	18	253.63				
	Error(B*P)	4686.2	18	260.344				
Gastroc	Phase (P)	64.62	1	64.62	2.005	0.174	0.1	0.268
	Bar (B)	104.653	1	104.653	1.648	0.215	0.084	0.229
	P * Group (G)	202.566	1	202.566	9.595	0.006	0.348	0.834
	B * G	123.753	1	123.753	1.949	0.18	0.098	0.262
	B * P	9.045	1	9.045	0.569	0.46	0.031	0.11
	B * P * G	11.026	1	11.026	0.694	0.416	0.037	0.124
	Error(P)	580.611	18	293.201				
	Error(B)	1142.93	18	63.496				
	Error(B*P)	286.001	18	15.889				

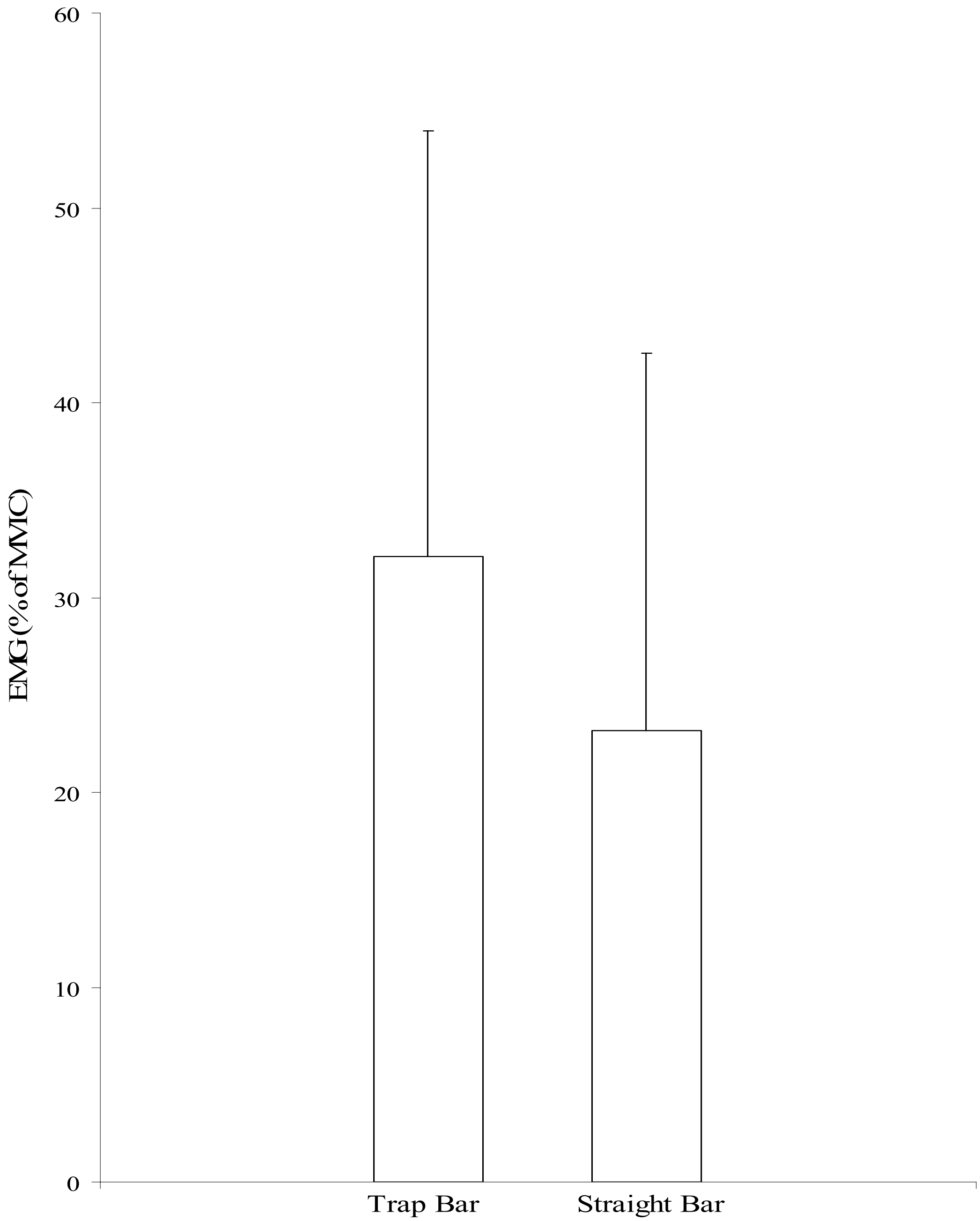

Figure 4-1. Mean quadriceps EMG level. There was a significant difference found between bar conditions.

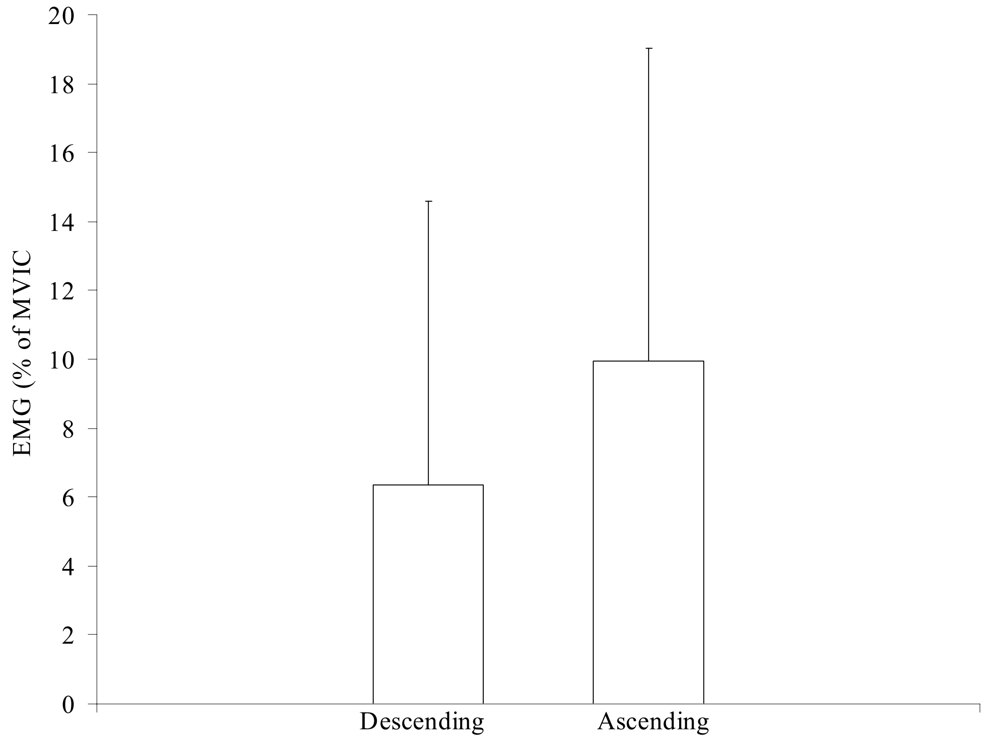

Figure 4-2. Mean gluteal EMG level during each phase of the squat. There was a significant difference found between phases.

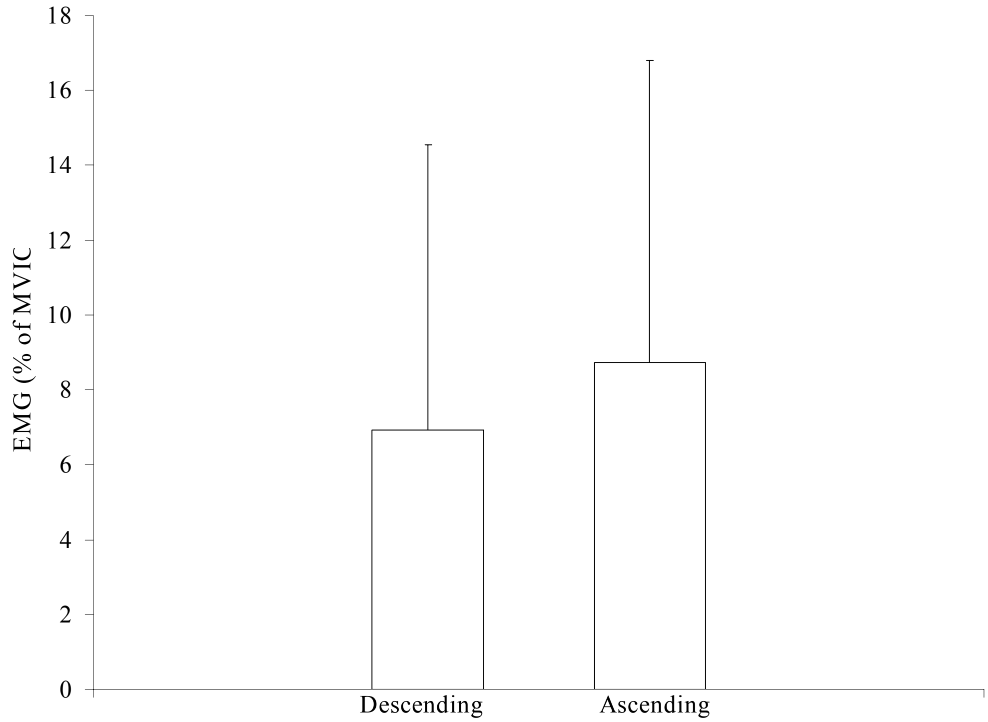

Figure 4-3. Mean hamstring EMG level during each phase of the squat. There was a significant difference found between phases.

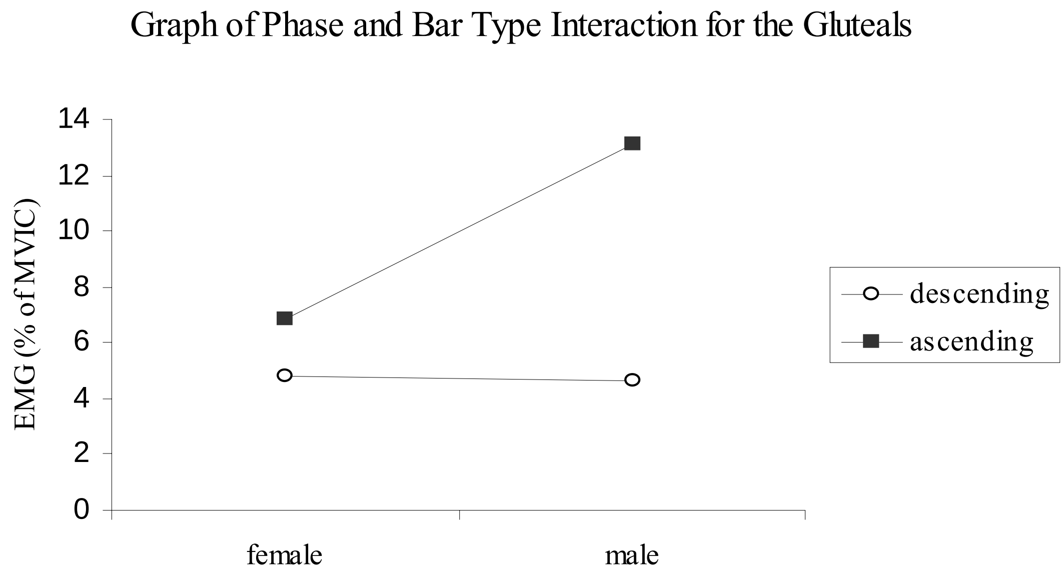

Figure 4-4. There was a significant interaction between gender and phase in the gluteal muscle group. The difference in gluteal muscle activity between the descending and ascending phases was greater in males than females.

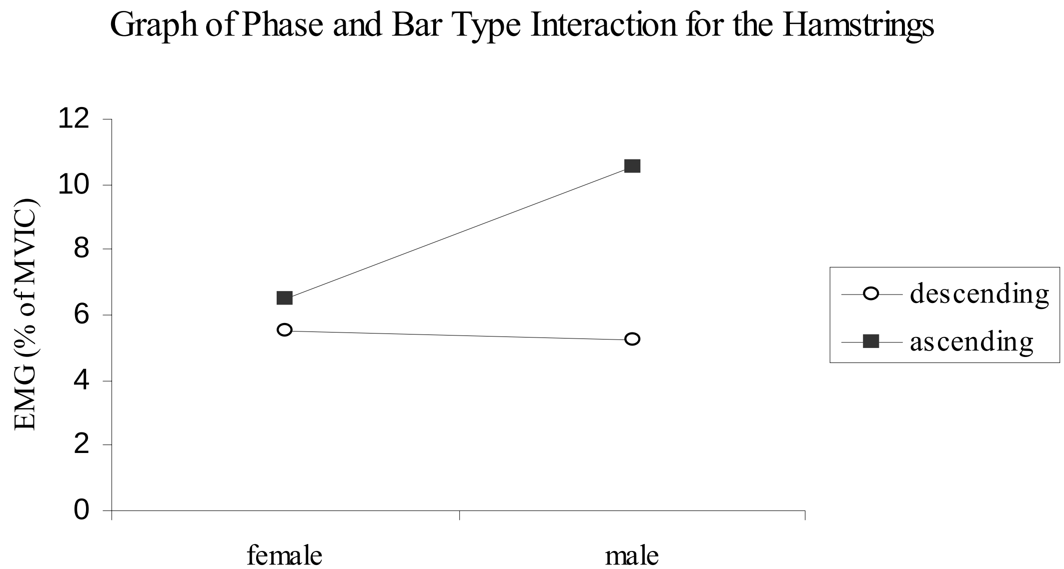

Figure 4-5. There was a significant interaction between gender and phase for the hamstring muscle group. The difference in hamstrings activity between the descending and ascending phases was greater in males than females.

Graph of Phase and Bar Type Interaction for the Quadriceps

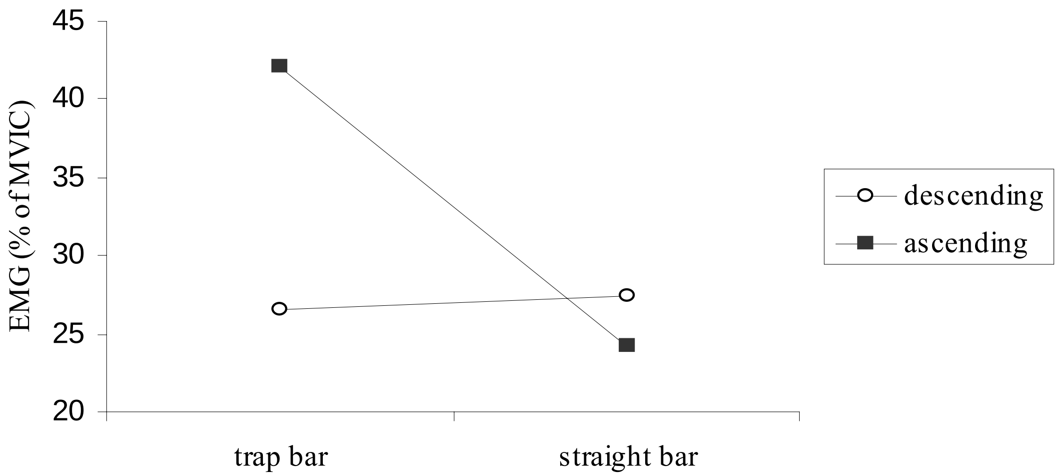

Figure 4-6. There was a significant interaction between bar type and phase for the quadriceps muscle group. The difference in quadriceps activity between the descending and ascending phases was greater when using the trap bar than the straight bar.

Peak Resultant Joint Forces and Moments

The 2x2x2 repeated measures ANOVA revealed significant differences between the two bar types in the maximum knee compressive and anterior shear forces, and the maximum knee extension moment (Figures 4-7, 4-8, & 4-9, Tables 4-4, 4-5, & 4-6). However, there were no significant differences between bar types observed in the knee angle at the instant of maximum knee compressive force.

Table 4-4. Normalized peak joint forces (mean ± SD):

	Male				Female			
Force (N/kg)	Trapezoid Bar		Straight Bar		Trapezoid Bar		Straight Bar	
	Desc	Asc	Desc	Asc	Desc	Asc	Desc	Asc
Compressive	-14.21 (7.66)	-14.02 (6.34)	-8.54 (1.34)	-8.59 (0.95)	-12.04 (6.04)	-13.89 (10.25)	-7.84 (1.54)	-7.84 (1.40)
Anterior Shear	7.57 (4.40)	9.87 (7.31)	3.91 (1.23)	3.98 (1.16)	7.14 (3.36)	5.82 (2.61)	4.99 (1.87)	4.25 (1.23)

Table 4-5. Normalized peak joint moments (mean ± SD):

	Male				Female			
Moment (Nm/kg)	Trapezoid Bar		Straight Bar		Trapezoid Bar		Straight Bar	
	Desc	Asc	Desc	Asc	Desc	Asc	Desc	Asc
Extension	-9.50 (7.89)	-9.3 (6.53)	-2.76 (1.10)	-2.78 (0.87)	-6.46 (4.63)	-5.92 (5.54)	-2.73 (0.76)	-2.82 (0.70)

Table 4-6. ANOVA statistics for different dependent measures (between subjects:

Measure	Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
Max. knee comp. force	Phase (P)	3.728	1	3.728	0.595	0.452	0.038	0.112
	Bar (B)	535.58	1	535.58	8.308	0.011	0.356	0.769
	P * Group (G)	4.946	1	4.946	0.79	0.388	0.05	0.132
	B * G	0.08334	1	0.08334	0.001	0.972	0	0.05
	B * P	3.35	1	3.35	0.528	0.479	0.034	0.105
	B * P * G	5.425	1	5.425	0.856	0.37	0.054	0.14
	Error(P)	93.904	15	6.26				
	Error(B)	967.038	15	64.469				
	Error(B*P)	95.123	15	6.342				
Max. knee anterior shear force	Phase (P)	0.01755	1	0.01755	0.002	0.964	0	0.05
	Bar (B)	160.294	1	160.294	9.573	0.007	0.39	0.824
	P * Group (G)	22.49	1	22.49	2.709	0.121	0.153	0.338
	B * G	48.794	1	48.794	2.914	0.108	0.163	0.359
	B * P	2.265	1	2.265	0.343	0.567	0.022	0.085
	B * P * G	9.56	1	9.56	1.448	0.247	0.088	0.204
	Error(P)	124.525	15	8.302				
	Error(B)	251.167	15	16.744				
	Error(B*P)	99.009	15	6.601				

Table 4-6. Continued:

Measure	Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta	Observed Power
Max. knee Ext. moment	Phase (P)	0.474	1	0.474	0.262	0.616	0.017	0.077
	Bar (B)	431.912	1	431.912	8.766	0.01	0.369	0.79
	P * Group (G)	0.111	1	0.111	0.062	0.807	0.004	0.056
	B * G	42.4	1	42.4	0.861	0.368	0.054	0.14
	B * P	0.853	1	0.853	0.567	0.463	0.036	0.109
	B * P * G	0.207	1	0.207	0.138	0.716	0.009	0.064
	Error(P)	27.133	15	1.809				
	Error(B)	739.071	15	49.271				
	Error(B*P)	22.543	15	1.503				
Forces ratio	Phase (P)	0.48	1	0.48	1.168	0.297	0.072	0.173
	Bar (B)	0.0018	1	0.0018	0.002	0.966	0	0.05
	P * Group (G)	1.65	1	1.65	4.014	0.064	2.11	0.466
	B * G	3.859	1	3.859	4.074	0.062	2.14	0.472
	B * P	0.092	1	0.092	0.21	0.654	0.014	0.071
	B * P * G	0.663	1	0.663	0.138	0.716	0.009	0.209
	Error(P)	6.164	15	0.411				
	Error(B)	14.206	15	0.947				
	Error(B*P)	6.651	15	0.443				

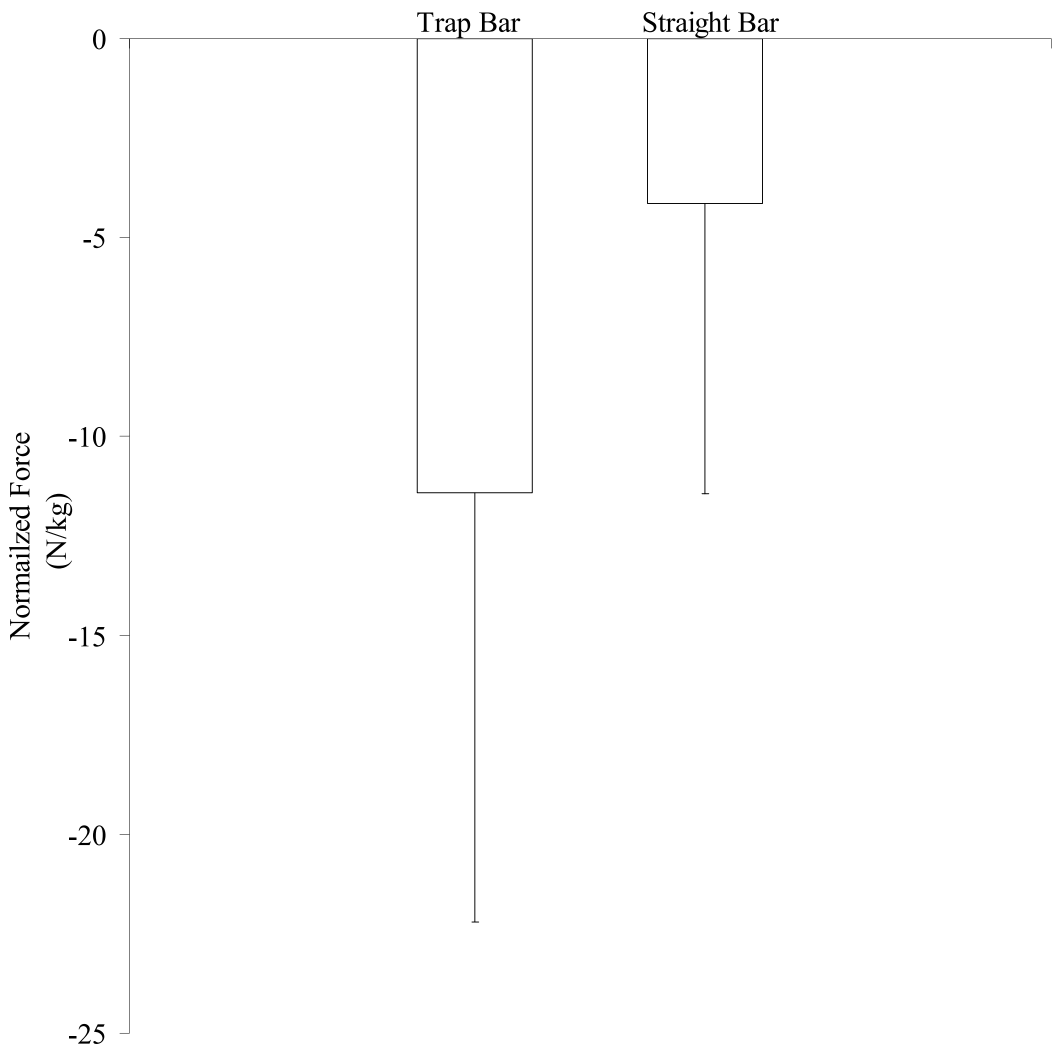

Figure 4-7. Mean net knee maximum compressive force. There was a significant difference found between bar conditions.

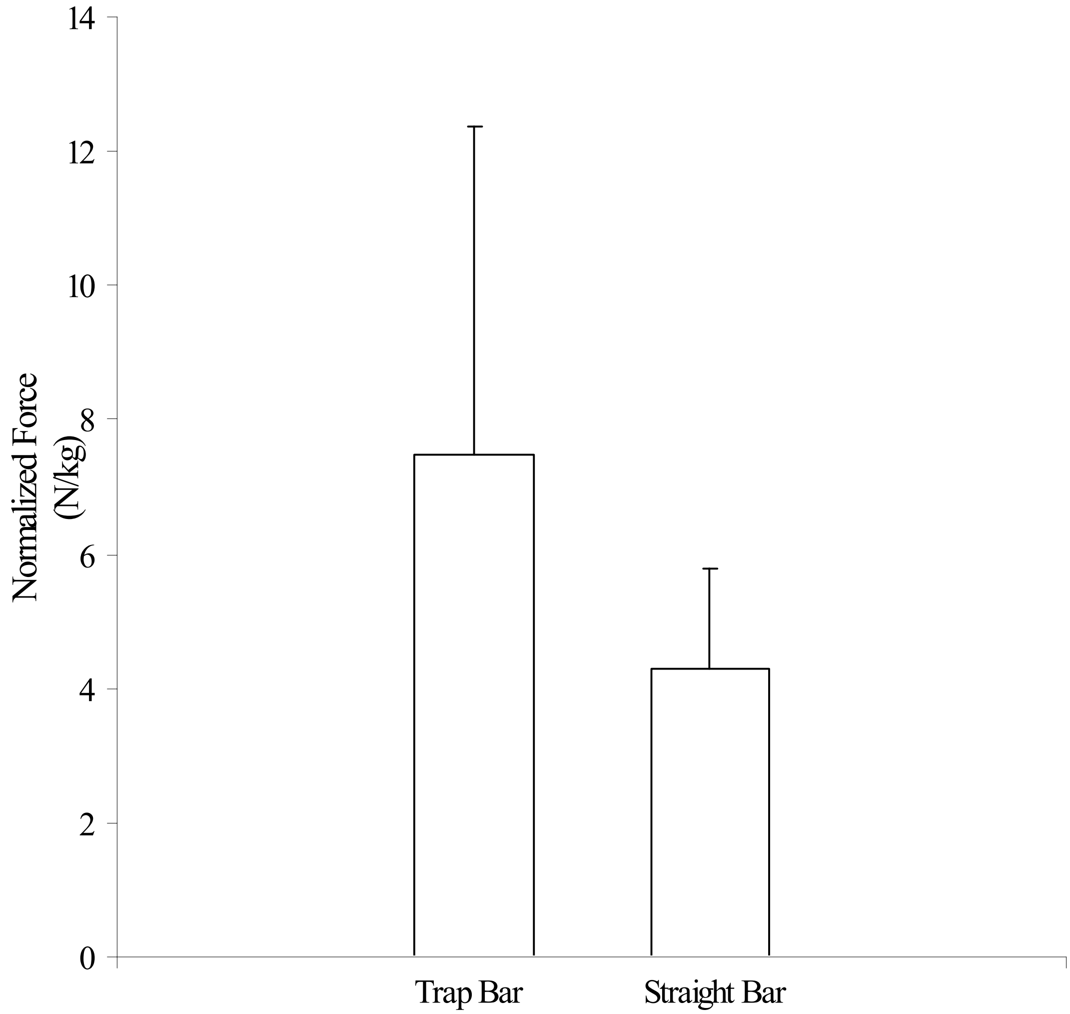

Figure 4-8. Mean net knee maximum anterior force. There was a significant difference found between bar conditions.

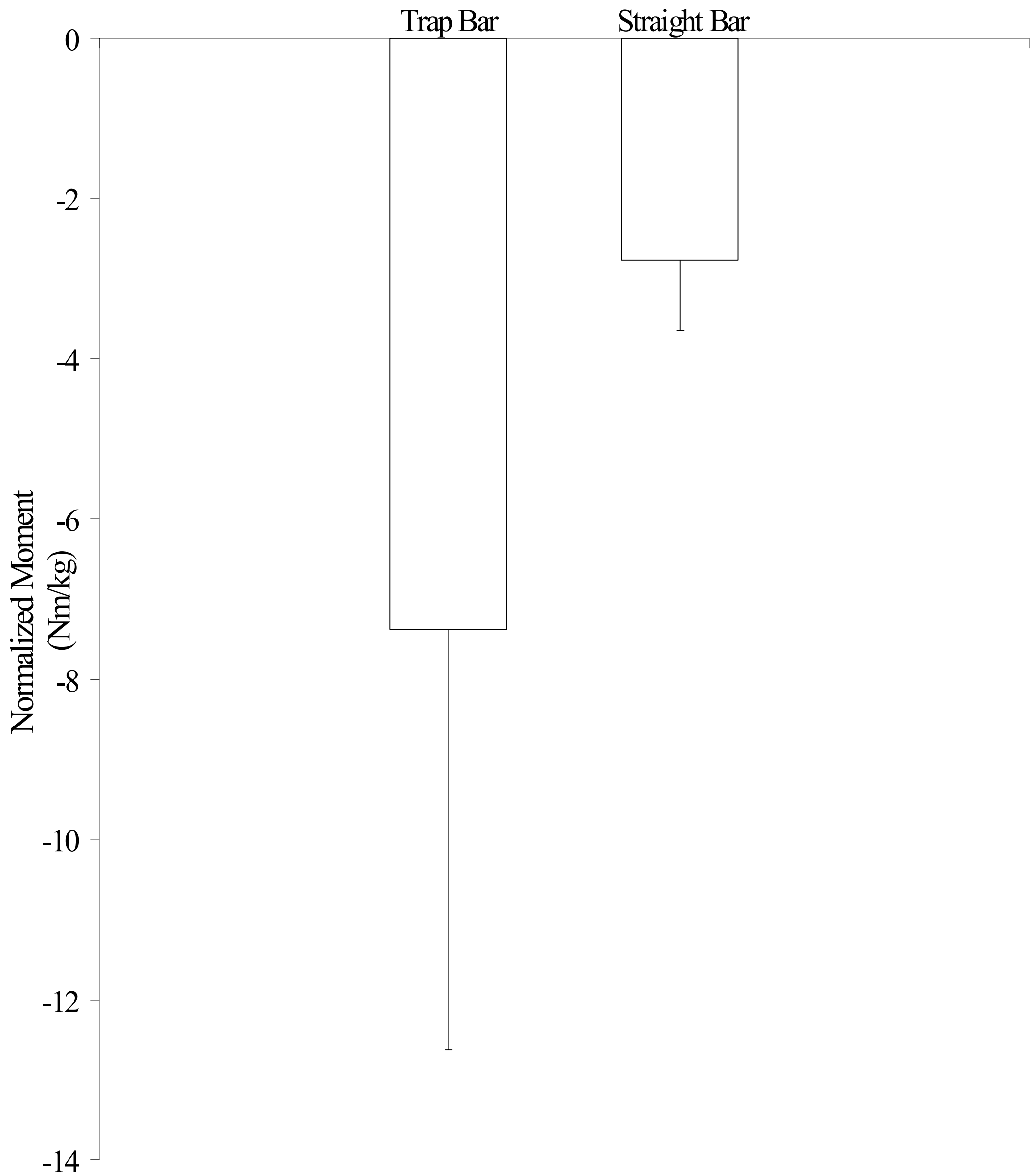

Figure 4-9. Mean net knee maximum extension moment. There was a significant difference found between bar conditions.

The t-tests revealed significant differences between genders in Q-angle and normalized hip breadth (Figures 4-10 & 4-11, Tables 4-7, 4-8, & 4-9).

Table 4-7. Width and angle measurements (mean ± SD):

Measurement	Male	Female
Max. knee flexion angle trapezoid bar (°)	124 ± 39	126 ± 31
Max. knee flexion angle straight bar (°)	107 ± 14	86.83 ± 18
Q-Angle (°)	8 ± 1	12 ± 3
Normalized hip-width (m/m)	0.140 ± 0.09	0.151 ± 0.011

Table 4-8. T-Test analysis for Q-angle and hip width:

		F	Sig.	t	df	Sig. (2-tailed)	Mean diff	Std. Error diff.	95% confidence interval of the diff	
									Lower	Upper
Q-angle										
	a*	6.918	0.017	3.208	18	0.005	3.35	1.0442	1.1563	5.5437
	b*			3.208	11.938	0.008	3.35	1.0442	1.0736	5.6264
Normalized hip width										
	a*	6.918	0.017	3.208	18	0.005	3.35	1.0442	1.1563	5.5437
	b*			3.208	11.938	0.008	3.35	1.0442	1.0736	5.6264

a* equal variances assumed
b* equal variances not assumed

Table 4-9. T-Test analysis for instant of maximum knee angle:

		F	Sig.	t	df	Sig. (2-tailed)	Mean diff	Std. Error diff.	95% confidence interval of the diff	
									Lower	Upper
TK (°)	a*	1.982	0.178	0.089	16	0.931	1.465	16.5515	-33.623	36.5527
	b*			0.086	12.937	0.933	1.465	17.0623	-35.414	38.3442
SK (°)	a*	0.376	0.549	-2.622	15	0.019	-20.464	7.8047	-37.1	-3.8288
	b*			-2.664	14.751	0.018	-20.464	7.6822	-36.863	-4.0657

a* equal variances assumed
b* equal variances not assumed
TK- maximum knee angle during the trap bar squat
SK-maximum knee angle during the straight bar squat

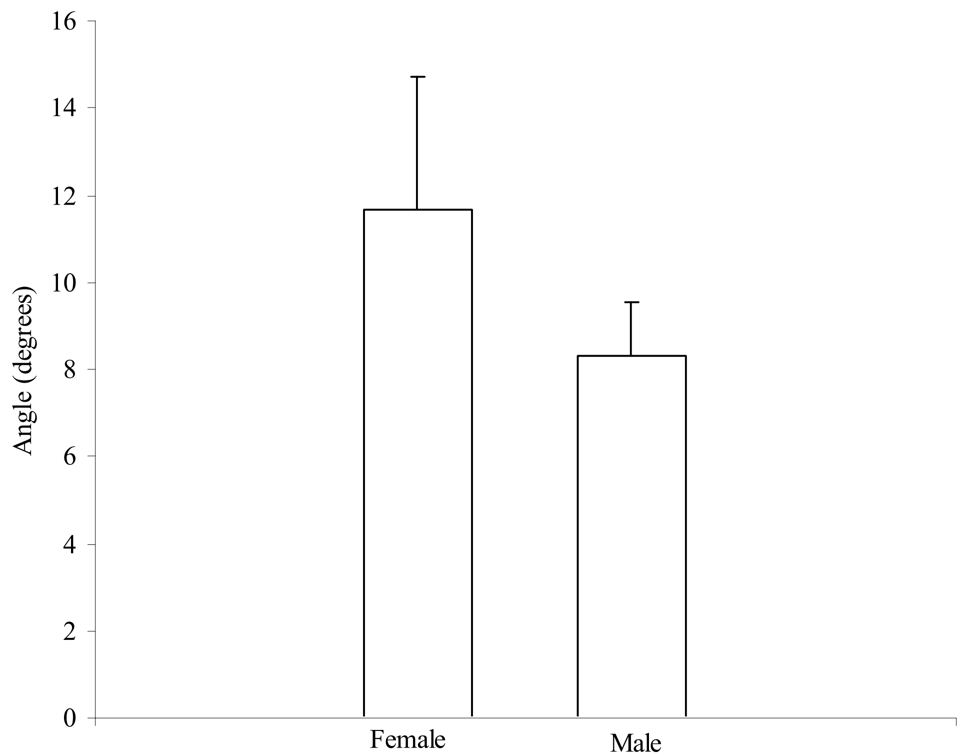

Figure 4-10. There was a significant difference found between males and females for Q-angle.

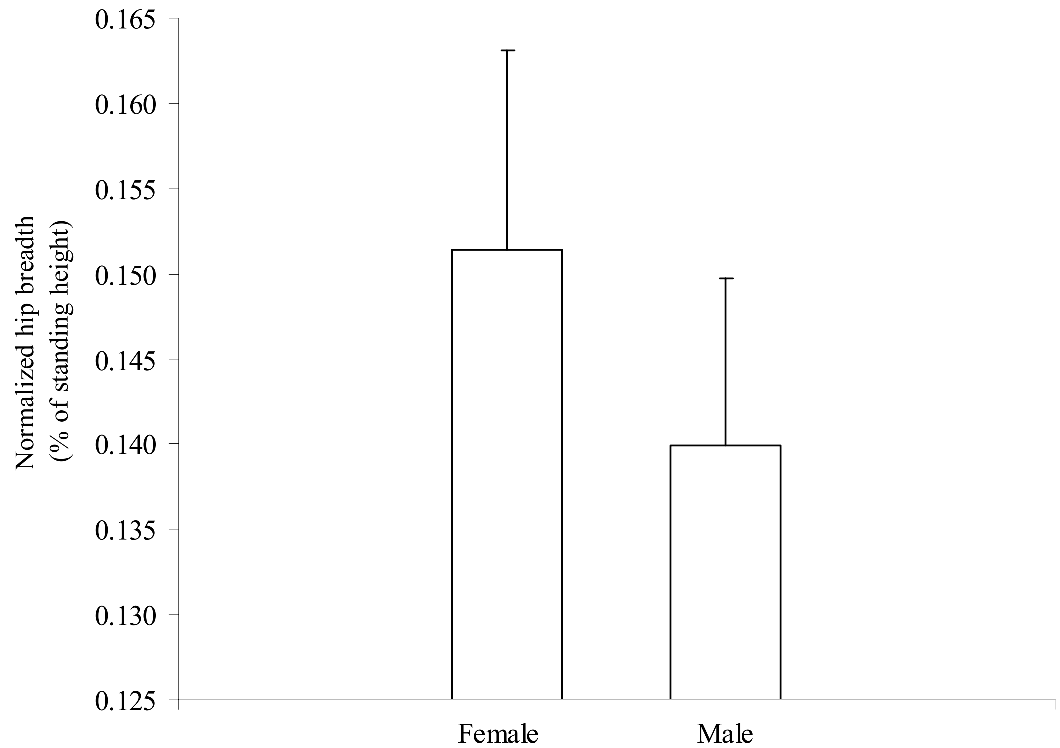

Figure 4-11. There was a significant difference found between males and females for normalized hip breadth.

CHAPTER 5
DISCUSSION

Physical preparation for sports is essential for success and injury reduction. Closed kinetic chain exercises, such as squats are often recommended and touted as a good muscle builder for the legs with some referring to it as the "pillar of strength" exercise for the lower extremity (Lombardi, Dubuque, & Brown, 1989). This is in part due to the belief that the benefits of squatting outweigh the risks associated with the exercise.

The biomechanics of squatting has been studied using various squat techniques with the straight bar. For example, Stuart et al. (1996) studied tibiofemoral joint kinetics and muscle activity during the dynamic squat with the straight bar. Their study focused on variations of squatting using the straight bar but had a limited subject pool. That is to say the subject pool consisted of only six healthy male participants. Studies that have such a small homogeneous sample size can be useful for further research, although the findings of these studies cannot be explicitly applied to people who are outside of that subject pool parameters. Hence, the focus of this investigation was to study the differences in groups that were not fully represented in the literature. This study investigated the effects of the straight and trapezoid squat bars, genders, and the ascending and descending phases of the squat on muscle activity of the hamstrings, quadriceps, gastrocnemius and gluteal muscles and tibiofemoral joint mechanics during a dynamic squat. It was the intent of this investigation to make available practical recommendations for the use of the two studied squat techniques as a functional training or rehabilitative modality. Previous research studies on related topics were used to aid in formulating the hypotheses of this experiment and evaluating the findings of this study.

Muscle Activity

Muscle activity was affected significantly by phase rather than bar type. The hypothesis that mean gastrocnemius, quadriceps, and hamstring muscle activity would be greater during the trap bar squat was partially supported as the quadriceps muscle group was the only muscle group that resulted in a higher value that was significantly different between bar types. McCaw and Melrose (1999) found greater muscle activity during the ascent phase as compared to the descent phase for gluteus maximus and gastrocnemius activity with as much as 2.5 times greater muscle gluteus maximus activity and 50% greater hamstrings activity during the ascent phase of the squat as compared to the descent phase. The findings of this study follow those of McCaw and Melrose. The results showed approximately 50% and 20% higher muscle activity levels during the ascent phase as compared to the descent phase for the gluteals and hamstrings, respectively.

It is reasonable to assume that the hamstrings and gluteals muscles activation increased during the ascent phase is in part due to the demand on hip extension. In an upright position or at the start of the descent phase the hamstrings and gluteals muscles are relatively low because of the small hip extension moment needed for that posture however, at the beginning of the ascent phase these muscle groups are more active because of the large hip extension moment needed to maintain a squat position. Furthermore the higher percentages found in McCaw and Melrose may be attributed to differences in subject pools, MVIC collection position, and the load value the subjects were required to lift.

There are a number of factors such as electrode placement that can affect EMG levels and thus the percentages were not explicitly compared. Instead the activation pattern during the movement was compared and found to be similar between the two studies. Higher muscle activity was expected during the ascent phase due to the motion against gravity. Signorile et al. (1995) found that the highest muscle activity level reached occurred at 90º of knee flexion for the quadriceps and these results support the assumption that the greatest muscle activity will occur where the resistance arm of the upper body weight and barbell about the knee is longest.

There were significant interactions observed for muscle activity and phase. Specifically there was a significant interaction between the gluteal, and hamstring muscle groups and phases for the male subjects. Although this does not explicitly support the hypothesis that mean gluteal, quadriceps, hamstrings, and gastrocnemius activity will be greater during the ascent phase, it does imply that there is a difference between muscle activity of the lower extremities during the ascent and decent phases of the squat.

Forces and Moments

The parameters used to assess tibiofemoral joint kinetics were maximum net compressive force, maximum net anteriorly directed force and maximum net knee extension moment. These factors were chosen in accordance with previous literature (Stuart et al., 1996) and on the possible protective effects they may have on the tibiofemoral joint and its surrounding connective tissue, specifically the anterior cruciate ligament (ACL). The hypothesis that the maximum compressive knee joint force would be greater in the female subjects was not supported by the results of this investigation.

When loaded the ACL provides a posteriorly directed shear force at the tibiofemoral joint and the hamstrings act as an ACL protagonist (More et al., 1993).

However, the hamstrings provide a posteriorly directed shear force at the tibiofemoral joint only at certain knee angles. The results of this study showed an increase in hamstrings muscle activity during the ascent phase of the squat in the trap and straight bar squatting techniques. There were significant differences found between bar types for the net compressive force at the tibiofemoral joint. Compressive force is accepted as a protective mechanism to the knee joint when performing closed chain activities such as the dynamic squat (Escamilla et al., 1998). Specifically it is thought that compressive force at the knee can reduce the shear forces opposed by the ACL and posterior cruciate ligament (PCL) at the knee thus, protecting these ligaments. The trapezoid bar resulted in a higher normalized net compressive force than the straight bar squat. This suggests that, the trap bar squat is a possible training exercise post ACL or PCL reconstruction.

The trap bar also showed a higher value for net anterior shear at the knee which supported the hypothesis that maximum anterior shear force would be greater during the trap bar squat. An anteriorly directed tibiofemoral shear force at the knee signifies PCL loading as explained through static analysis of the posterior draw test. The PCL and ACL provide opposite shear forces at the knee. During the anterior draw test the resultant force is a posteriorly directed force signifying ACL loading. Anteriorly directed shear force then signifies PCL loading. The higher net compressive force at the knee observed during the trap bar squat although considered a protective mechanism to the cruciate ligaments of the knee may be negated due to the increased anteriorly directed shear present. Establishing a standard for the ratio of compressive force to shear force is possibly a more adequate measure for determining the mechanical effects of the squat on the tibiofemoral joint. This is mainly because excessive compressive shear forces can be injurious to the cruciate ligaments whereas excessive compressive force can be damaging to the menisci and articular cartilage (Escamilla, 2001). Hence, one measure alone is inadequate when evaluating the effect of the squat because higher values do not explain the possible effects of forces present.

Gender Comparisons

Hip breadth and quadriceps angle were the two structural factors measured and compared in this study. For comparison normalized hip widths were used. As did in other investigations, significant differences in hip width and quadriceps angle were found between genders. This supports the hypotheses that there would be significant differences between hip width, and Q-angle between males and females of this study. These finding however, do not prove that hip breadth or quadriceps angle had a definitive effect on muscle activity or knee joint kinetics partly because the differences observed in muscle activity and knee joint kinetics were not between the two genders.

As a matter of comparison the effect of differences in hip width and Q-angle between males and females are easier to observe during higher impact exercises than in the squat. Studies have related injuries to the lower extremities, specifically the knee joint in women to landing and cutting maneuvers in sports such as volleyball and basketball. While the squat is a closed kinetic chain exercise it does not have a takeoff or landing instants nor does it require the same “change of direction” as sports such as soccer or basketball require. Thus, the knee is not subject to the same laterally directed forces during the squat as it would during a cutting maneuver during sports.

The menstrual cycle may have an effect on muscle activation and tendon elasticity in women. The female subjects of this investigation were not surveyed regarding their menstrual cycle thus, menstruation is a possible limitation that may offer a partial explanation to the muscle activation observed in the female subjects. Other limitations to gender comparisons may include muscle strength. Assuming muscle strength has a significant effect on lifting ability, the actual percentage of the one repetition maximum squat per subject lifted may differ between subjects. Simply put, each subject may be better equipped to handle a higher percentage of their body mass.

Bar Type Comparisons

The rhomboidal shape of the trap bar allows a lifter to stand within its frame to perform squats and the load lifted is limited by grip strength of the lifter as the bar is held at the hands and not loaded across the shoulders as with the straight bar. The loading position of the trap bar presents a safety feature absent with the straight bar as grip strength should significantly reduce the amount of weight lifted. The disadvantage perhaps is in the dimension of the bar. By standing within the frame of the trap bar a lifter is restricted by the frame as he or she lifts thus, the physical stature of a lifter can be a disadvantage when using the trap bar.

Despite the size of the lifter presenting a possible disadvantage when using the trap bar there is an added advantage to the rhomboidal design and loading position with the trap bar. The lifter is restricted by grip strength. That is to say the lifter can only load the bar with as much weight was he or she could hold. It is reasonable to assume that someone's grip strength will not exceed the amount of weight that person could support across the shoulders while in an upright position. This is significant because in a special population the amount of weight lifted can be restricted. The failure point for the subject's grip due to fatigue should occur at a lower weight than the back or leg muscles.

Foot position was not manipulated for this study because it was unlikely to result in a statistically significant difference for muscle activity (Boyden, Kingman & Dyson, 2000). Therefore, each subject was allowed to position their feet according to their own comforts. It was assumed that foot position would have no effect on muscle activity or joint kinetics. Findings of Boyden et al. (2000) were the basis for this decision however, their study consisted of a sample size of six experienced male subjects. With the trap bar squat, changes in leg and foot position to accommodate the bar may (e.g., feet point forward) have had an effect on muscle activity, knee joint kinetics and kinematics.

Stance width was controlled for this study primarily because changes in stance width can have an effect on joint kinetics and kinematics (Escamilla, 2001). Although not manipulated in this study self adjustments foot position during the trap bar squat may have lead to adjustments in the way the lifter performed the squat and possibly change the kinetics and kinematics of the study. These adjustments were not explicitly observed in this study however, it is possible that such adjustments did occur and played a role in the statistical differences between bar types for the joint kinetic and kinematics measures and the significant interaction observed for bar type and quadriceps muscle activity.

Summary and Conclusion

This study investigated the effects of two squat techniques on tibiofemoral joint mechanics and muscle activity. Nineteen healthy subjects with no history of injury were recruited from the University of Florida. Each subject participated in one testing session which consisted of trapezoid bar and straight bar squat trials. Significant interactions and main effects were found within subjects for the mean EMG levels of the quadriceps, gluteals and hamstrings muscle groups. Significant differences were found between trapezoid and straight bar conditions for the maximum compressive and maximum anteriorly directed forces at the knee, and the maximum knee extension moment.

The straight bar and trapezoid bar squats are closed kinetic chain exercises that produce compressive and shear forces at the tibiofemoral joint. The results of this study revealed significant differences between these exercises that may lead to improved use of each of these squat techniques in any setting be it rehabilitation or strengthening and conditioning oriented. The overall effect of each bar type will be favorable when used in the correct setting. Despite no significant interaction or main effect on the gastrocnemius which is a secondary knee flexor the techniques tested showed significant effects on the other major muscle groups of the legs.

While it is not possible to definitively state which squatting technique is better it is possible to state that these two techniques may have more positive effects when used together rather that singly. Individuals who show a deficiency in one area of muscle activity will benefit from use of each technique singly or in concert which also suggests that one technique will be superior over the other depending on the condition of the muscle group being trained. For instance the trap bar resulted in higher muscle activity for the quadriceps muscle, thus with a subject that presents with quadriceps weakness the quadriceps dominant nature of the trap bar squat would make it an adequate exercise to increase quadriceps muscle strength

Implications

Comparison of the straight bar and trapezoid bar squat techniques revealed significant difference in muscle activity and knee joint kinetics between these two techniques. These differences may contribute to further studies investigating the effects of each technique in a rehabilitation setting and/or strength and conditioning setting. From an application standpoint this research can be used to aid in prescribing exercise for specific injuries of the legs. Each technique can be used singly, in cooperation or combined with other exercise and rehabilitation techniques to achieve the greatest benefits of any rehabilitative or strengthening and conditioning regimen.

APPENDIX A
IRB APPROVAL

IRB APPROVAL

UNIVERSITY OF FLORIDA INSTITUTIONAL REVIEW BOARD

1. TITLE OF PROJECT: Analysis of Knee Mechanics: Differences between female and male athletes during the squat exercise.

2. PRINCIPAL INVESTIGATOR(s): *(Name, degree, title, dept., address, phone #, e-mail & fax)*
Francis Forde, B.S., Graduate Teaching Assistant, Dept. of Exercise and Sport Sciences, P.O. Box 118205, 392-0584 ext. 1374, fforde@ufl.edu

3. SUPERVISOR (IF PI IS STUDENT): *(Name, campus address, phone #, e-mail & fax)*
Mark Tillman, Ph.D., Assistant Professor, Dept. of Exercise and Sport Sciences, P.O. Box 118205 [(352) 392-0584 ext. 1237]

4. DATES OF PROPOSED PROJECT: From ____12/02______ To ____12/03______

5. SOURCE OF FUNDING FOR THE PROJECT: N/A
(As indicated to the Office of Research, Technology and Graduate Education)

6. SCIENTIFIC PURPOSE OF THE INVESTIGATION:

The purpose of this study is to investigate the influence of weightlifting techniques on lower extremity kinematics and kinetics. Specifically we will investigate lower extremity joint angles, joint forces and muscular activity during the performance of the squat using an Olympic bar and a Trapezoid (trap) bar.

7. DESCRIBE THE RESEARCH METHODOLOGY IN *NON-TECHNICAL* LANGUAGE:
The UFIRB needs to know what will be done with or to the research participant(s).

Each participant will be required to perform two lifting techniques, one using the Olympic bar and the other using the trap bar. When performing the squat with the Olympic bar, the load is supported behind the neck on the upper portion of the trapezius muscle (shoulder muscles). During the trap bar squat, the load is held using handles located on both sides of the bar with the arms extended at the sides. Participants will perform a maximum of 5 repetitions of each lift using 75% of their body weight as resistance. Each session will consist of a total of 8 sets with varying foot position and stance widths. Each participant will only have to attend one session.

Each participant will be fitted with reflective markers placed over bony landmarks and will be filmed while performing each of the exercises. Surface electrodes will be placed over the muscles of the front and back of the legs, and back.

8. POTENTIAL BENEFITS AND ANTICIPATED RISK:
(If risk of physical, psychological or economic harm may be involved, describe the steps taken to protect participant.)

Inherent risks associated with resistance exercise include muscle and joint soreness as well as joint and muscle pain. Untrained individuals have a greater likelihood to experience these effects. Therefore in this study we will specifically recruit participants who currently participate in some form of a strength and conditioning regimen. The benefit of this research may result in the recommendation of a safe alternative exercise to the standard Squat and Dead Lift exercises.

9. DESCRIBE HOW PARTICIPANT(S) WILL BE RECRUITED, THE NUMBER AND AGE OF THE PARTICIPANTS, AND PROPOSED COMPENSATION (if any):
Thirty volunteers will be recruited from the sport and fitness classes in the Department of Exercise and Sport Sciences

10. DESCRIBE THE INFORMED CONSENT PROCESS. INCLUDE A COPY OF THE INFORMED CONSENT DOCUMENT (if applicable).
See attached Consent Form.

Please use attachments ONLY when space on the form is insufficient.

_______________________________ _______________________________
Principal Investigator's Signature Supervisor's Signature

____
Department Chair's Signature

APPENDIX B
INFORMED CONSENT FORM

Informed Consent Agreement

Project Title: Analysis of Knee Mechanics: Differences between female and male athletes during the squat exercise
Please read this consent agreement carefully before you decide to participate in this study.

Purpose of the study:
The purpose of this study is to investigate the influence of weightlifting techniques on lower extremity muscle activity, kinematics and kinetics. Specifically we will investigate lower extremity joint angles, joint forces and muscular activity during the performance of the squat performed using a Trapezoid bar and an Olympic straight bar.

What you will do in the study:
You will be required to perform two lifting techniques one using the Olympic bar and the one using the trap bar. When performing the squat with the Olympic bar, the load is supported behind the neck on the upper portion of the trapezius muscle (shoulder muscles). During the trap bar squat, the load is held using handle grips located at both ends of the bar with the arms extended at the sides. You will perform a maximum of 5 repetitions of each lift using 75% of your body weight as resistance. The total number of sets per session will be 8 with varying foot positions and stance widths. You will only have to attend one session.

You will be fitted with reflective markers placed over bony landmarks and will be filmed while performing each of the exercises. Surface electrodes will be placed over the muscles of the front and back of the legs, and back.

Time required:
All experimental conditions will be conducted in one testing visit that will last approximately two hours.

Risks:
Inherent risks associated with resistance exercise include muscle and joint soreness as well as joint and muscle pain and injury. These are temporary effects, usually lasting 1–3 days.

Benefits/Compensation:
There is no monetary compensation or direct benefit to you for participation in this project. This research may result in the recommendation of a safe alternative exercise to the standard squat exercises.

Confidentiality:
Your information will be assigned a code number. The list connecting your name to this number will be kept in a locked file. When the study is completed and the data have been analyzed, the list and all video files will be destroyed. Your identity will be kept confidential to the extent provided by law

Voluntary Participation:
Your participation in this study is completely voluntary. There is no penalty for not participating. For your safety, you will not be allowed to participate in this study if you have a history of past illnesses or injuries that may reoccur as a result of your participation and cause harm to you.

Right to withdraw from the study:
You may withdraw your consent at anytime from this study without penalty.

Whom to contact if you have questions about the study:
Francis Forde, B.S., Graduate Teaching Assistant, Dept. of Exercise and Sport Sciences, P.O. Box 118205 [(352) 392-0584 ext. 1374]
Mark Tillman, Ph.D., Assistant Professor, Dept. of Exercise and Sport Sciences, P.O. Box 118205 [(352) 392-0584 ext. 1237]
Whom to contact about your rights in the study:
UFIRB Office, Box 112250, University of Florida, Gainesville, FL 32611-2250

Agreement:
I have read the procedure described above, I voluntarily agree to participate in the procedure and I have received a copy of this description.

Participant: ____ **Date:** ________________________

APPENDIX C
SAMPLE RAW DATA

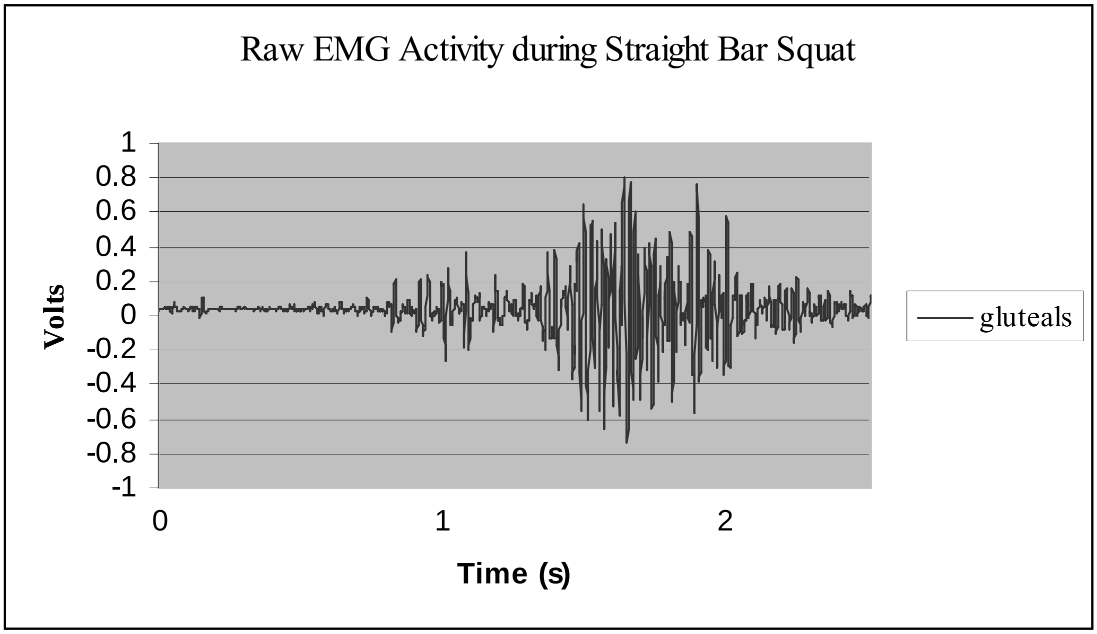

Figure C-1. Raw EMG for the gluteals for the straight bar squat

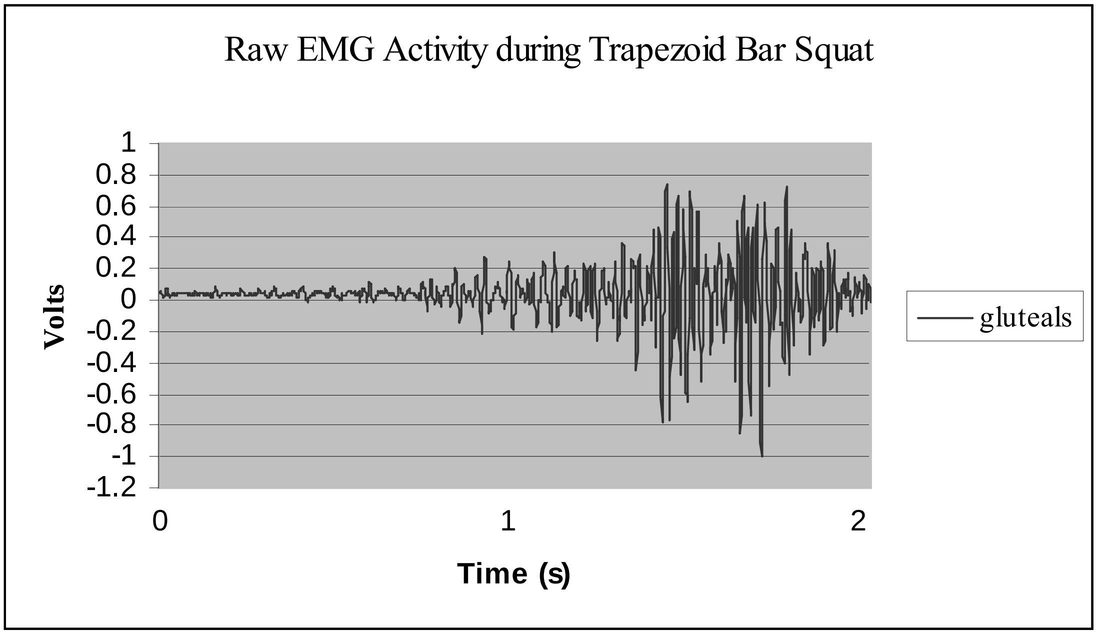

Figure C-2. Raw EMG for the gluteals for the trapezoid bar squat

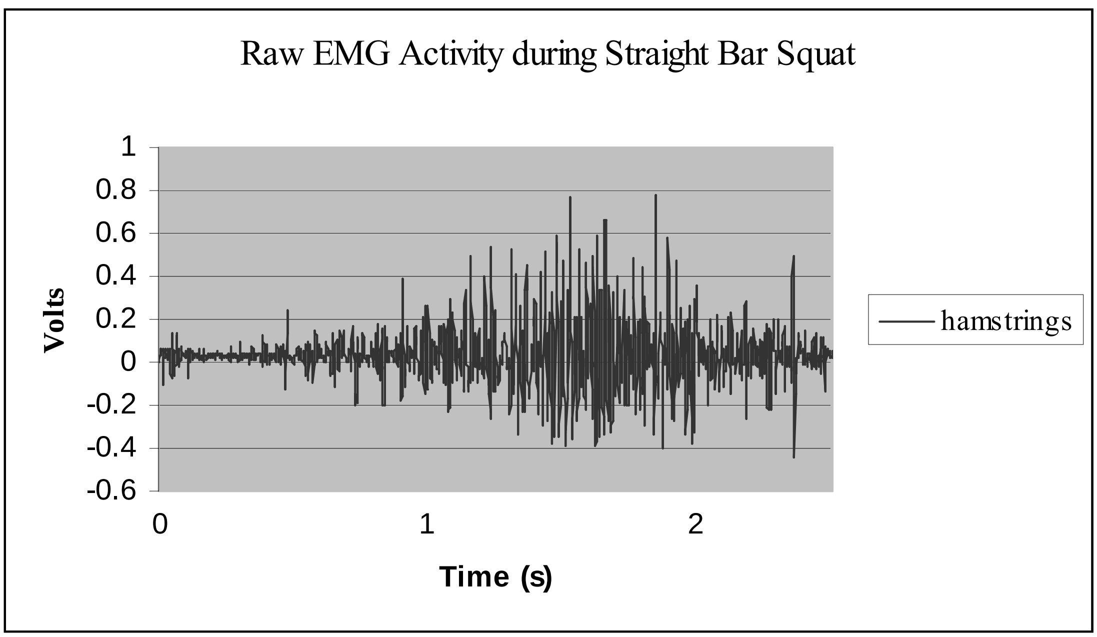

Figure C-3. Raw EMG for the hamstrings for the straight bar squat

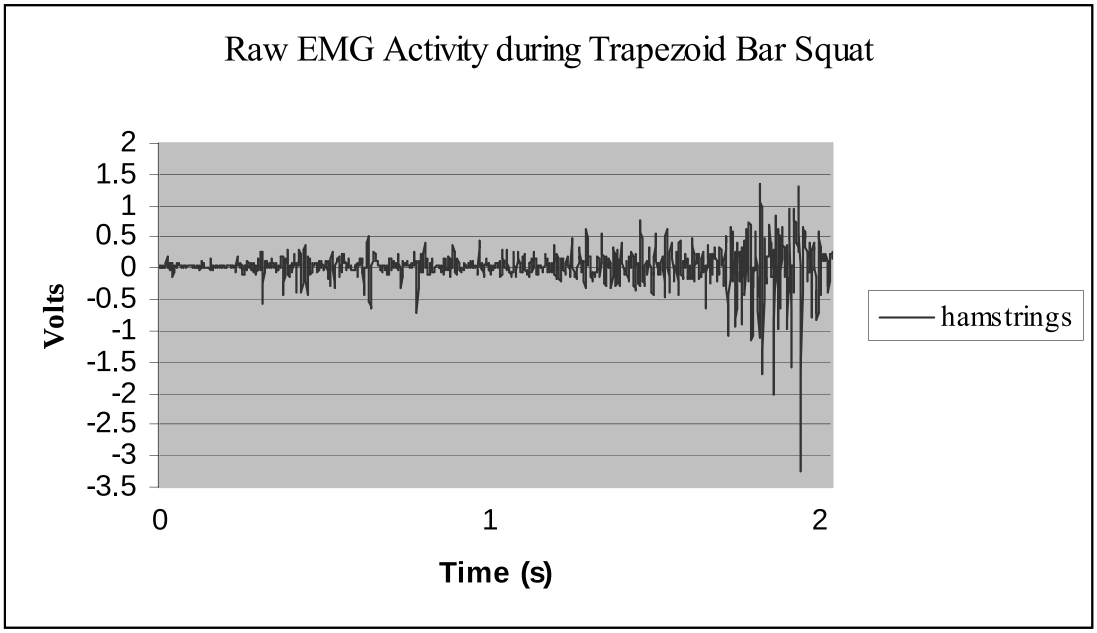

Figure C-4. Raw EMG for the hamstrings for the trapezoid bar squat

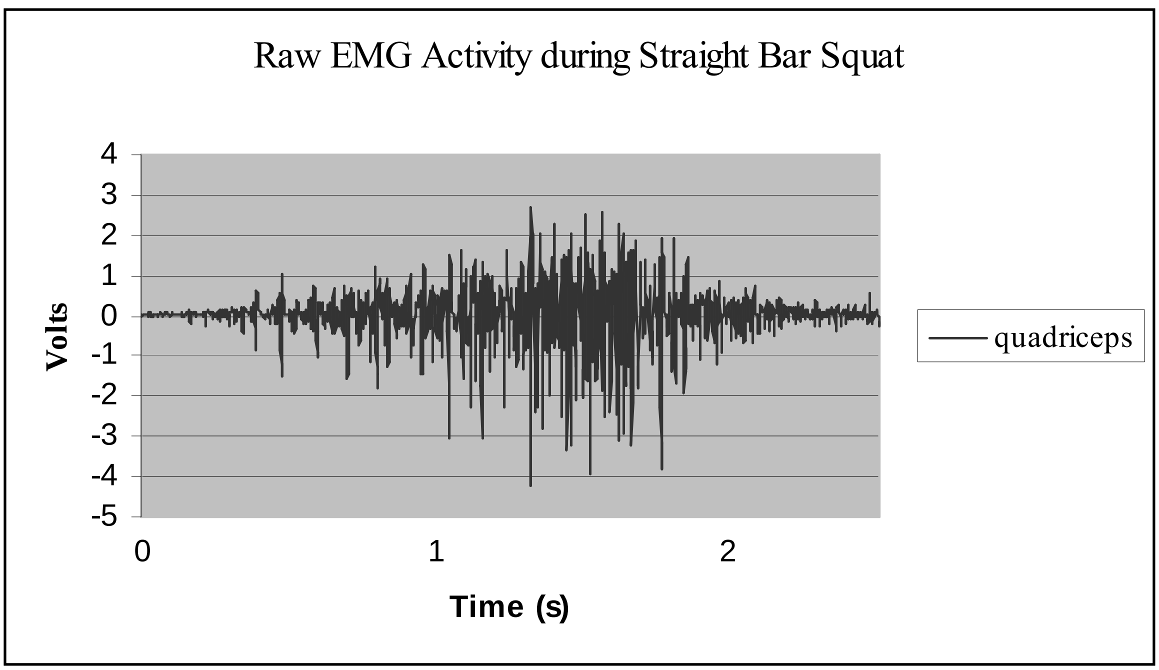

Figure C-5. Raw EMG for the quadriceps for the straight bar squat

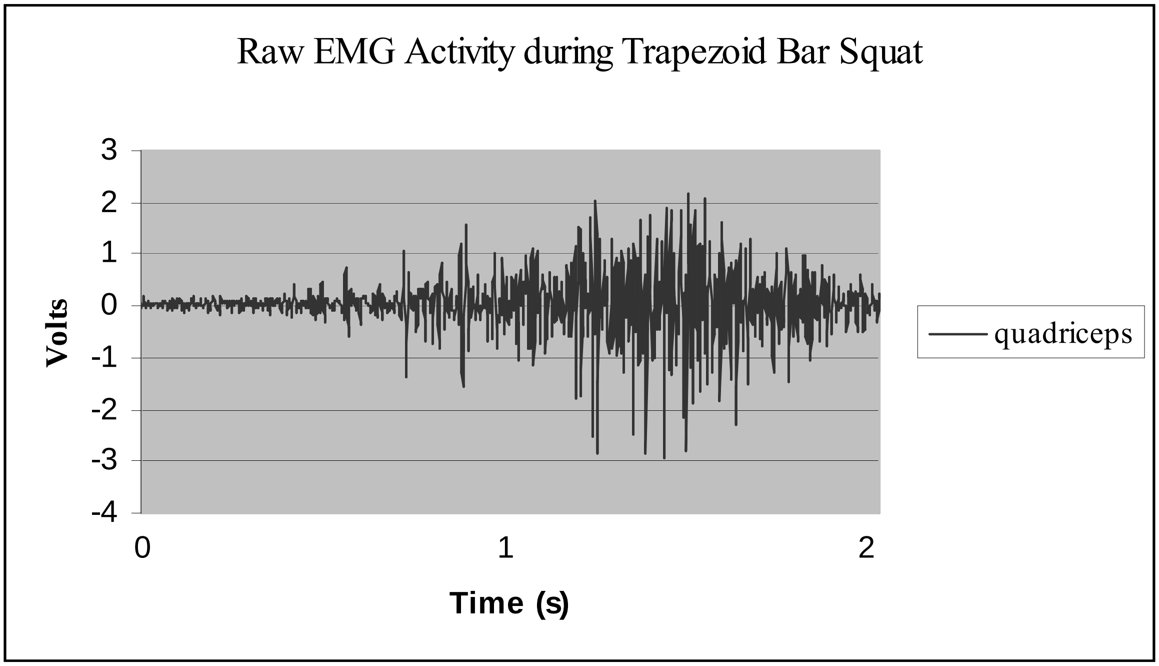

Figure C-6. Raw EMG for the quadriceps for the trapezoid bar squat

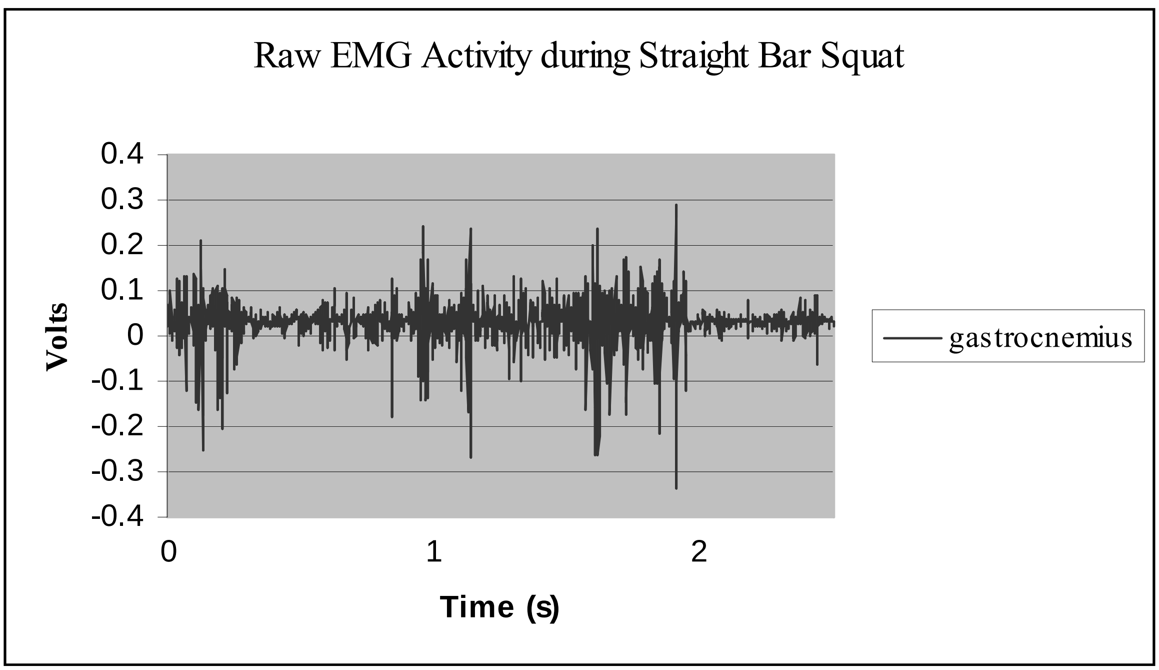

Figure C-7. Raw EMG for the gastrocnemius for the straight bar squat

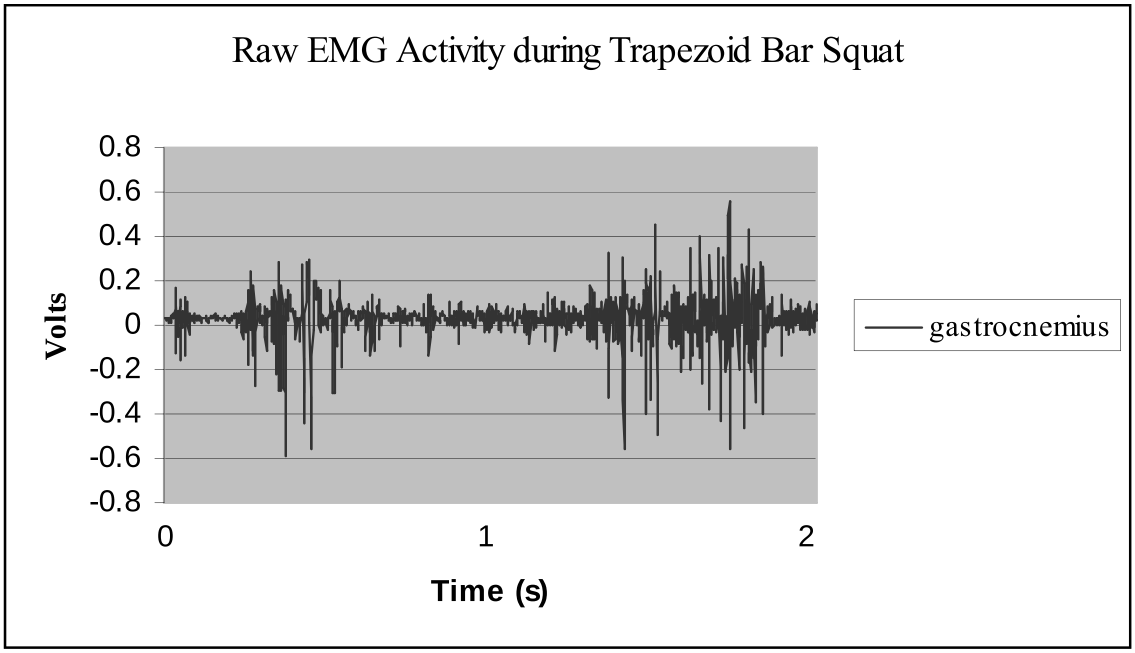

Figure C-8. Raw EMG for the gastrocnemius for the trapezoid bar squat

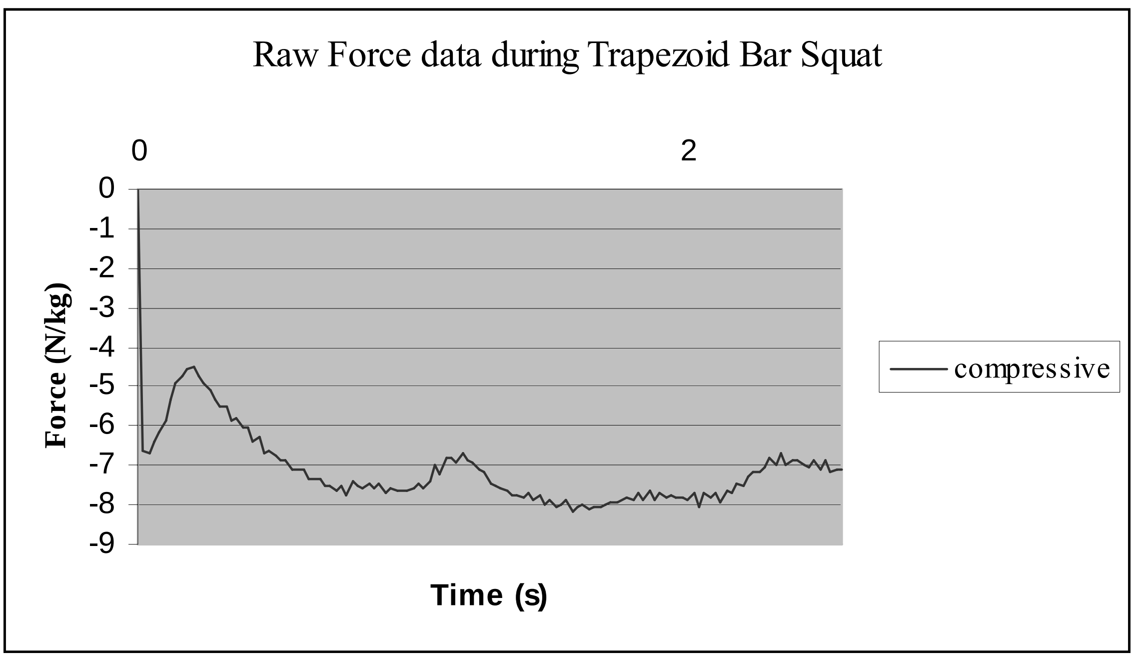

Figure C-9. Raw compressive force data for the trapezoid bar squat

Figure C-10. Raw compressive force data for the straight bar squat

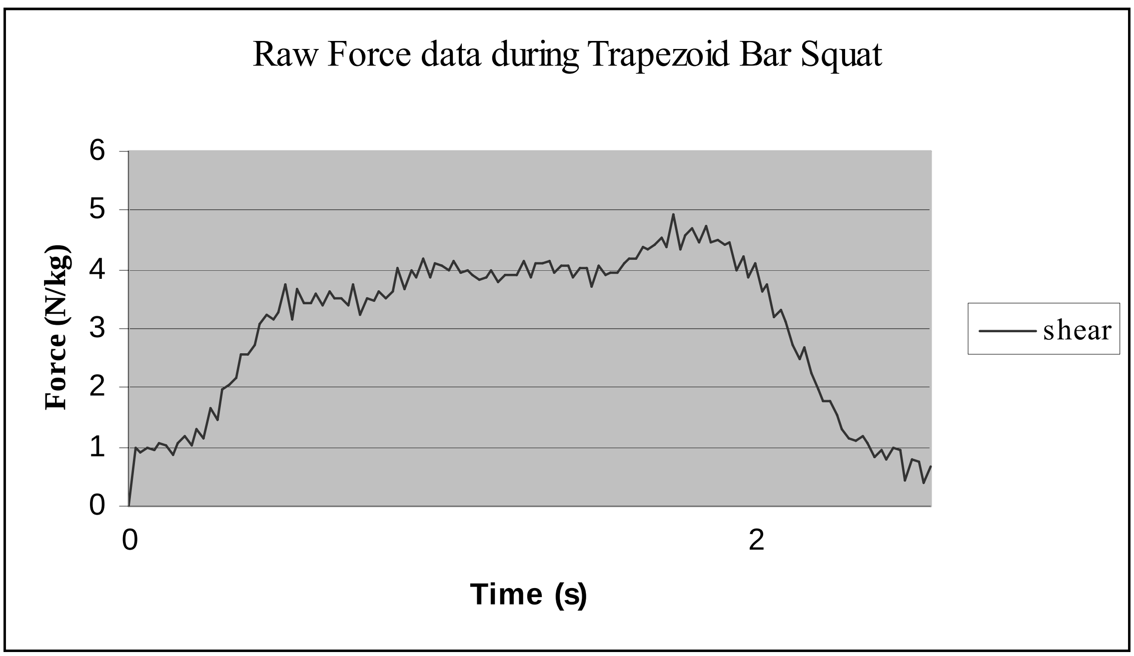

Figure C-11. Raw shear force data for the trapezoid bar squat

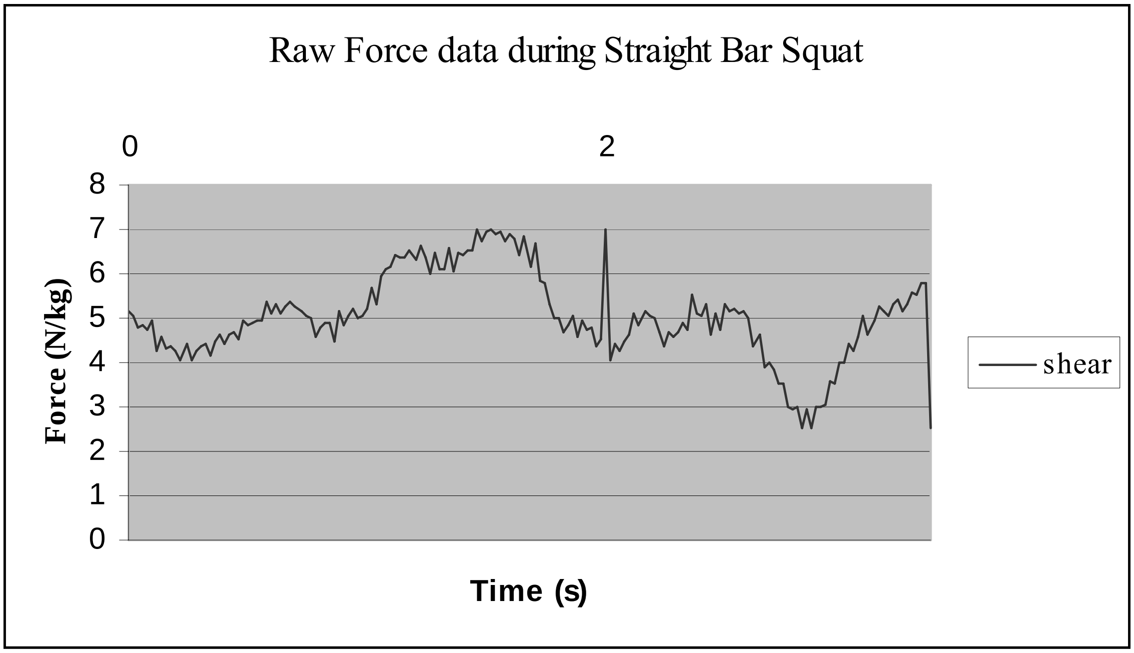

Figure C-12. Raw shear force data for the straight bar squat

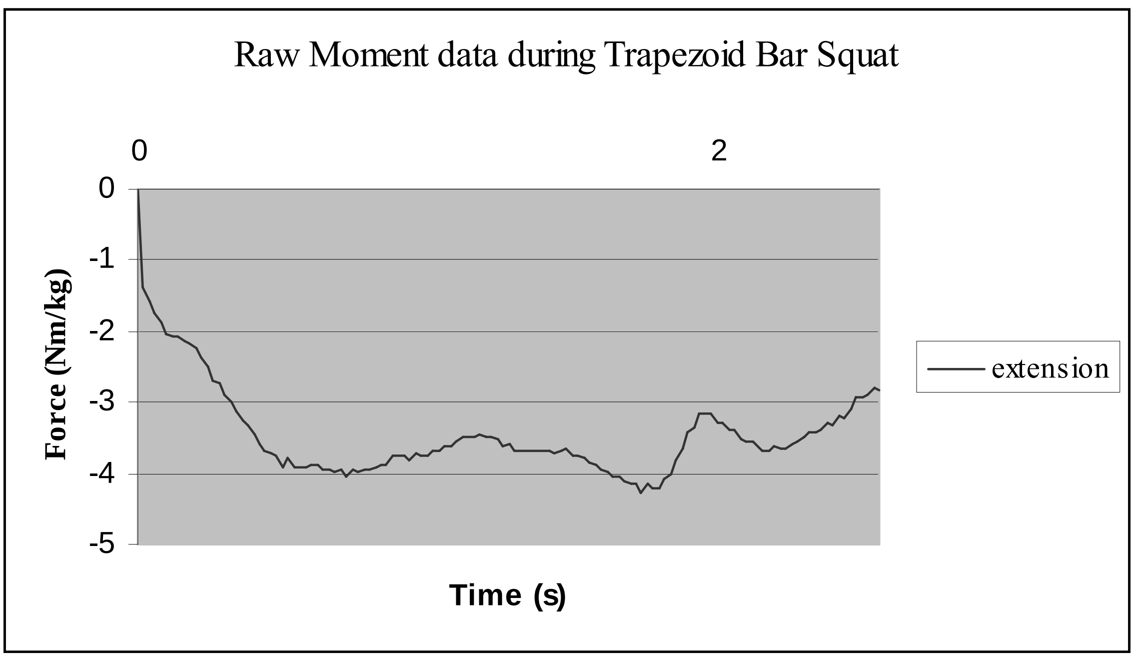

Figure C-13. Raw extension moment data for the trapezoid bar squat

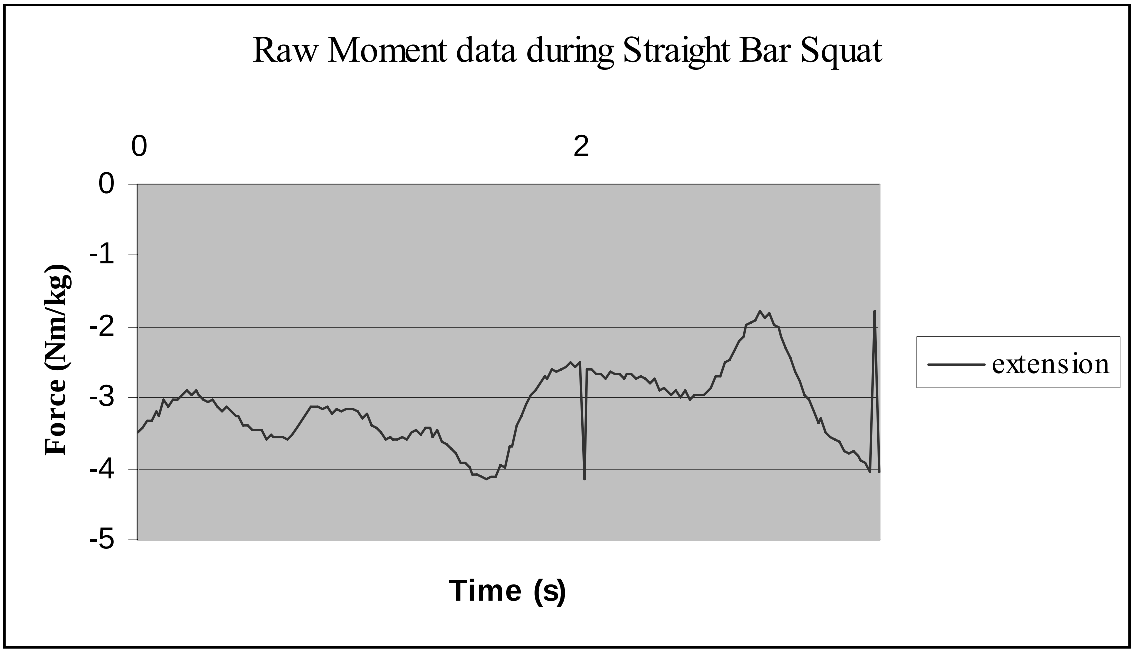

Figure C-14. Raw extension moment data for the straight bar squat

REFERENCES

Arendt, E. A., Agel, J., & Dick, R. (1999). Anterior cruciate ligamanet injury patterns among collegiate men and women. *Journal of Athletic Training, 34*(2), 86-92.

Bergstrom, K. A., Brandseth, K., Fretheim, S., Tvilde, K., & Ekeland, A. (2001). Activity-related knee injuries and pain in athletic adolescents. *Knee Surg. Sports Traumatol Arthrosc, 9*(3), 146-150.

Brask, B., Lueke, R. H., & Soderberg, G. L. (1984). Electromyographic analysis of selected muscles during the lateral step-up exercise. *Phys. Ther, 64*(3), 324-329.

Butler, D. L., Noyes, F. R., & Grood, E. S. (1980). Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J. Bone Joint Surg. Am, 62*(2), 259-270.

Chandler, T. J., Wilson, G. D., Stone, M. H. (1989). The squat exercise: Attitudes and practices of high school football coaches. *National Strength and Conditioning Association Journal, 1*(6), 30-34.

Dufek, J. S., & Bates, B. T. (1991). Biomechanical factors associated with injury during landing in jump sports. *Sports Med, 12*(5), 326-337.

Escamilla, R. F. (2001). Knee biomechanics of the dynamic squat exercise. *Med. Sci. Sports Exerc, 33*(1), 127-141.

Escamilla, R. F., Fleisig, G. S., Lowry, T. M., Barrentine, S. W., & Andrews, J. R. (2001). A three-dimensional biomechanical analysis of the squat during varying stance widths. *Med. Sci. Sports Exerc, 33*(6), 984-998.

Escamilla, R. F., Fleisig, G. S., Zheng, N., Barrentine, S. W., Wilk, K. E., & Andrews, J. R. (1998). Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Med. Sci. Sports Exerc, 30*(4), 556-569.

Fleming, B. C., Renstrom, P. A., Ohlen, G., Johnson, R. J., Peura, G. D., Beynnon, B. D., et al. (2001). The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J. Orthop. Res, 19*(6), 1178-1184.

Guerra, J. P., Arnold, M. J., & Gajdosik, R. L. (1994). Q angle: Effects of isometric quadriceps contraction and body position. *J. Orthop. Sports Phys. Ther, 19*(4), 200-204.

Hahn, T., & Foldspang, A. (1997). The q angle and sport. *Scand. J. Med. Sci. Sports, 7*(1), 43-48.

Harner, C. D., Xerogeanes, J. W., Livesay, G. A., Carlin, G. J., Smith, B. A., Kusayama, T., et al. (1995). The human posterior cruciate ligament complex: An interdisciplinary study. Ligament morphology and biomechanical evaluation. *Am. J. Sports Med, 23*(6), 736-745.

Hattin, H. C., Pierrynowski, M. R., & Ball, K. A. (1989). Effect of load, cadence, and fatigue on tibio-femoral joint force during a half squat. *Med. Sci. Sports Exerc, 21*(5), 613-618.

Haycock, C. E., & Gillette, J. V. (1976). Susceptibility of women athletes to injury. Myths vs reality. *Jama, 236*(2), 163-165.

Hewett, T. E., Lindenfeld, T. N., Riccobene, J. V., & Noyes, F. R. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am. J. Sports Med, 27*(6), 699-706.

Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am. J. Sports Med, 24*(6), 765-773.

Hung, Y. J., & Gross, M. T. (1999). Effect of foot position on electromyographic activity of the vastus medialis oblique and vastus lateralis during lower-extremity weight-bearing activities. *J. Orthop. Sports Phys. Ther, 29*(2), 93-102; discussion 103-105.

Huston, L. J., Greenfield, M. L., & Wojtys, E. M. (2000). Anterior cruciate ligament injuries in the female athlete. Potential risk factors. *Clin. Orthop. Relat. Res*(372), 50-63.

Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular performance characteristics in elite female athletes. *Am. J. Sports Med, 24*(4), 427-436.

Hutchinson, M. R., & Ireland, M. L. (1995). Knee injuries in female athletes. *Sports Med, 19*(4), 288-302.

Ireland, M. L. (1999). Anterior cruciate ligament injury in female athletes: Epidemiology. *Journal of Athletic Training, 34*(2), 150-154.

Isear, J. A., Jr., Erickson, J. C., & Worrell, T. W. (1997). Emg analysis of lower extremity muscle recruitment patterns during an unloaded squat. *Med. Sci. Sports Exerc, 29*(4), 532-539.

Liu, S. H., Al-Shaikh, R. A., Panossian, V., Finerman, G. A., & Lane, J. M. (1997). Estrogen affects the cellular metabolism of the anterior cruciate ligament. A potential explanation for female athletic injury. *Am. J. Sports Med, 25*(5), 704-709.

McCaw, S. T., & Melrose, D. R. (1999). Stance width and bar load effects on leg muscle activity during the parallel squat. *Med. Sci. Sports Exerc, 31*(3), 428-436.

Meyers, E. J. (1971). Effect of selected exercise variables on ligament stability and flexibility of the knee. *Res. Q, 42*(4), 411-422.

More, R. C., Karras, B. T., Neiman, R., Fritschy, D., Woo, S. L., & Daniel, D. M. (1993). Hamstrings--an anterior cruciate ligament protagonist. An in vitro study. *Am. J. Sports Med, 21*(2), 231-237.

Nagura, T., Dyrby, C. O., Alexander, E. J., & Andriacchi, T. P. (2002). Mechanical loads at the knee joint during deep flexion. *J. Orthop. Res, 20*(4), 881-886.

Ninos, J. C., Irrgang, J. J., Burdett, R., & Weiss, J. R. (1997). Electromyographic analysis of the squat performed in self-selected lower extremity neutral rotation and 30 degrees of lower extremity turn-out from the self-selected neutral position. *J. Orthop. Sports Phys. Ther, 25*(5), 307-315.

Noyes, F. R., Mooar, P. A., Matthews, D. S., & Butler, D. L. (1983). The symptomatic anterior cruciate-deficient knee. Part i: The long-term functional disability in athletically active individuals. *J. Bone Joint Surg. Am, 65*(2), 154-162.

Russell, P. J., & Phillips, S. J. (1989). A preliminary comparison of front and back squat exercises. *Res. Q. Exerc. Sport, 60*(3), 201-208.

Schutz, R. W., Gessaroli, M. E, 132-149. (1987). The analysis of repeated measures designs involving multiple dependent variables. *Research Quarterly for Exercise and Sport, 2*.

Shambaugh, J. P., Klein, A., & Herbert, J. H. (1991). Structural measures as predictors of injury basketball players. *Med. Sci. Sports Exerc, 23*(5), 522-527.

Signorile, J. F., Kacsik, D., Perry, A., Robertson, B., Williams, R., Lowensteyn, I., et al. (1995). The effect of knee and foot position on the electromyographical activity of the superficial quadriceps. *J. Orthop. Sports Phys. Ther, 22*(1), 2-9.

Stuart, M. J., Meglan, D. A., Lutz, G. E., Growney, E. S., & An, K. N. (1996). Comparison of intersegmental tibiofemoral joint forces and muscle activity during various closed kinetic chain exercises. *Am J Sports Med, 24*(6), 792-799.

Toth, A. P., & Cordasco, F. A. (2001). Anterior cruciate ligament injuries in the female athlete. *J. Gend. Specif. Med, 4*(4), 25-34.

Toutoungi, D. E., Lu, T. W., Leardini, A., Catani, F., & O'Connor, J. J. (2000). Cruciate ligament forces in the human knee during rehabilitation exercises. *Clin. Biomech. (Bristol, Avon), 15*(3), 176-187.

Wickiewicz, T. L., Roy, R. R., Powell, P. L., & Edgerton, V. R. (1983). Muscle architecture of the human lower limb. *Clin. Orthop. Relat. Res.*(179), 275-283.

Wilk, K. E., Escamilla, R. F., Fleisig, G. S., Barrentine, S. W., Andrews, J. R., & Boyd, M. L. (1996). A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *Am. J. Sports Med, 24*(4), 518-527.

Zhang, L. Q., & Wang, G. (2001). Dynamic and static control of the human knee joint in abduction-adduction. *J. Biomech, 34*(9), 1107-1115.

Zheng, N., Fleisig, G. S., Escamilla, R. F., & Barrentine, S. W. (1998). An analytical model of the knee for estimation of internal forces during exercise. *J. Biomech, 31*(10), 963-967.

BIOGRAPHICAL SKETCH

Francis Forde received a BS in exercise physiology from the University of Massachusetts at Boston. He then pursued a Master of Science degree in biomechanics at the University of Florida. Upon completion of his Master of Science degree, Francis plans to continue his studies and expand his knowledge of biomechanics.