EFFECT OF SQUATTING SPEED ON LOWER EXTREMITY KINEMATICS AND KINETICS DURING STABLE AND UNSTABLE SQUAT

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

IN THE GRADUATE SCHOOL OF THE

TEXAS WOMAN'S UNIVERSITY

DEPARTMENT OF KINESIOLOGY

COLLEGE OF HEALTH SCIENCE

BY

Mohammad Hasan B.S., M.S.

DENTON, TEXAS

December 2018

DEDICATION

I dedicate this dissertation to my parents, wife, sisters, brothers, and in-laws who have supported me through the entire studying years and encouraging and blessings that went along with it.

ACKNOWLEDGEMENT

I would like to offer special thanks to my committee members for their time and understanding, who each played a role in leading me down the path to completion. Their advices and help brought this dissertation to light.

I would like to thank Dr. Young-Hoo Kwon for his guidance and effort from the beginning that went beyond what was expected and his help to achieve my academic goals. Without him, this project would not have been completed.

I would like to thank Dr. David Nichols for his support, feedback, patience and assistance that has greatly improved the final product.

I would like to thank Dr. Mark Hamner for his support, patience and feedback in mathematics and statistic.

I would also like to thank Dr. Sangwoo Lee for his involvement, support, and feedback in the process of completing this dissertation.

I would also like to thank Dr. Lisa Silliman-French for her support, assisting and editing my dissertation.

I would like to thank my colleagues who worked and sweat beside me during the many projects and activities in searching for true understanding. I appreciate their knowledge, friendship, and strength.

I would especially like to thank my family (parents, wife, children, brothers, sister, and in-laws), especially my parents and wife for their incessant encouragement.

ABSTRACT

MOHAMMAD HASAN

EFFECT OF SQUATTING SPEED ON LOWER EXTREMITY KINEMATICS AND KINETICS DURING STABLE AND UNSTABLE SQUAT

DECEMBER 2018

The purpose of the study was to investigate the effects of surface instability and movement speed on key kinematic and kinetic factors (ground reaction force, moment arm [MA], resultant joint moments) in the lower extremity joints (ankles, knees, and hips) during squat. A total of 30 healthy college students (8 males and 22 females) performed six different squat conditions based on two surfaces (stable and unstable) and three speeds (slow, moderate, and fast). Normalized peak resultant joint moments (RJM) of the lower extremity joints (i.e., hips, knees, and ankles) were extracted from each trial. Two two-way repeated-measure MANOVAs (2 x 3) were performed. The first MANOVA test was to compare resultant joint moment variables, whereas, the second MANOVA test was conducted to compare ground reaction force and moment arm variables with the speed and surface condition being the factors in both. The first MANOVA with RJM variables revealed a significant speed * surface interaction ($p < .001$). The fast speed condition showed significantly larger RJMs of the lower extremity joints than the moderate and slow speed conditions and the moderate speed condition showed larger RJMs than the slow speed condition in both surface conditions. Significant larger hip and ankle RJMs and lower knee RJM observed in the unstable surface condition across speed conditions. The second MANOVA with GRF and MA variables revealed no significant speed * surface interaction ($p = .055$). However, significant main effects of speed factor ($p < .001$) was observed in the ground reaction force (GRF) and surface factor ($p < .001$) was observed in the moment arm (MA). Significant larger GRFs observed on the fast speed condition than the moderate and slow speeds and the moderate speed condition showed larger GRFs than the slow speed condition in all joints. The unstable surface condition revealed larger hip and ankle MAs and significantly lower knee MA than the stable surface condition. Ensemble average normalized RJM patterns were analyzed. The overall shapes of the hip and knee RJM patterns were similar to those of the MA patterns and the trends were similar in both surface conditions. The surface conditions generated very different ankle joint MA patterns, whereas, the ankle RJM patterns were similar to the MA patterns. The peaks RJM of the lower extremity joints were observed hovering around the maximum knee flexion (MKF) of squat. Based on the results of this study, the unstable surface condition would induce larger force acting on the hip and ankle joints and lower force acting on the knee joint compare to the stable surface condition.

Keywords: Instability, Resultant joint moment, Moment arm, Ground reaction force, Speed

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The squat engages many body parts and is considered one of the most popular exercises in the field of strength and conditioning for improving lower extremity functions. As a fundamental component of exercise, squats are often included in many training programs to improve athletic performance (Adams, O'Shea, O'Shea, & Climstein, 1992; Braidot, Brusa, Lestussi, & Parera, 2007; Rajamohan, Kanagasabai, Krishnaswamy, & Balakrishnan, 2010). Squats have been reported as beneficial for multiple populations such as adolescents, adults, and the elderly. Squat motion exercise is similar to many daily life activities such as working in the backyard, lifting boxes, transitioning from sitting to standing, and picking up children (Gullett, Tillman, Gutierrez, & Chow, 2009; Palmitier, An, Scott, & Chao, 1991). In sports such as weightlifting and powerlifting, the squat motion is an integral part of the performance (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). It is considered one of the best exercises to enhance the quality of life since squatting incorporates multiple joints and muscles (Acker et al., 2011; Hemmerich, Brown, Smith, Marthandam, & Wyss, 2006; Leffler et al., 2012; Schoenfeld, 2010). Squats are also used in clinical-rehabilitation to strengthen lower body muscles and connective tissues after injuries or surgery (Schoenfeld, 2010).

The squat is an exercise that can be performed in many different conditions and several factors, such as body posture, foot position, foot angle, and additional external weight, can influence squat kinematics and kinetics. Recently, strength and conditioning coaches, physical therapists, and rehabilitation clinicians seeking to improve the lower body strength have used unstable surface training. Foam pads, BOSU balls, stability balls, wobble boards, and balance discs are frequently used to create an unstable surface on which the exercise is performed. One of the reasons for the new found popularity of unstable surface squatting is that it offers an opportunity to increase ankle range of motion (ROM). Ankle stability and ROM are the primary factors that influence lower extremity kinematics and kinetics during the squat task (Bell, Padua, & Clark, 2008). Squatting on unstable surface using balance disks under the foot would influence hip and knee kinematics and kinetics when compared with squatting on a stable surface (Macrum, Bell, Boling, Lewek, & Padua, 2012).

Existing unstable surface research has looked at a variety of factors such as varying external loads, foot placements, depth, single leg, and changes in stretch-shortening cycle. Muscle activation and several kinematic factors have also been studied as exercising on an unstable surface causes greater muscle activation (Anderson & Behm, 2005; Norwood, Anderson, Gaetz, & Twist, 2007). One aspect of unstable surface squatting that has not been widely investigated is the speed of squatting motion.

Speed is a mechanical factor that can influence lower extremity kinematics and kinetics of the squat exercise. Movement speed is a key determinant of force and power output during exercise (Cronin & Hansen, 2005). Strength and conditioning professionals frequently prescribe increased squat speed to athletes due to the strong correlations observed between squatting speed and performance improvement (Dahlkvist, Mayo, & Seedhom, 1982; Jovanovic & Flanagan, 2014; Schoenfeld, 2010). The advantages that speed offers have encouraged specialists to incorporate training drills that improve and develop the speed potential through individualized training prescriptions.

Previous studies on speed in the unstable surface squatting conditions have focused on the correlations between velocity and external loading on the knee joint (Escamilla et al., 2001; McCaw & Melrose, 1999; Miller, Sedory, & Croce, 1997; Ninos, Irrgang, Burdett, & Weiss, 1997). Despite potential interactions between squat speed and stability condition (stable and unstable), most of the previous research has individually focused on either squat speeds or surface conditions. Therefore, understanding how speed variation affects lower extremity kinematics and kinetics during the stable and unstable squat can help to determine speed effects on exercise intensity. It is vital and essential to take specific attention of the speed of the motion and how the foot and ankle interface with the ground (instability), at the same time as studying the motion's kinematics and kinetics, in view of the new observed recognition of unstable surface training. Testing the resultant joint moment (RJM) and ground reaction force (GRF) generated during unstable squatting in the lower extremity may lead to improved training and rehabilitation programs designed to enhance functional outcomes.

Purpose of the Study

The purpose of the study was to investigate the effects of surface instability and movement speed on key kinematic and kinetic factors (ground reaction force, moment arm [MA], resultant joint moments) in the lower extremity joints (ankles, knees, and hips) during squat.

Research Questions/Hypotheses

1. As squatting speed increases the ground reaction forces acting on the feet and the joint moments of the lower extremity joints would increase.

2. The unstable surface condition would produce larger ground reaction force, moment arms and lower extremity net joint moments than the stable condition.

Significance of the Study

Squatting is an essential component of strength and conditioning programs and physical rehabilitation prescriptions. Understanding the kinematics and kinetics of the squat is important for both athletic and rehabilitation communities. The advantages that unstable squat exercise offers have lead many coaches and therapists to incorporate training drills that aim to improve lower extremity strength. There have been numerous investigators who have researched the effects of the unstable squat, but these investigators have focused on the effects of the unstable squat on the muscle activation without an emphasis on mechanical differences (Norwood et al., 2007). Further, as the surface condition changes while squatting, the mechanical response of the lower extremity joints is unknown. Because of this, a controversy exists about the safety and benefits of squats. The interaction of instability and speed on squat biomechanics (i.e., kinematics and kinetics) has not been previously examined which is now needed to complement the existing literature.

Therefore, the results of this study may contribute to the base of knowledge on squatting mechanics by providing kinematic and kinetic information on the movement of the lower extremity joints in response to different squat speed during stable and unstable surfaces. Research in this topic brings many benefits and potential to the scientific strength and conditioning community. The results of this study along with the current research in this area could assist practitioners, coaches, and strength and conditioning professionals to acquire a comprehensive understanding about squat kinematics and kinetics related to the impact of the squat to make more accurate and safer exercise prescriptions. Understanding the effects of instability aspect may help not only athletes and rehabilitation personnel but also every individual for daily life activities.

Assumptions

1. The body is a linked segment system with frictionless pin joints connecting body segments.
2. Each segment is a rigid body with constant mass, length, and moments of inertia about its center of mass (COM).
3. Reflective marker placement is accurate and precise.

Delimitations

1. Participants will perform the squat barefoot.
2. Participants will be required to gaze straight while performing the squat to minimize the effects of direction of gaze.
3. Participants will be required to do the squat with knee flexion approximately 90˚ in all squat's conditions.
4. Participants will be required to maintain whole feet in contact with the ground and balance disk from descent to ascent.

Limitations

1. Participants' skill levels are not similar.
2. The squat depth is consistent among the participants.

Definition of Terms

Global reference frame: the laboratory coordinate system in which body marker coordinates are calculated.

Ground reaction force (GRF): the force acting on the body by the ground in reaction to the force applied to the ground by the body.

Instability: the state of being unstable (lack of stability).

Inverse dynamics: an indirect method of determining resultant joint forces and moments based on motion data of the body (kinematics), inertial parameters, and ground reaction forces and moments.

Kinematics: the area of mechanics that deals with description of motion in terms of position, velocity, and acceleration of the whole body or body segments without regard for the causes of those motions.

Kinetics: the area of mechanics that deal with explanation of motion by focusing on the causes of motion, such as resultant joint forces and moments.

Local reference frame: a moving reference frames attached to a segment and meaningful only in the given segment.

Resultant joint force: the sum of joint contact force and muscle forces acting across the joint.

Resultant joint moment: the sum of the torques produced by muscles about the joint.

Torque: the ability of the force to cause rotation on a lever: force * moment arm. In this study the levers are the segments and the force is the muscle force produced.

CHAPTER II

LITERATURE REVIEW

This chapter includes the following sections: Literature Search, Description of Squat Motion, Lower Extremity Joint Movement, Force during Squatting, Ground Reaction Force, Speed of the Squat, Foot Status, Stability of Surface, and Summary.

Literature Search

The literature presented in this study was performed using computerized systematic databases such as PubMed, Google Scholar, and Texas Woman's University Libraries Web to capture all relevant articles that investigated the effectiveness of stability and speed. The literature search used the following terms and synonyms: squat training, unstable training, squat instability, stable and unstable squat, squat on different surfaces, unbalanced squat, stability and lower extremities, squat balance, incline squat, decline squat, foot status in squat, restricted squat, restricted ankle in squat, ankle range of motion, squat speed, squat velocity, cadence, squat's ground reaction force, squat resultant joint moment, and lower extremity and squat.' The search was limited to the English language and availability of full-text of original articles in academic journals. Further, the reference lists of all included articles that relatively associated with the research hypotheses were investigated to identify additional studies for inclusion in the database. A total of 217 articles from the three databases were examined. After screening each article, papers not associated with the research hypotheses were excluded (83 not associated and 134 included).

Description of Squat Motion

Even when squat conditions differ, the overall technique remains similar (McCaw & Melrose, 1999; Schoenfeld, 2010). The squat begins in the upright standing position with full extension of the hips and knees. Movement is initiated with knee and hip flexion (descending phase) to the desired depth that is reversed by knee and hip extension (ascending phase) and return to the initial standing position (see Figure 1).

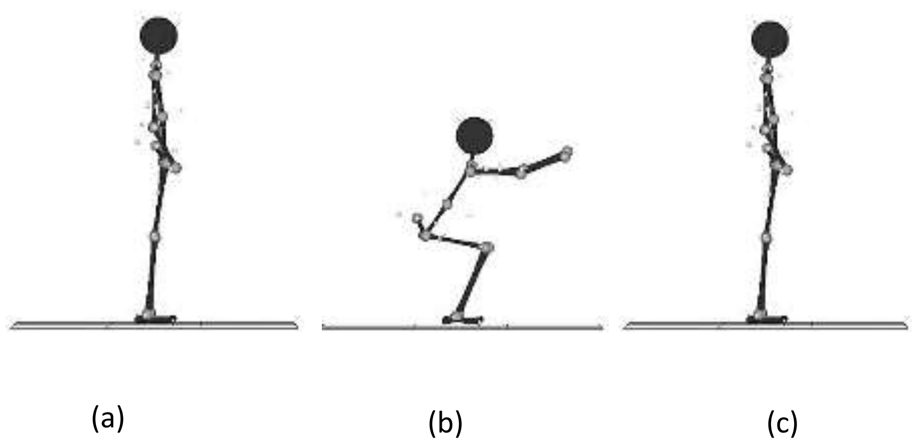


Figure 1. General movement during the squat: (a) starting position (upright standing position), (b) maximum knee flexion (getting to the desired depth), and (c) ending position (upright standing position).

The squat motion performance depends on the movement coordination of lower extremity joints (Czaprowski, Biernat, & Kendra, 2012). Squat motion represents the flexion and extension of the knee and hip joints. The squat is a closed kinetic chain exercise that simultaneously induces ankle flexion, knee flexion, and hip flexion (Blatnik, Skinner, & McBride, 2012; Palmitier et al., 1991) because the foot is fixed and in direct contact with the immobile surface, usually the ground or the base of a machine. The force generated by the body is applied to the ground through the foot. Squat biomechanics has become an important topic in research to understand muscle activity and movement safety due to the large variety of squat techniques and equipment that have been developed over the years. There is no particular form for squatting, but it is an exercise concept. Biomechanical outcomes differ when changing the load position (bar, dumbbells, overhead, front, back, held at the sides), form (1 or 2 legs), foot placement, speed, etc. Different equipment imposes specific degrees of mechanical constraint to the squat exercise. Understanding the biomechanical outcomes of squat technique manipulation allows muscular and joint forces occurring during squatting to be controlled and is fundamental to the design of strength and conditioning programs, rehabilitation, and injury prevention (Fleming, Oksendahl, & Beynnon, 2005; Selburne & Pandy, 1998).

As mentioned earlier, the squat motion activates not only the lower extremity muscles but the upper extremity muscles as well. The lower extremity muscles activated during the squat involve hip extensors, hip adductors, hip abductors, quadriceps, hamstrings, and triceps surae. The upper extremity muscles also play a significant role during squatting as supporting muscles. Core muscles include the abdominals, obliques, latissimus dorsi, thoracolumbar fascia, erector spine, gluteus, trapezius, and rhomboids. These muscles work as stabilizers of the trunk and help maintain body posture.

Lower Extremity Joint Movement

The lower extremities refer to the entire legs from the hip to the toes. These extremities are external articulated organs that carry out different locomotion functions. They are extensions from the pelvis to support body weight and maintain balance. Therefore, the lower extremities are comprised of the bones of the thigh, shank, and foot connected by the hip, knee, and ankle joints, respectively.

Hip

The hip is a ball and socket joint that serves as the articulation between the head of the femur and the acetabulum of the os coxae (Schoenfeld, 2010). It allows for movement in all planes, including flexion/extension in the sagittal plane, abduction/adduction in the frontal plane, and internal/external rotation and horizontal abduction/adduction in the transverse plane (Signorile, Kwiatkowski, Caruso, & Robertson, 1995; van Eijden, Weijs, Kouwenhoven, & Verburg, 1987). Anatomical variations of the hip joint determine how broad of a range of motion can be achieved in each of these movements (Signorile et al., 1995). When performing the squat, hip torques increase by increasing hip flexion. It is said that maximal torque at the hip occurs at the end of the descending phase of the squat (Chandler & Stone, 1991; Nagura, Dyrby, Alexander, & Andriacchi, 2002) and is influenced by distal joints (Fry, Smith, & Schilling, 2003).

Knee

The knee joint consists of the tibiofemoral joint and the patellofemoral joint. The tibiofemoral joint carries out sagittal plane movement from 0 to roughly 160º of flexion, (Li et al., 2004; Signorile et al., 1995; van Eijden et al., 1987). The knee joint is a hinge joint that regulates the force of the tibia and femur and primarily allows for flexion and extension. A small amount of axial rotation is also present at the joint during flexion and extension. When performing squats, this results in slight shifting of the center of rotation at the knee during the squat. The patellofemoral joint is a gliding joint and acts as a lever (increases mechanical advantage) in extension due to the greater force arm allowing for more effective knee flexion. The knee is supported by ligaments and cartilage that limit anterior tibial translation, internal/external rotation and prevent varus/valgus motion at the knee. In regards to squatting, force increases at the tibiofemoral and patellofemoral joint when the knee angle is increased (knee flexion; Gullett, Tillman, Gutierrez, & Chow, 2009; Nagura et al., 2002).

Ankle

The ankle is the most distal joint in the lower extremity connecting the foot and shank segments and consists of the talocrural and subtalar joints. Ankle joint has a certain range of motion (ROM) in different directions. Movements that can be performed at the ankle are dorsiflexion, plantar flexion, eversion, inversion, abduction, and adduction (Hall, 2012; Signorile et al., 1995; van Eijden et al., 1987). Dorsiflexion and plantar flexion occur at the talocrural joint whereas all other motions occur at the subtalar joint or as a combination of those joints (Hall, 2012). The main ankle motions during the squat are plantarflexion and dorsiflexion. Plantar flexion is pointing the toes away from the rest of the body and dorsiflexion is the movement that performs when pointing the toes toward the head. The ankle complex contributes significant support and aids in biomechanical factors during the squat performance (Hung & Gross, 1999). The ankle joint status during particular squat exercise condition may alter the biomechanical outcomes (Markolf, Gorek, Kabo, & Shapiro, 1990). When the ankle has more range of motion the area of force acting in the ankle joint during the movement is altered (Rodgers, 1988). A study observed the displacement of the center of pressure (COP) in the feet during squatting and reported that the COP position changes during acceleration and deceleration by shifting toward the heel during the acceleration and toward the toes during deceleration (Dionisio, Almeida, Duarte, & Hirata, 2008).

Limited ankle joint mobility has been contributed to serious effects on biomechanical components either kinematics or kinetics (Piva, Goodnite, & Childs, 2005; Witvrouw, Lysens, Bellemans, Cambier, & Vanderstraeten, 2000). Limited ankle joint ROM has been shown to influence proximal joints such as the knee and hip. Bell, Padua & Clark, (2008) compared lower extremity ROM between two groups performing squat. The first group kept the knee over the toes when performing the squat while the second group performed the squat by passing the toes past the knee naturally. The researchers (Bell, Padua & Clark, 2008) used wood heel lift equipment to change ankle ROM and reported that it prevented the knee from passing the toes. Increased ankle ROM also leads to greater force production that may help to improve sports skills (Starrett, 2013). The demands on the ankle can be addressed independently, but the demands on the knee and hip are intrinsically linked to each other.

Force during Squatting

Two forces act on the body when squatting. The first is linear force, which is the product of mass and acceleration. The direction of the force is the direction that gravity is pulling: straight down. The second is moment (angular force) which is force applied about an axis. It is the product of the force applied and the distance from the axis perpendicular to the direction the force is being applied (muscles contractions produce movement). Muscles produce a linear force, pulling on bones that act as levers, producing flexor or extensor moments at the joints they cross, with joints working as the axes of rotation. In the squat, lower extremity muscles produce extensor moments at the knee and hip that exceed the flexor moments at those joints imposed by bodyweight. Even generated force is transferred efficiently through a straight line, yet human movement is performed due to angular motion produced by the musculoskeletal system (Winter, 2009).

Ground Reaction Force

Ground reaction force (GRF) is the reaction of the force exerted by the body to the ground, which has equal magnitude, but opposite direction (from the ground up to the foot) applied to the foot and ankle structures (Fowles & Cassiday, 2005). The foot and ankle have to transmit these GRF to the proximal joints (knee and hip). When performing the squat, force vectors are continuously being transmitted up and down the body. Ground reaction forces are transferred from the distal to the proximal part of the lower extremity during movement (Winter, 2009). The weight and forces applied at the proximal extremities also move down to the ground through the body. Based on this concept, as body movements differ, a different GRF to the body may be produced. The GRF has shown to be a major factor for lower extremity joints movement such as for the knee joint (Escamilla, 2001; Shoemaker & Markolf, 1985). In contrast, increases in GRF on the lower extremity produces discomfort and elicits pain, especially for the knee during squatting (Eastlack, Hargens, Groppo, Steinbach, White, & Pedowitz, 2005). In the squat, as knee angle change, GRF changes positively (Dali, Justen, Ahmad, & Othman, 2013).

Speed of the Squat

Squat speed has been the subject of much biomechanical research (Gonzalez-Badillo & Sanchez-Medina, 2010; Jidovtseff, Harris, Crielaard, & Cronin, 2011; Jovanovic & Flanagan, 2014; Sakamoto & Sinclair, 2006). Previous researchers have examined the effect of changing the speed of the squat exercise on lower extremities joint forces (Miletello, Beam, & Cooper, 2009). Joint kinetics of the lower extremity joints has been examined during different squat speeds and findings indicate that an increase in squat speed results in increased joint moment (Schoenfeld, 2010). The total force experienced by the lower extremity joints is a combination of the body mass and inertial forces. Based on this information, altering the speed of body motion could be used to manipulate the squat exercise and have different biomechanical outcomes. Faster movement speed has a positive relationship with joint force (Hattin, Pierrynowski, & Ball, 1989). A similar result was reported by Dahlkvist, Mayo, and Seedhom (1982) in which knee joint force increased during faster speed in the squat. Further, a study by Morrissey, Harman, Frykman, & Han, (1998) compared squatting performed within 1 s and 2 s. The result was significantly different with the higher force generated in the knee joint during the faster cadence (1 s). Based on the result of this study, the researcher emphasizes why squat speed is an important parameter for squat performance.

Although the benefits of a faster speed of movement can be transferred to many sporting activities, a lower speed would be advisable for those seeking to reduce joint-related forces. Researchers have reported that squatting in slow speed is an effective exercise for increasing muscular strength in middle-aged and older adults (Westcott et al., 2001). Watanabe et al. (2015) investigated whether exercising in a slow movement can be applied to resistance training using bodyweight. They had two experimental groups. One was exercising in slow speed (3 s eccentric and 3 s concentric) and the other exercising in normal speed (1 s eccentric and 1 s concentric). It was reported that exercising in slow speed can improve physical function in the elderly. The results revealed significant improvement in upper and lower limb strength, and maximum leg extensor power for both groups.

Foot Status

Among the lower extremity segments, the foot is the segment with which the human body contacts the ground. The most common method of manipulating foot contact with the ground is to modify ankle joint angle, such as inclining or declining the foot. When performing the squat, the ankle is required to facilitate balance and control in both eccentric and concentric movements (Potvin, McGill, & Norman, 1991; Signorile, Kwiatkowski, Caruso, & Robertson, 1995). The GRF vector direction will differ while the body is moving due to the foot interaction with the ground (Zhang, Guo, An, & Chen, 2013). Therefore, the proximal joints will be affected (Markolf et al., 1990). Since GRF influences the mechanical movement of the human body, it can offer some useful information about the lower extremities (Willson & Kernozek, 1999). Obtaining the GRF based on how foot contact is made with the ground is extremely beneficial for making a correct judgment for the athletes training and rehabilitation.

Changes in foot status during squatting affect biomechanical factors (force). Bell et al. (2008) reported that lack of control in the ankle joint might decrease the control of knee joint movement. In clinical rehabilitation settings, incline and decline boards are considered a useful, easy, and effective intervention for individuals suffering from specific knee problems (Jonsson & Alfredson, 2005; Purdam, Cook, Hopper, & Khan, 2003; Young, Cook, Purdam, Kiss, & Alfredson, 2005). Kongsgaard et al. (2006) assumed that reducing ankle and hip joint flexion during the decline squat moves the knee joint further from the line of the center of mass, which allows for increased force at the knee joint. A study conducted to examine the effects of decline squat in lower extremity joints compared two decline board angles to a flat squat. Joint moments of ankle, knee, and hip were calculated by two-dimensional inverse dynamics. The hip and ankle moment were lower in the decline squat with an angle greater than 15˚, whereas the knee moment increased strongly with knee flexion during the decline squats. In addition, the GRF vector ran perfectly vertical during the decline condition (Zwerver, Bredeweg, & Hof, 2007). Another study determined the effect of reduced dorsiflexion ROM on knee flexion angle and lower extremity muscle activation during the descent phase of the squat. The researcher compared wedge and no-wedge squat. It was reported that limiting ankle dorsiflexion during squatting resulted in changes in muscle activation during the descent phase of the squat (i.e., decreased activity of the quadriceps musculature and increased activity of the soleus). These changes were thought to be attributed to changes in knee and ankle kinematics during the wedge condition (e.g., decrease in peak knee flexion angle and ROM during the wedge condition; Macrum, 2008). Lack of flexibility and range of motion of the ankle joint can cause patellofemoral (Knee joint) pain, which can result in poor squatting technique (Denegar, Hertel, & Fonseca, 2002). Toutoungi, Lu, Leardini, Catani, and O'Connor (2000) as well as Hemmerich et al. (2006) compared feet flat and heels elevated during the squat and reported that the stress generated is higher in the heels elevated condition through the descending and ascending phases.

Stability of Surface

Recently, instability exercise training has been growing and expanding for both strength and conditioning and clinical rehabilitation programs. The application of instability exercises can be found in many different fields such as strength and conditioning professionals, clinicians, physical therapists, coaches, personal trainers and the like. The benefits of exercising in an unstable condition range from improved activities of daily living, improved injury recovery, and improved overall health and performance (Behm & Colado Sanchez, 2013; Mattacola & Dwyer, 2002). Devices with varying degrees of stability are used to mimic the demands of the various tasks (Behm & Colado Sanchez, 2013; Behm, Drinkwater, Willardson, & Cowley, 2010). Unstable devices promote body disequilibrium or imbalance: as the body moves, the center of mass changes and moves the center of mass outside the area of support. As a result, the surface distorts readily in response to the reaction forces associated with changes in the center of pressure.

Training on an unstable surface is a common method that can be seen in exercise programs. The idea behind exercising on an unstable surface came on purpose to change the contact status between the ground and the body. This can potentially be performed at any interface between the human body and a surface it contacts. Exercising on unstable surfaces is a challenging task that has been shown to elicit improvements in strength by stressing the neuromuscular system to a higher degree than exercising on a stable surface (Behm, Anderson, & Curnew, 2002; Behm et al., 2010; Behm, Muehlbauer, Kibele, & Granacher, 2015). Additionally, this type of training (unstable squat exercise) may increase strength and torque production (Kibele & Behm, 2009). Free weight exercises that used to be traditionally performed on the stable surface are also performed on unstable devices. In gyms, for example, people use balance discs or waddle boards to perform the squat exercises in different methods. Further, some people use a swiss ball to lie back on it and perform chest exercises. Individuals can formulate exercises in a way that it could be used as an unstable condition. Creating an unstable surface, by using instability devices, allows unstable exercises to be performed anywhere and anytime (i.e., home, gyms, or sporting facilities).

Previous studies have used unstable surfaces to determine muscle activation differences compared with stable condition (using electromyography; EMG). In some studies, the bench press exercise was used to examine the effect of stable and unstable conditions on muscles activation. It was reported that unstable condition increased upper extremity muscles activation more than stable condition (Behm, Leonard, Young, Bonsey, & MacKinnon, 2005; Marshall & Murphy, 2006; Norwood et al., 2007), indicating different levels of muscle activation between conditions. Additionally, performing the squat in different levels of instability by using balance discs resulted in greater trunk muscle activation (Anderson & Behm, 2005). Even though unstable exercise training requires reduced training load compared to stable surface training it has been shown to increase the neuromuscular system stimulation of youth and seniors (Behm et al., 2010; Behm & Colado, 2012; Behm & Colado Sanchez, 2013; Behm, Drinkwater, Willardson, & Cowley, 2011).

Understanding the effects of unstable surfaces on squat biomechanics is needed. It would make sense to perform squat exercise on an unstable surface because, typically, the squat motion involved in most sports and daily activities occur in various degrees of ground contact. More research is warranted to evaluate the effects of performing other standing, dynamic movements on an unstable surface on biomechanical factors of the lower extremity. For example, RJM, MA, and GRF need to be evaluated more extensively during squatting to a better understanding of the effects of instability on the squat to determine whether this method is useful in term of biomechanical components or not.

Summary

Previous researchers have conducted numerous investigations on the squat because it is a widely used exercise in strength and conditioning field and clinical-rehabilitation. After examining the previous research related to unstable surface exercise, it is evident that more research is needed to evaluate the effects of squat movements performed on an unstable surface. Many researchers have investigated how the unstable surface affects the lower extremity muscles. Moreover, their research in the unstable squat has been focused on either squat depth or external load variation. The other main factor that influences the lower extremity joints in squat is speed. Previous researchers have emphasized that the faster the squat speed, the larger the magnitude of torque produced. However, research studies on the squat have not been conducted in a combination of surface stability and speed variation. There is also a lack of empirical evidence to compare the speed of squat on how body-joint mechanics change during stable and unstable conditions. These factors need to be evaluated on the lower extremity joints more extensively, to give the strength and conditioning field a better understanding of the effects of unstable surface training, whether the result is positive or negative in regards to what it is believed this form of exercise is used for.

Due to the lack of empirical evidence, it is critical to examine the kinematic and kinetic comparisons between the stable and unstable squat in response to various speeds. If a significant difference were reported, practitioners would need to consider carefully not only choosing which stability condition to prescribe for their patients and athletes, but also selecting an appropriate squat speed. Therefore, the findings will help therapists and coaches to acquire a better understanding about squatting exercises, which will enable them to instruct their patients and athletes more effectively and safely.

CHAPTER III

METHODS

This chapter is divided into the following sections: Participants, Trial Conditions, Data Collection, Data Processing, Data Analysis, and Statistical Analysis.

Participants

A total of 30 healthy college students (8 males and 22 females) were recruited for this study. The age range of the participants was between 18 to 35 years old (mean age: 22.1 ± 2.8 years; mass: 66.1 ± 10.1 kg; height: 163.9 ± 8.3 cm). All participants have had prior squat experience of at least 1 year (self-reported) with no knee injury history at least 12 months prior to this study. All participants were able to perform squats without postural issues.

All participants signed the informed consent form approved by Texas Woman's University's Institutional Review Board prior to participation in this study. The purpose and procedures of the study were thoroughly explained to the participants.

Trial Conditions

Each participant performed squat trials in six different conditions: two surface conditions (stable and unstable) * three speeds (slow, moderate, and fast). Five trials were collected in each surface-speed condition. Unstable squats were performed with feet on balance disc. Circular balance discs (13.5 in. diameter with 3.5 in inflation; HemingWeigh product, New York) were used in this study in the unstable condition. The speeds were controlled by using a metronome app installed on a mobile device. The slow speed condition was defined as 3 s for each phase of the squat (3 s moving down and 3 s moving up). The moderate speed condition was defined as 2 s for each phase of the squat. In the fast speed condition, the squat was performed as fast as possible. The order of squat conditions was assigned randomly prior to dynamic (squat) trials. A minimum 10-min warm-up period was allowed prior to data collection to reduce the risk of injury and onset of premature fatigue during the data collection.

To minimize the chance of fatigue, sufficient rest period was allowed between squat trials and between squat conditions. Only the squat trials when the thigh become parallel to the ground during the descending phase were considered successful. All squat conditions were performed using body weight (no additional external load). Participants were allowed to have sufficient practice prior to data collection.

Data collection

A 10-camera optical motion capture system (VICON, Centennial, CO, USA) running at 250 Hz were used to capture coordinates of the reflective markers placed on the participant's body. A total of 21 reflective markers were attached to participant's body (see Figure 2). A static trial (T-pose with arms 90˚ abducted) was captured first and squat trials were captured after static-only markers were removed to prevent interferences by these markers during the squat motion (see Table 1). The static trial was used later in the dynamic trials in locating the joint centers in the absence of the static-only markers. The reflective markers were attached to participants' body by the principal investigator only to ensure consistency in marker placement across subjects.

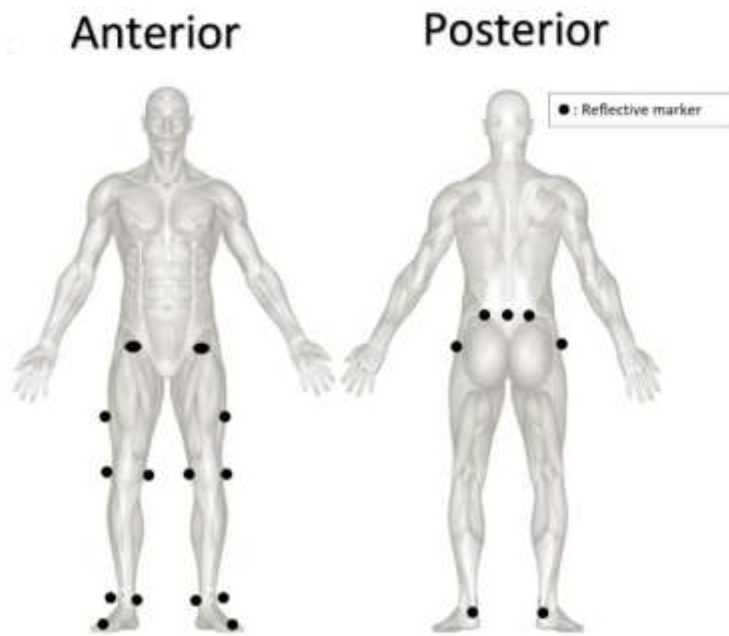


Figure 2. Marker locations.

Participants were asked to change into specific clothing for optical motion capture (tightly-fitting dark spandex short/shirt) in a separate preparation room. Camera calibration was performed before each data collection session. The Z-axis and Y-axis of the global reference frame were aligned vertically upward and forward, respectively. Two AMTI force plates (Model OR6; Advanced Mechanical Technology, Inc., Watertown, MA, USA) were used to collect the GRF data.

Data Processing

The three-dimensional marker coordinates (captured motion) and GRF data were imported into Kwon3D Motion Analysis Suite (Version XP, Visol Inc., Seoul, Korea) for subsequent data processing and analysis via C3D files (http://www.c3d.org). Marker labeling was performed with VICON's Nexus software and coordinates and force plate data were saved to C3D-format files. Kinematic and kinetic variables were computed in Kwon3D. The raw coordinates were digitally filtered using a Butterworth 4th-order zero phase lag low-pass filter with a cut-off frequency of 6 Hz.

In this study, the lower body was defined as a system of seven segments (pelvis, thighs, shanks, and feet; see Table 1). The locations of the lower extremity joints centers (hips, knees, and ankles) were computed from the marker coordinates.

Table 1

The 27-point (21 markers) body model/marker set used in this study

Segment	Markers/computed points	Description
Pelvis	Markers (5)	Five pelvic markers: right and left anterior superior iliac spines (ASIS) markers, right and left posterior superior iliac spines (PSIS) markers and sacrum marker.
	Computed (6)	Right and left mid-iliac points, right and left hip joints, and mid-pelvis and mid-hip points. The hip joint centers will be computed using the 'Tylkowski-Andriacchi Method' (Kwon et al., 2012). The mid-iliac point is the mid-point of the ipsilateral ASIS and PSIS markers. Mid-pelvis point is the mid-point of the mid-iliac points. Mid-hip point is the mid-point of the hip joints.
Legs	Markers (8*2)	Four thigh markers each (greater trochanter (GT), lateral thigh (LT), and medial and lateral epicondyles markers), two shank markers each (lateral and medial malleoli markers), and two-foot markers each (toe and heel markers). The greater trochanter markers and the medial femoral epicondyle markers will be removed in the motion trials.
	Computed (2*2)	Knee joints and ankle joints. The knee joint center will be located indirectly in the motion trials using the 'Extended Mid-PointMethod.' The ankle joint center is the midpoint of the lateral and medial malleoli markers.

The local reference frames of the segments were defined based on the markers and computed points. The X-, Y-, and Z-axes of segmental reference frames were aligned with the anatomical axes (mediolateral, anteroposterior, and longitudinal, respectively) of the segments. To define a local reference frame, an anatomical plane was defined first using two axes (the main axis and temporary axis on the plane; see Table 2). The third axis was then defined by using the cross product of the two unit vectors of the anatomical plane defined earlier. The true second axis was determined by using the cross product of the first and third axes.

Table 2

Definitions of Segmental Reference Frames

Segment	Main axis	Non-orthogonal axis	Plane described
Pelvis	L ASIS to R ASIS (+X axis)	L ASIS to Mid PSIS (temporary -Y axis)	XY plane (Transverse)
Thigh	KJC to HJC (+Z axis)	HJC to mid-thigh marker (temporary +X axis)	XZ plane (Frontal)
Shank	AJC to KJC (+Z axis)	KJC to mid shank marker (temporary +X axis)	XZ plane (Frontal)
Foot	Toe to Heel (+Z axis)	Heel to AJC (+Y axis)	YZ plane (Sagittal)

Abbreviations: R (right), L (left), ASIS (anterior superior iliac spine), PSIS (posterior superior iliac spine), HJC (hip joint center), KJC (knee joint center), and AJC (ankle joint center).

Data Analysis

To analyze the captured motion, the squat motion was divided into two phases using three events defined based on the vertical position of the center of mass (COM) (see Figure 3). The first event, Start, was defined as full hip and knee extension at the beginning of the motion; where the vertical COM position was maximum. The second event, maximum knee flexion (MKF) was where the vertical COM position became minimum (at the maximal depth achieved of the squat). The last event, End is the point where vertical COM position became maximum again after MKF. The Descending Phase (DP) is the interval between Start and MKF, whereas, the Ascending Phase (AP) is the interval from MKF to End.

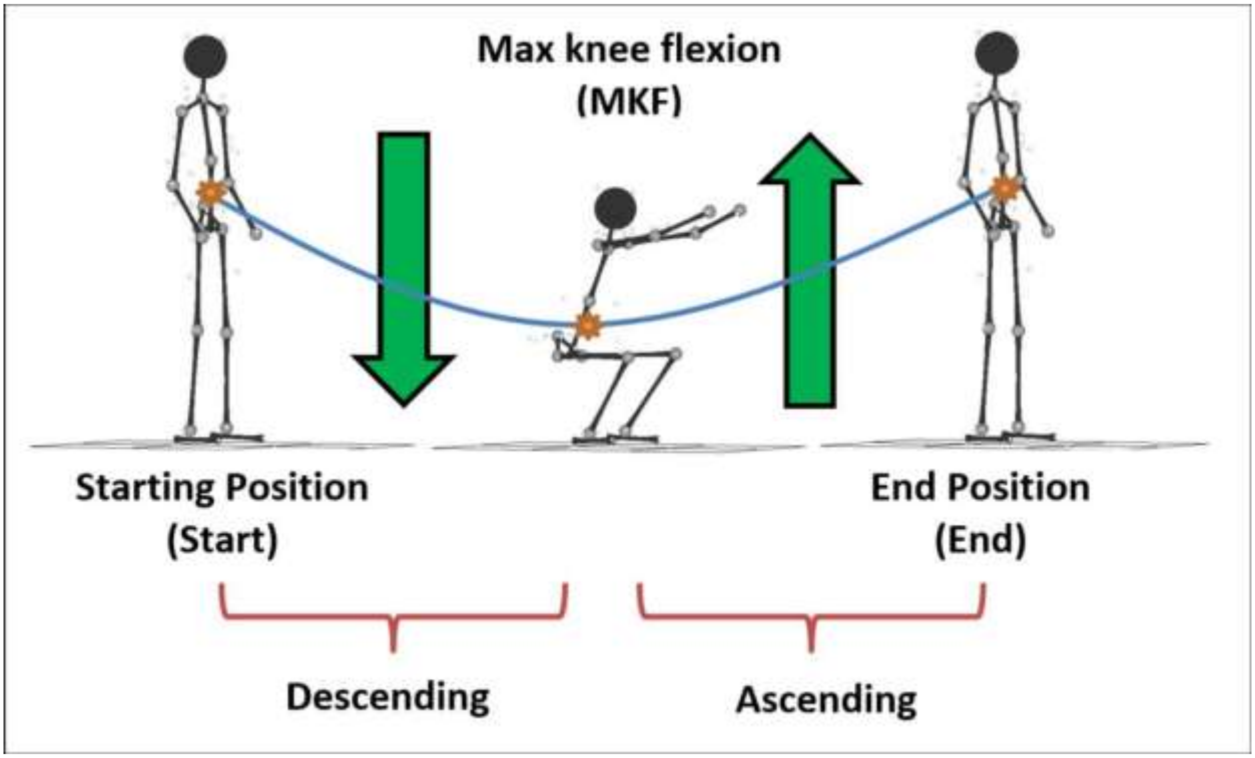


Figure 3. Events and phases of the squat motion: Start, descending phase (DP), maximum knee flexion (MKF), ascending phase (AP), and End.

Kinetic Analysis

The resultant joint forces and moments acting on the hip, knee, and ankle joints were calculated through the inverse dynamics procedure:

$$\mathbf{F}_j = \sum_s \frac{d\mathbf{P}_s}{dt} - \sum_s \mathbf{W}_s - \mathbf{F}_e \tag{1}$$

$$\mathbf{N}_j = \sum_s \left(\frac{d\mathbf{L}_s}{dt} + r_{js} \times \frac{d\mathbf{P}_s}{dt}\right) - \sum_s (\mathbf{r}_{js} \times \mathbf{W}_s) - (\mathbf{r}_{je} \times \mathbf{F}_e + \mathbf{N}_e) \tag{2}$$

where *j* is the current joint (joint of interest), s is a segment distal to the joint, $\mathbf{F}$ is the resultant joint force acting at the joint, $\mathbf{P}$ is the linear momentum of a distal segment, $\mathbf{W}$ is the weight of a distal segments, $\mathbf{F}_e$ is the ground reaction force acting on the foot, $\mathbf{N}$ is the resultant joint moment generated by the muscles about the joint, $\mathbf{L}$ is the local angular momentum of a distal segment due to the rotation of the segment about its own COM, r_{js} is the relative position vector drawn from the joint center to a distal segment's COM, $\mathbf{r}_{je}$ is the relative position vector drawn from the joint center to the point at which the ground reaction force acts (center of pressure), and $\mathbf{N}_e$ is ground reaction moment (GRM) acting on the foot.

Ensemble average patterns of the GRF and lower extremity net joint moments in the sagittal plane were established. Between the legs, kinetic symmetry was not assumed, and the larger peak force/moment values were extracted and used in the analysis. The force and moment data were normalized to the body weight to eliminate the effect of individual differences. Ensemble average patterns of the moment arms were extracted for each lower extremity joint (hip, knee, and ankle) and used in the analysis. The moment arm data were normalized to segmental length (hip moment arm to thigh length and knee/ankle moment arms to shank length), respectively.

Statistical Analysis

The dependent variables were the maximum net joint moments of the lower extremity joints and the ground reaction force and moment arms at the time of maximum net joint moment. The mean values of five repeated trials performed by each participant in each squat condition were computed and used in the statistical analysis. All statistical analyses were conducted using SPSS 22 (SPSS, Inc., Chicago). Two two-way repeated-measure MANOVAs (2 x 3) were performed. The first MANOVA test was to compare resultant joint moment variables, whereas, the second MANOVA test was conducted to compare ground reaction force and moment arm variables with the speed and surface condition being the factors in both. An alpha level of .05 was set for all statistical operations (0.025 for each MANOVA). Further, post-hoc tests (Bonferroni adjustment) were performed to determine the differences within squatting at stable and unstable surfaces across speeds (slow, moderate, and fast) for significant factor effect or interaction.

CHAPTER IV

RESULTS

This chapter is divided into the following sections: Resultant Joint Moment, and Ground Reaction Force and Moment Arm. Comparison of RJM, and GRF and MA were made between stable and unstable surfaces and among slow, moderate, and fast speeds for each lower extremity joints (hip, knee, and ankle).

Resultant Joint Moment

The first MANOVA with RJM variables revealed a significant speed * surface interaction (Wilk's $\lambda = .242$, $F = 12.513$, $p < .001$). Therefore, subsequent inter-speed comparisons were performed for each surface condition and inter-surface comparisons were conducted for each speed condition. Post-hoc tests revealed significant differences in the hip, knee, and ankle joints.

Overall, the fast speed condition showed significantly larger hip RJMs than the moderate and slow conditions and the moderate speed condition showed larger hip RJMs than the slow condition in both surface conditions (see Table 3; see Figure 4). The fast condition generated larger knee RJMs than the moderate and slow conditions in both surface conditions. In the stable condition, the moderate speed condition also showed a larger RJM than the slow condition. In the ankle joint, the fast condition showed a significantly larger RJM than the moderate and slow speeds in the unstable squat condition only.

In addition, significant differences in hip RJM (stable < unstable), knee RJM (stable > unstable), and ankle RJM (stable < unstable) were observed in both slow and moderate speed conditions (see Table 3; see Figure 5). The fast speed condition, however, revealed significant differences in knee RJM (stable > unstable), and ankle RJM (stable < unstable) only.

Ground Reaction Force and Moment Arm

The second MANOVA with GRF and MA variables revealed no significant speed * surface interaction (Wilk's λ = .397, F = 2.282, p = .055). However, both speed (Wilk's λ = .005, F = 272.458, p < .001) and surface (Wilk's λ = .279, F = 10.323, p < .001) factors revealed significant factor effects.

There were significant differences in the GRF at the time of maximum RJM among the speed conditions in the hip, knee, and ankle joints (see Table 4; see Figure 6). Overall, the fast speed condition revealed larger GRFs than the moderate and slow speeds and the moderate speed condition showed larger GRFs than the slow speed condition in all joints.

The surface conditions revealed significant differences in MA formed by the GRF against the hip, knee, and ankle joints at the time of peak RJM (see Table 4; see Figure 7). The unstable condition revealed larger hip and ankle MAs than the stable condition. The stable condition, however, showed significantly larger knee MA than the unstable condition.

Table 3

Summary of the Normalized Resultant Joint Moments (Nm/kg)

Joint	Slow		Moderate		Fast	
	Stable	Unstable	Stable	Unstable	Stable	Unstable
Ankle	-0.23 ± 0.02	-0.26 ± 0.02*	-0.19 ± 0.04	-0.26 ± 0.02*	-0.24 ± 0.02	-0.30 ± 0.02$^{\$\&}$*
Knee	0.75 ± 0.17	0.66 ± 0.14*	0.81 ± 0.19$^{\$}$	0.68 ± 0.15*	0.99 ± 0.23$^{\$\&}$	0.81 ± 0.23$^{\$\&}$*
Hip	-0.67 ± 0.22	-0.73 ± 0.16*	-0.71 ± 0.21$^{\$}$	-0.79 ± 0.17$^{\$}$*	-1.07 ± 0.35$^{\$\&}$	-1.02 ± 0.23$^{\$\&}$

* Significantly different from the matching Stable condition (p < .05)
$^{\$}$ Significantly different from the matching Slow condition (p < .05)
$^{\&}$ Significantly different from the matching Moderate condition (p < .05)

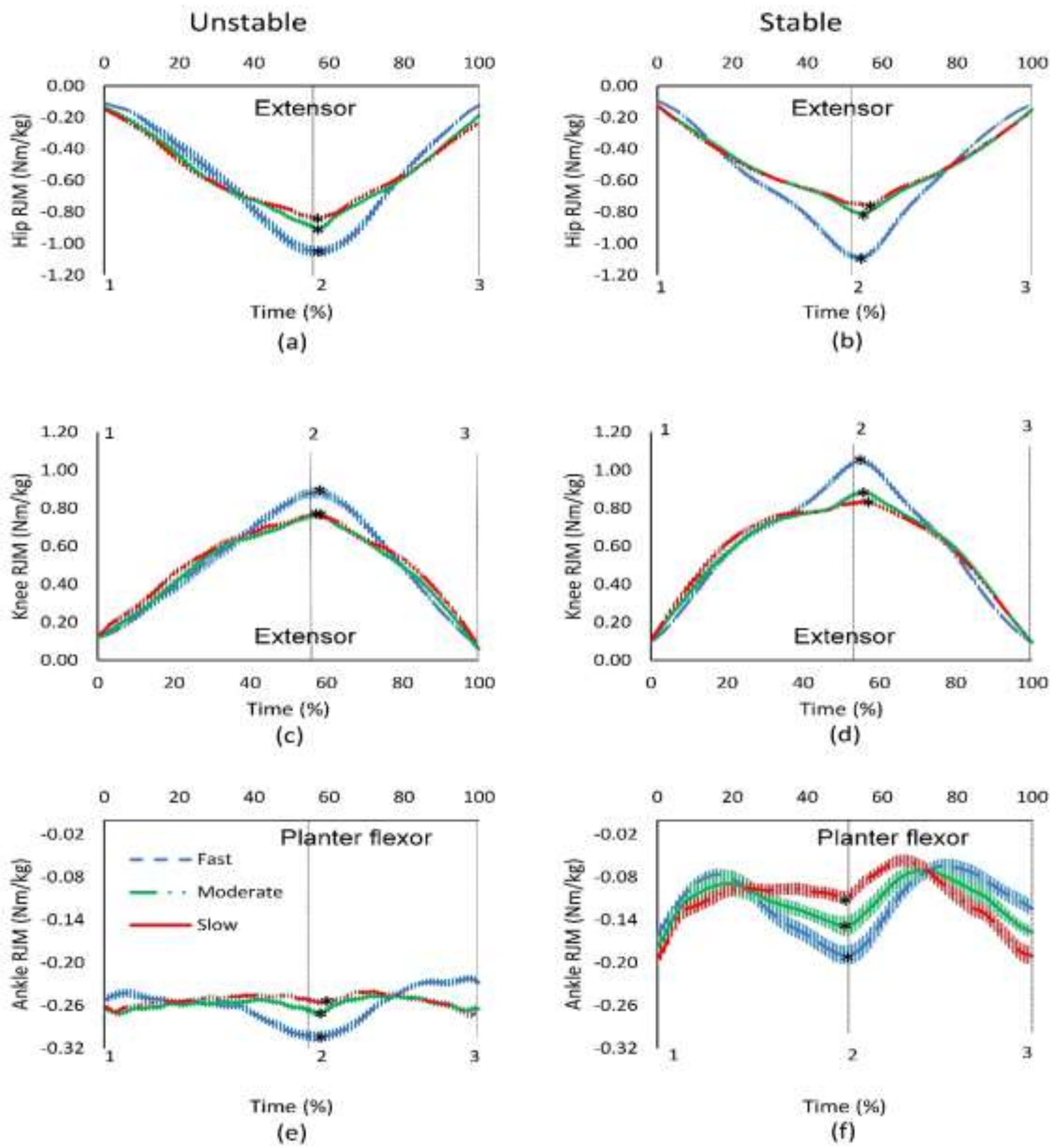


Figure 4. Comparison of the ensemble average patterns of the normalized resultant joint moments (RJM) of the lower extremity joints among the speed conditions. Events: 1 – Start, 2 – Maximum Knee Flexion, and 3 – End. The peaks marked with "*" were used in the statistical analysis.

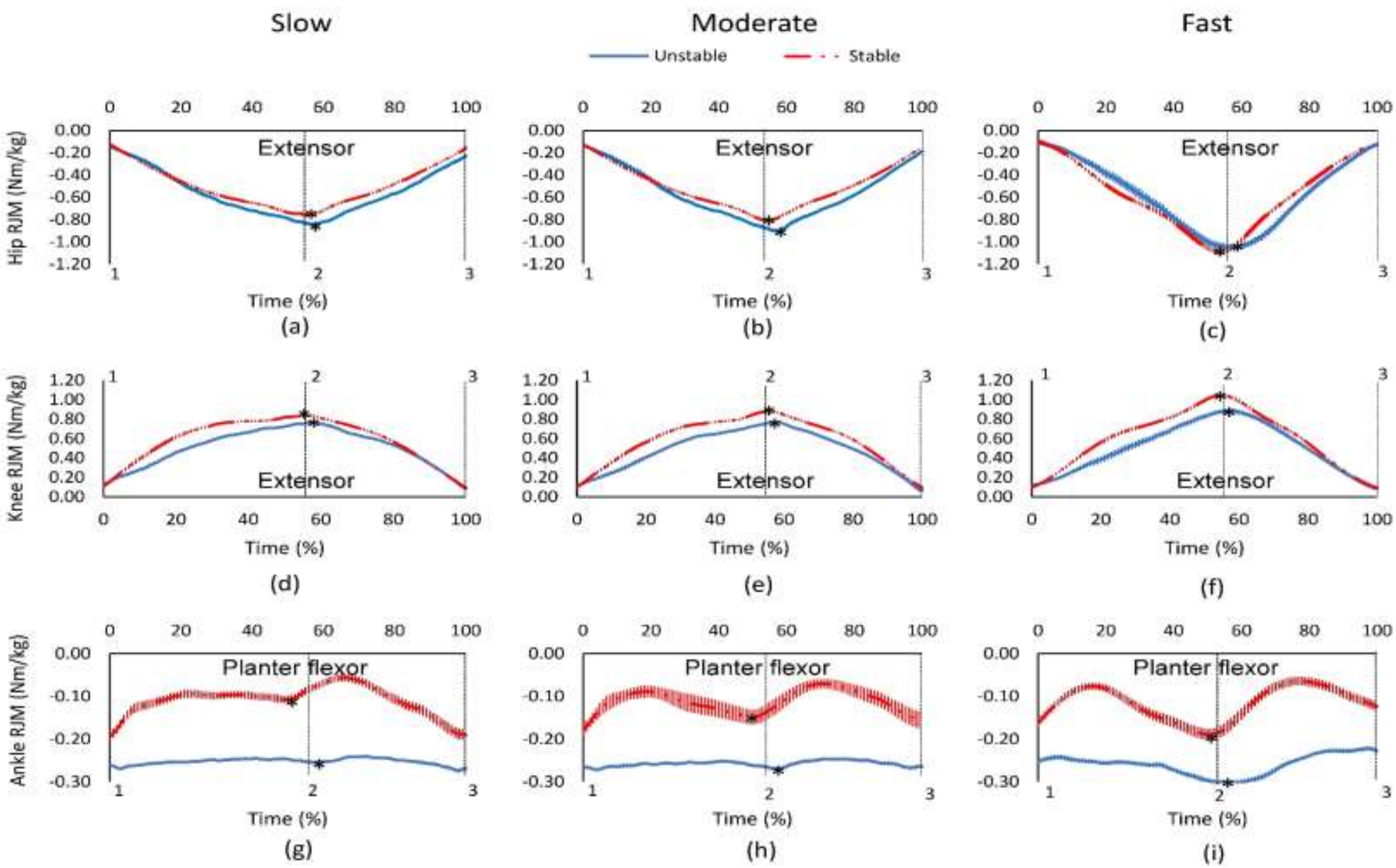


Figure 5. Comparison of the ensemble average patterns of the normalized resultant joint moment (RJM) of the lower extremity joints between the surface conditions. Events: 1 – Start, 2 – Maximum Knee Flexion, and 3 – End.

Table 4

Summary of the Normalized Ground Reaction Forces and the Normalized Moment Arms

Variable		Slow		Moderate		Fast		Factor effects*
		Stable	Unstable	Stable	Unstable	Stable	Unstable	
GRF (N/kg)	Ankle	5.15 ± .32	5.18 ± .25	5.61 ± .33	5.69 ± .12	6.68 ± .49	6.78 ± .17	Speed (Fast > Moderate > Slow)
	Knee	5.34 ± .10	5.26 ± .12	5.77 ± .12	5.86 ± .18	6.86 ± .72	6.70 ± .19	
	Hip	5.13 ± .08	5.20 ± .14	6.03 ± .61	5.91 ± .21	6.62 ± .28	6.78 ± .16	
MA (m/m)	Ankle	0.07 ± 0.01	0.09 ± 0.01	0.07 ± 0.01	0.09 ± 0.01	0.06 ± 0.01	0.07 ± 0.01	Surface (Unstable > Stable)
	Knee	0.34 ± 0.09	0.30 ± 0.08	0.35 ± 0.08	0.31 ± 0.09	0.33 ± 0.08	0.29 ± 0.07	Surface (Stable > Unstable)
	Hip	0.35 ± 0.10	0.38 ± 0.12	0.35 ± 0.11	0.39 ± 0.12	0.36 ± 0.11	0.39 ± 0.10	Surface (Unstable > Stable)

* ($p < .05$)

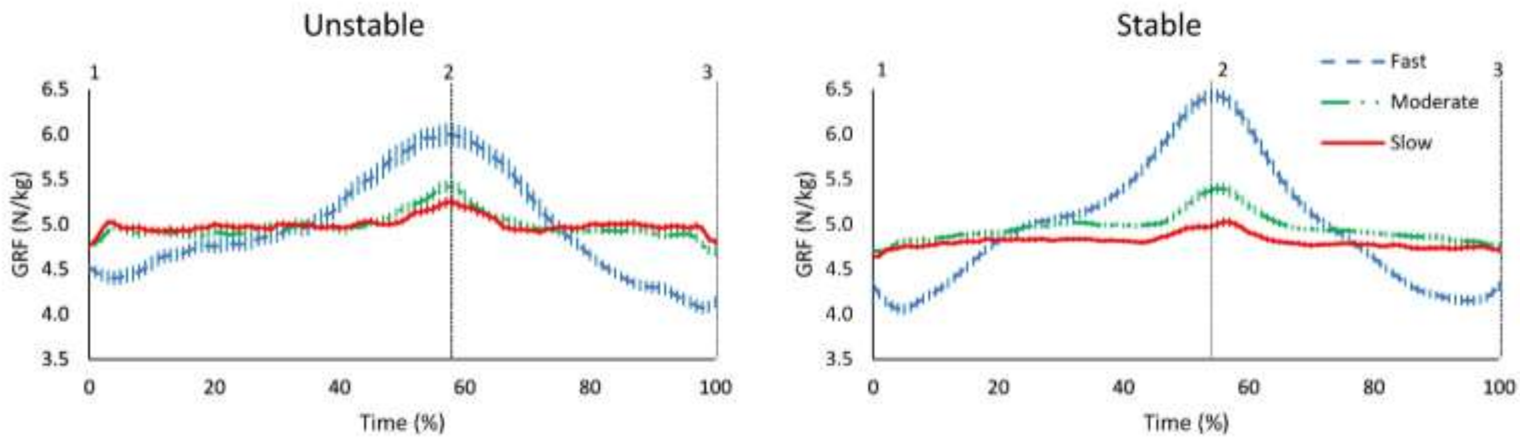


Figure 6. Comparison of the ensemble average patterns of the normalized ground reaction force (GRF). Events: 1 – Start, 2 – Maximum Knee Flexion, and 3 – End.

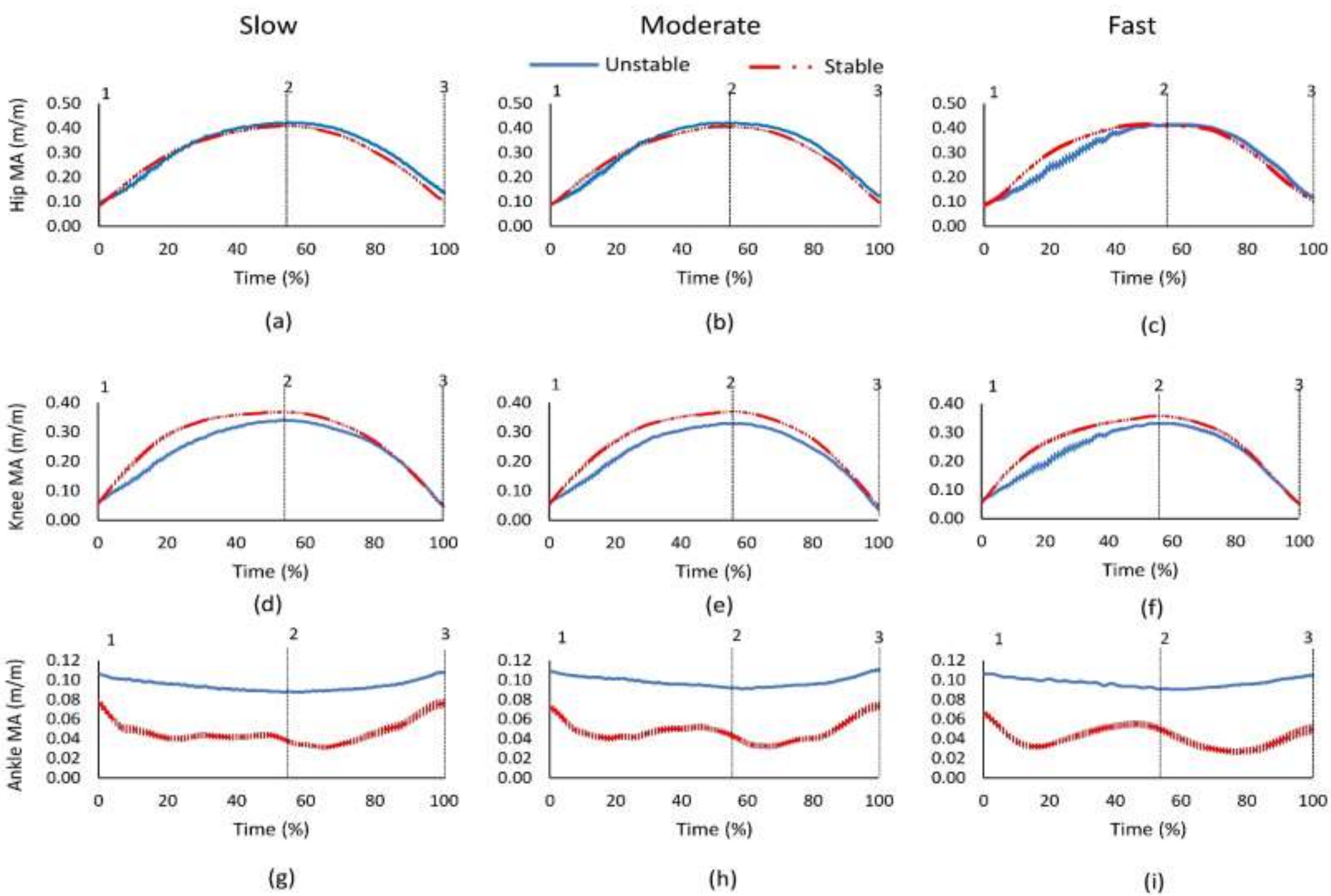


Figure 7. Comparison of the ensemble average patterns of the normalized moment arm (MA). Events: 1 – Start, 2 – Maximum Knee Flexion, and 3 – End.

CHAPTER V

DISCUSSION

The purpose of this study was to investigate the effects of surface instability and movement speed on RJM, GRF, and MA of the lower extremity joints during squat. The most fundamental difference between the stable and unstable squats is the orientation of the foot (Bell et al., 2008; Kibele & Behm, 2009). The whole foot contacts the ground in the stable condition, while in the unstable squat a more plantar-flexed foot orientation is allowed and the foot orientation can change during the squat motion. The flat foot orientation in the stable squat can restrict the shank motion, and the lower extremity joints may respond differently to various squat speeds.

The RJM for a given joint can be broken down to three terms: inertial, gravitational, and external (see Equation 2). The inertial term is the portion of the RJM used in angularly accelerating the segments distal to the joint of interest, while the external term is the moment acting on the joint due to the GRF/GRM. The gravitational term is the portion of the RJM relieved by the moments generated by the weights of the distal segments about the joint. The inertial term is dependent on the accelerations of the lower extremity segments, and the gravitational term is posture-dependent (see Equation 2). Figure 8 shows the moment terms derived from the fast-stable condition: (1) the inertial terms are minimal in all joints; (2) the gravitational terms are also minimal in the ankle and knee joints; (3) while the gravitational term is not negligible in the hip joint, this term is independent from the speed of the squat motion as long as the depth of the squat remains similar across the speed conditions; (4) the majority of the lower extremity joint RJM thus comes from the external moment generated by the GRF/GRM; (5) the external term can also be further divided into the portion generated by the GRF about the joint center and the moment acting directly on the foot (i.e., GRM), but the GRM should be negligible since the squat motion does not involve much torsional interaction between the foot and ground. Therefore, it is reasonable to assess the burden on the lower extremity joints by using the GRF and the MAs formed by the GRF vector against the joints.

The ensemble average patterns of the RJM, GRF, and MA (see Figures 4-7) revealed several generalizable observations. Firstly, the overall shapes of the RJM patterns were similar to those of the MA patterns. The MAs of the hip and knee joints increased as the descending motion progressed and decreased during the ascending motion after reaching their maximum values near MKF (see Figures 7a-7f). With this, both the hip and knee joints showed increase of the extensor moments during the descending phase followed by decreases in the ascending phase (see Figures 4a-4d). The trends were similar in both surface conditions.
Throughout the entire squat cycle, the ankle joint consistently developed plantar flexor-dominant moment (see Figures 4e-4f; Macrum et al., 2012; Markolf et al., 1990). Unlike the other two joints, the RJM of the ankle joint was largest at the start and end of the squat cycle in most conditions except the fast-unstable condition. The surface conditions generated very different ankle joint MA patterns (see Figure 7g-7i). In the unstable condition, the ankle joint MA decreased gradually during the descending phase and increased back in the ascending phase. The stable condition however revealed a very different pattern in which the MA decreased and then increased in both the descending and ascending phases. This suggests that the descending/ascending motion in the stable squat condition can be further broken down to two different phases based on the changes in ankle MA. It was speculated that the allowance of

reorientation of the foot during the unstable squat induced a more natural flow of motion and yielded the single-peak MA pattern. Further investigation on this aspect is warranted. The ankle RJM patterns were similar to the MA patterns.

The hip and knee joint moment patterns were characterized by the sharp increases in magnitude near MKF (see Figures 4a-4d and 5a-5f), and this is primarily due to the increase in the GRF near the event (see Figure 6). Among the speed conditions, only the fast condition revealed a continuous unweighing-loading pattern (Vahdat & Ghomsheh, 2018). In the squat, unweighing (average individual foot GRF < 4.91 N/kg) occurs at the beginning of the descending phase (causing downward acceleration) or at the end of the ascending phase (causing upward deceleration). The active loading occurs after the initial unweighing phase to decelerate the body downward and then accelerate upward (HÄkkinen, & Komi, 1983). In the slow and moderate speed conditions, slight unloading was observed at the beginning and end of the squat cycle, but the GRF largely remained constant during the rest of the cycle. In the fast condition, the GRF changed continuously (see Figure 6), suggesting that the countermovement squat pattern was employed in this particular speed condition (HÄkkinen, & Komi, 1983). The slow and moderate speed conditions were in fact not that different from each other in the perspective of inducing active unweighing-loading. The trends were similar in both surface conditions.

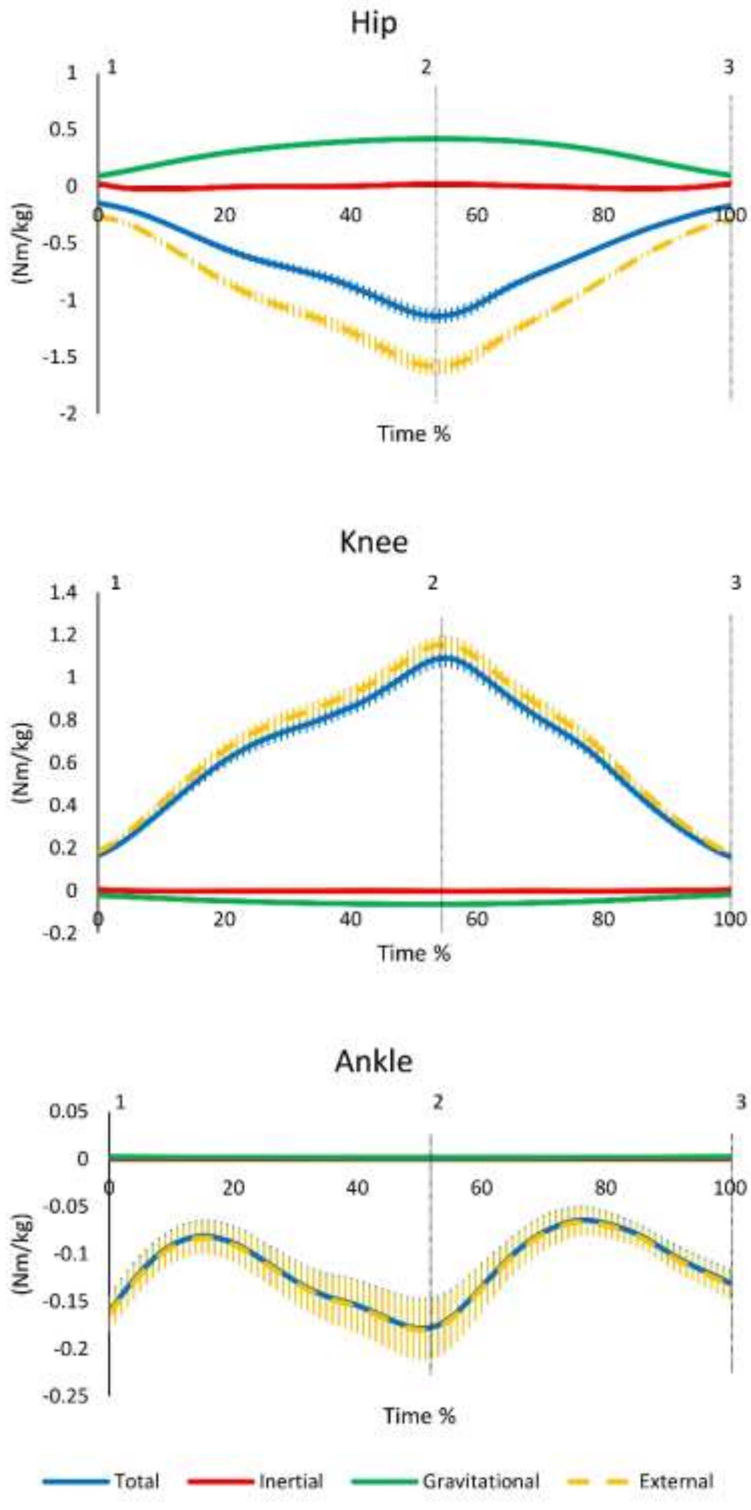


Figure 8. Break-down of the RJM to the inertial, gravitational, and external terms: fast-stable condition (*n* = 30).

Among the joints, the shortest MAs characterized the ankle joint. This is because, during the squat, the COP, the point of action of the GRF, hovers under the mid-foot area (Rodgers, 1988). The MAs of the knee and hip joints increase substantially since the joints move away from the GRF's line of action as knee flexion increases (see Figure 9). With the foot in a more plantar-flexed position, the unstable condition was characterized by a longer ankle MA. This is due to the increased loading on the ball of the foot in the unstable condition than in the stable condition. With this foot alignment, the unstable condition tended to provide shorter MA for the knee joint and longer MA for the hip joint than the stable condition.

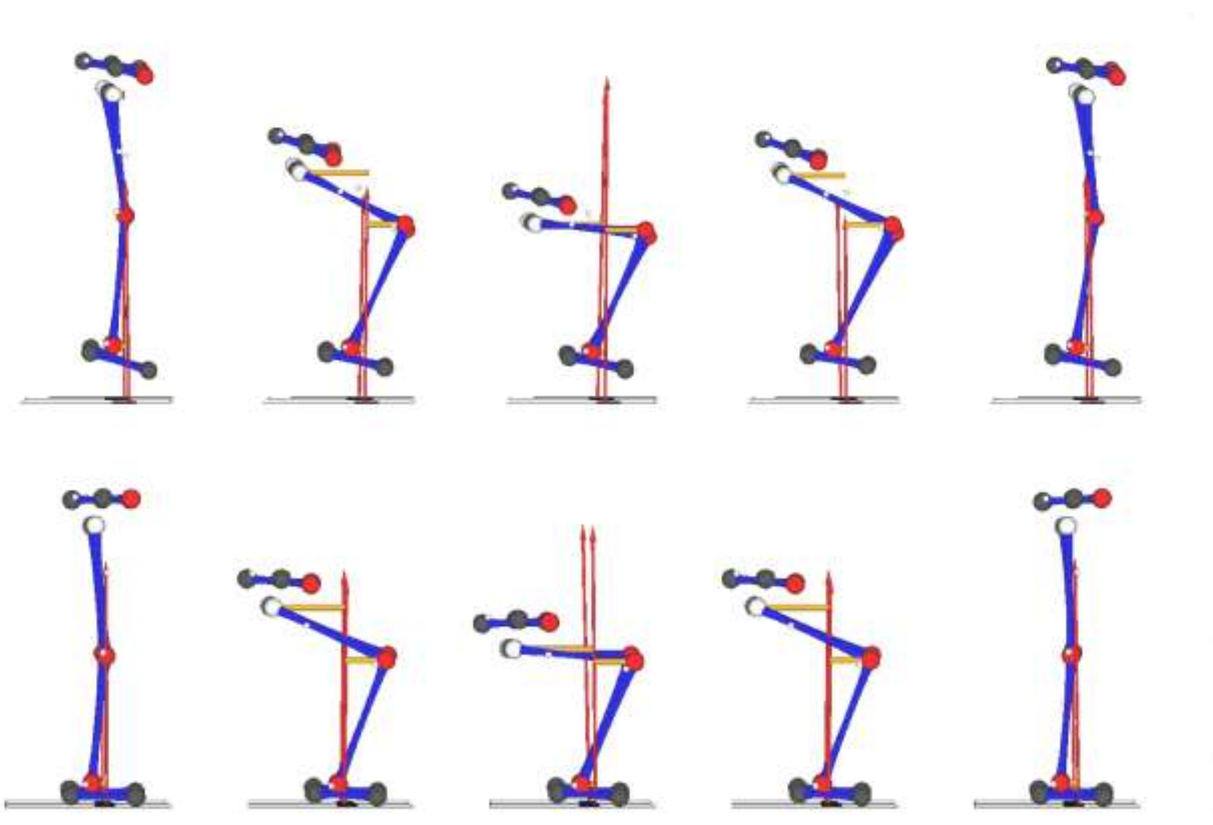


Figure 9. Comparison of the MAs and the GRF's line of action changes in squat during unstable and stable surface conditions.

Since the external moment is the product of GRF and MA, changes in the GRF and MA directly affect the magnitude of the peak RJM. The significant speed * surface interaction observed in the peak RJM variables (see Table 3) were essentially caused by the significant speed factor effect in the GRF variables and the significant surface effect in the MA variables (see Table 4). The unstable condition revealed longer ankle and hip MAs and shorter knee MA at the time of peak RJM than the stable condition. All speed conditions showed significant differences in GRF at the time of peak RJM.

The longer MA could explain the significantly larger RJM of the ankle and hip joints observed in the unstable surface condition from the joint centers to the GRF vector. The GRF vector associated with the COP shifts in response to the foot orientation. The COP was shifted during the unstable surface condition because of promoted ROM of the foot by the unstable surface where the ankle joint was allowed to move to planter flexion movement (Anderson & Behm, 2005). The MA length would be affected based on the foot orientation motion. As a result, the COP position acting on the foot would be shifted farther anteriorly to the ankle joint center and alter the perpendicular distance between the GRF vector and the joint center of the ankle and hip joints (Jagodinsky, Fox, Decoux, Weimar, & Lu, 2015). This alteration can be explained as due to the change in the GRF vector position which affected by the position of the COP shift acting on the foot (Wu & Hitt, 2005). As a result, the GRF vector line position from the ankle and hip joints centers were increased compared to squatting performance on the stable surface condition. Overall, the results of this study clearly demonstrated that performing squat on unstable surface condition increases the ankle planter flexor and hip extensor moments compared to the squatting performance on stable surface condition (see Figures 5a-5c, 5g-5i).

The significantly lower knee RJM observed on the unstable surface condition also can be explained by the changes on the MA length of the knee joint measured from the joint center to the line of GRF vector. Whereas MA length can be illustrated by the distance of the GRF vector from the knee joint center in response to the change of the foot orientation and the COP located on the foot during the squat motion. In the unstable surface condition, the GRF vector was placed closer to the knee joint center compared to the stable surface condition. Therefore, it could be said that the decreased knee extensor moment was caused by the COP shift toward the toe during the unstable surface condition. As a result, the MA from the knee joint center to the GRF vector decreased in the unstable surface condition that caused the lower knee extensor moments in the unstable surface condition (see Figures 5d-5f). Behm et al (2002), also, reported decreases in force output in the knee joints while seated on an unstable ball.

Moreover, the significant increase of the RJM of the lower extremity joints in the matching stability condition can be explained by the different GRF generated among slow, moderate, and fast speed conditions (see Figures 4a-4f). Based on an in-depth review of the literature, there were no other investigators who have measured the GRF during various speeds of squatting in different stability surface conditions. Since the RJM is a function of the magnitude of the applied force (GRF) and MA, the larger RJM peak can be explained as a result of larger GRF magnitude obtained during squatting based on speed condition (see Figure 6). The results of the GRF in this investigation can be explained by the squatting speed since the participants were squatting down to a desired fixed depth and back to the starting position within either 1 s, 2 s, or 3 s. Further, the participants did not have any additional external weight added to the body weight in order to complete the squatting task. Specifically, the GRF increased as squatting time decreased (Rahmani, Viale, Dalleau, & Lacour, 2001; Wilson, Murphy, & Pryor, 1994). Therefore, the effect of squatting speed on the GRF can be supported by the Newton's second law (Hall, 2012; Winter, 2009). This law defines a force to be equal to change in momentum (mass times velocity) per change in time. Based on the definition, the force acting on the body is a function of the mass of the participant and the acceleration of the movement (Hall, 2012; Winter, 2009). The observed differences in the GRF results of this study can be explained by different squatting speeds (acceleration) because there was no external load added to the participants during squatting. The results of this study were similar to previous study results on GRF and speed (see Figure 10) that reported a positive relationship between ground reaction force and speed of movement (Morrissey, Harman, & Johnson, 1995). Similar results were observed by Bentley et al. (2010) who reported that the acceleration during movement could alter the GRF. It was determined in this investigation that there was significantly higher GRF in the fast acceleration of squatting compared to the slow and moderate squatting. Similarly, Jason (2011) reported that using push-up exercises at different speeds, the GRF increased during weight bearing activities. Chung and Wang (2010) also investigated the effect of speed on GRF. It was observed peak ground reaction force increased as walking speed increased. Therefore, the result of this study does support the theory of the second law of Newton.

The investigator was not surprised that there were no statistical significant differences observed on the GRF between stable and unstable surface conditions (see Table 3) across speed conditions. In the current study, the body of the participant did not receive any additional force since the body mass was not influenced by the instability device. Whereas, the GRF is exerted in the opposite direction from the ground due to the weight of the body. As a result, it will never produce different value of the GRF on the body when performing the same squatting speed across the two stability surface conditions (see Figure 10). In addition, the GRF values in the stability surface conditions can be explained by the Newton's third law. The law states that for every action, there is an equal reaction in magnitude but in the opposite direction. Based on this definition, the increased GRF in this study was not possible without any other factors such as the speed of squat.

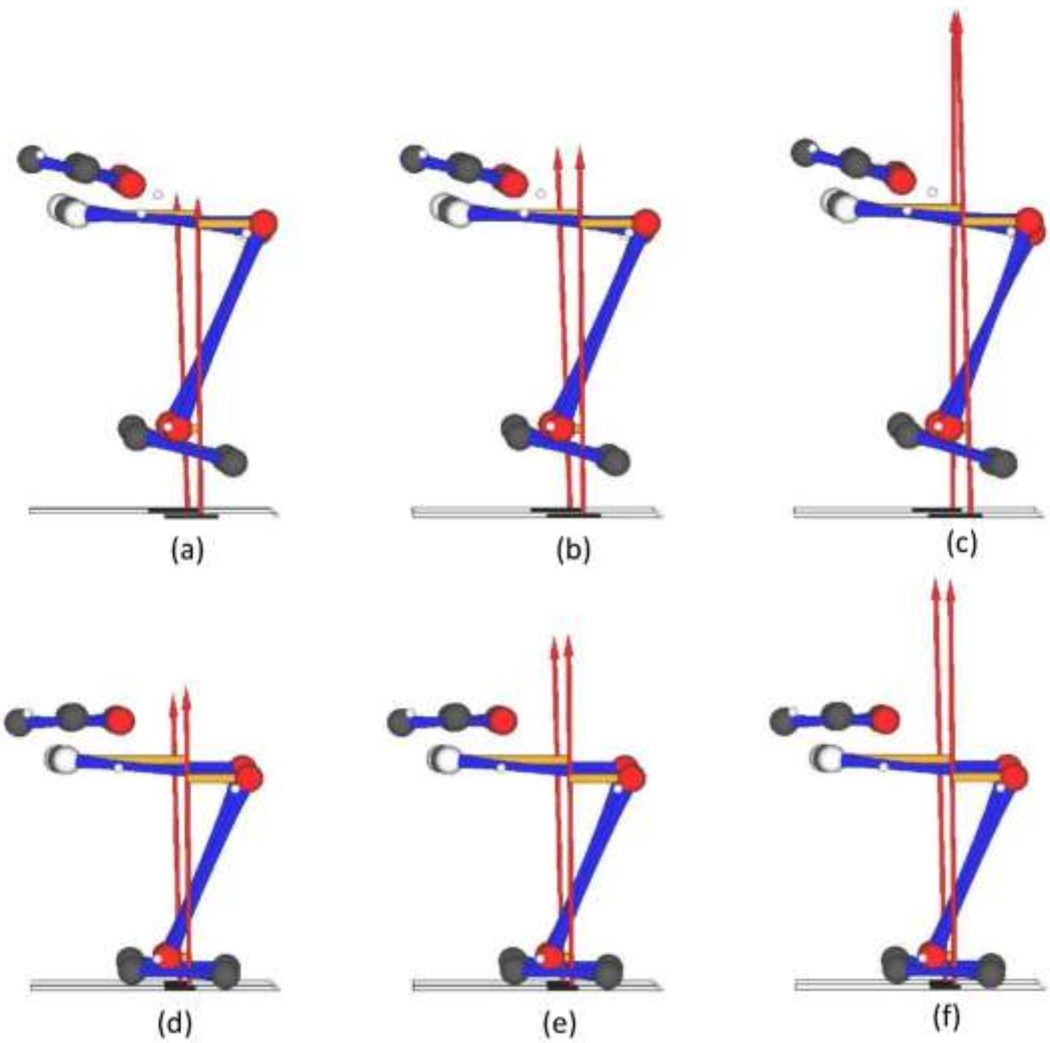


Figure 10. Comparison of the GRF vector direction and MA length between stable and unstable surface conditions during across squatting speed conditions. a – unstable*slow, b – Unstable*moderate, c – unstable*fast, d – stable*slow, e – stable*moderate, and f – stable*fast.

Practical Implications

Based on the result of this study, coaches should take both stability and speed conditions into account when prescribing squat exercise programs. In addition, participants can achieve higher loading with no additional external weight by simply increasing overall squatting speed. For coaches who want to achieve a maximum lower extremity force generation, squatting in the fast speed is more preferable than the slow and moderate speeds conditions. A fast speed will induce more lower extremity joints forces during the squat exercise. For athletes whom participate in a sport requiring power, fast speed squat is more appropriate.

Even though this research was conducted on healthy participants, the results of this study may contain clinical and rehabilitation suggestions such as manipulating stability surface condition and speed relationship could be a step toward tailored squat retraining for individuals with lower extremity joints issues. For physical therapists who want to control training effect for rehabilitation program, squatting during the unstable surface condition produce lower knee RJM than stable surface condition, whereas the stable surface condition produce lower hip and ankle RJMs compare to the unstable surface condition.

For people who want some advice on their exercise program, this study provided a quantitative guidance on lower extremity joints and a detailed instruction on the specific techniques of performing squat variants.

Limitations of the Study

The following limitations may have an effect on interpreting the results of the study:

- This study used an inflated mat to elicit an unstable surface, but there are many other forms of unstable surface devices with different forms and functions. The results of this study are only limited to the inflated mat and must not be assumed true for other unstable devices.
- All participants were recruited from a university population, so the results may only be applicable to college-aged participants.

Conclusion

The purpose of this study was to investigate the effects of surface instability and movement speed on key kinetic factors (i.e., RJM, GRF, MA) of the lower extremity joints during the squat. It was hypothesized that: (1) as squatting speed increases the GRF acting on the feet and the joint moments of the lower extremity joints would increase across surface conditions and (2) the unstable surface condition would induce larger lower extremity joint RJMs, GRFs, and MAs than the stable condition.

By investigating the RJM components (inertial, gravitational, and external), the majority of the lower extremity joint RJM becomes the external moment generated by the GRF and MA during the squat. The shapes of the RJM patterns of the lower extremity joints were similar to those of the MA patterns. The results from the hip and knee joints revealed increases of the extensor moments during the descending phase followed by decreases in the ascending phase. Further, the RJMs and MAs trends were similar in both surface conditions. Unlike the hip and knee joints, the ankle joint generated different shapes of the RJM and MA patterns between stable and unstable surface conditions. Moreover, the shapes of the RJM patterns among different squatting speed conditions in each stability condition were primarily due to the increase in the GRF. As squatting speed increased, the GRF magnitude increased and the trends were similar in both surface conditions.

The peak RJM variables were essentially caused by the significant surface effect in the MA variables and the significant speed factor effect in the GRF variables. In the surface conditions, the unstable condition revealed longer ankle and hip MAs and shorter knee MA at the time of peak RJM than the stable condition. Whereas among the speed conditions, the results from the fast condition revealed the largest GRF magnitude followed by the moderate condition and then the slow condition at the time of the peak RJM.

Based on the results, it was concluded that coaches could manipulate stability surface and speed conditions to improve athletes' performance according to the purpose of the exercise programs. Moreover, in clinical and rehabilitation, surface and speed conditions should be decided based on the exercising program for each joint. The unstable surface condition produces different RJMs in each lower extremity joint compare to the stable surface condition. The manipulation of the speed gradient can also increase the ability for the specialists to provide a proper exercise program.

References

Acker, S. M., Cockburn, R. A., Krevolin, J., Li, R. M., Tarabichi, S., & Wyss, U. P. (2011). Knee kinematics of high-flexion activities of daily living performed by male Muslims in the Middle East. *Journel of Arthroplasty*, *26*(2), 319-327. doi: 10.1016/j.arth.2010.08.003

Adams, K., O'Shea, J. P., O'Shea, K. L., & Climstein, M. (1992). The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *Journal of Applied Sport Science Research, 6*, 36-41. doi: 10.1519/00124278-199202000-00006

Anderson, K., & Behm, G. D. (2005). Trunk muscle activity increases with unstable squat movements. *Canadian Journal of Applied Physiology, 30*, 33-45. doi: 10.1139/h05-103

Behm, D. G., Anderson, K., & Curnew, R. S. (2002). Muscle force and activation under stable and unstable conditions. *Journal of Strength & Conditioning Research*, *16*, 416-422. doi: 10.1519/1533-4287(2002)016<0416

Behm, D. G., & Colado Sanchez, J. C. (2013). Instability resistance training across the exercise continuum. *Sport Health*, *5*, 500-503. doi: 10.1177/1941738113477815

Behm, D. G., & Colado, J. C. (2012). The effectiveness of resistance training using unstable surfaces and devices for rehabilitation. *International Journal of Sports Physical Therapy*, *7*(2), 226-241. PMID: 22530196

Behm, D. G., Drinkwater, E. J., Willardson, J. M., & Cowley, P. M. (2010). The use of instability to train the core musculature. *Applied Physiology, Nutrition, and Metabolism*, *35*, 91-108. doi: 10.1139/H09-127

Behm, D. G., Drinkwater, E. J., Willardson, J. M., & Cowley, P. M. (2011). The role of instability rehabilitative resistance training for the core musculature. *Strength & Conditioning Journal*, *33*, 72-81. doi: 10.1519/SSC.0b013e318213af91

Behm, D. G., Leonard, A. M., Young, W. B., Bonsey, W. A., & MacKinnon, S. N. (2005). Trunk muscle electromyographic activity with unstable and unilateral exercises. *Journal of Strength & Conditioning Research*, *19*, 193-201. doi: 10.1519/1533-4287(2005)19<193:TMEAWU>2.0.CO;2

Behm, D. G., Muehlbauer, T., Kibele, A., & Granacher, U. (2015). Effects of strength training using unstable surfaces on strength, power and balance performance across the lifespan: A systematic review and meta-analysis. *Journal of Sport Medicine*, *45*, 1645-1669. doi: 10.1007/s40279-015-0384-x

Bell, D. R., Padua, D. A., & Clark, M. A. (2008). Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement. *Archives of Physical Medicine and Rehabilitation*, *88*, 1323-1328. doi: 10.1016/j.apmr.2007.11.048

Bentley, J. R., Amonette, W. E., De Witt, J. K., & Hagan, R. D. (2010). Effects of different lifting cadences on ground reaction forces during the squat exercise. *Journal of Strength and Conditioning Research*, *24*, 1414-1420. doi: 10.1519/JSC.0b013e3181cb27e7

Blatnik, J. A., Skinner, J. W., & McBride, J. M. (2012). Effect of supportive equipment on force, velocity, and power in the squat. *Journal of Strength and Conditioning Research*, *26*, 3204-3208. doi: 10.1519/JSC.0b013e3182736641

Braidot, A., Brusa, M., Lestussi, F., & Parera, G. (2007). Biomechanics of front and back squat exercises. *Journal of Physics: Conference Series, 90*, 1-8.

doi: 10.1088/1742-6596/90/1/012009

Chandler, T. J., & Stone, M. H. (1991). The squat exercise in athletic conditioning: A position statement and review of the literature. *National Strength & Conditioning Association Journal*, *13*, 51-58.

Chung, M. J., & Wang, M. J. (2010). “The change of gait parameters during walking at different percentage of preferred walking speed for healthy adults aged 20–60 years. *Gait and Posture*, *31*, 131-135. doi: 10.1016/j.gaitpost.2009.09.013

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *Journal of Strength and Conditioning Research*, *19*, 349-357. doi: 10.1519/14323.1

Czaprowski, D., Biernat, R., & Kendra, A. (2012). Squat rules of performing and most common mistakes. *Journal of Sport Tourism, 19*, 3-12. doi: 10.2478/v10197-012-0001-6

Dahlkvist, N. J., Mayo, P., & Seedhom, B. B. (1982). Forces during squatting and rising from a deep squat. *English Medicine*, *11*, 69-76. doi: 10.1243/EMED_JOUR_1982_011_019_02

Dali, S., Justen, M., Ahmad, H., & Othman, Z. (2013). Comparison of ground reaction force during different angle of squatting. *Journal of Human Sport & Exercise*, *8*, 778-787. doi: 10.4100/jhse.2013.83.02

Denegar, C. R., Hertel, J., & Fonseca, J. (2002). The effect of lateral ankle sprain on dorsiflexion range of motion, posterior talar glide, and joint laxity. *Journal of Orthopaedic & Sports Physical Therapy*, *32*, 166-173. doi: 10.2519/jospt.2002.32.4.166

Dionisio, V. C., Almeida, G. L., Duarte, M., & Hirata, R. P. (2008). Kinematic, kinetic and EMG patterns during downward squatting. *Journal of Electromyography and Kinesiology*, *18*, 134-143. doi: 10.1016/j.jelekin.2006.07.010

Eastlack, R. K., Hargens, A. R., Groppo, E. R., Steinbach, G. C., White, K. K., & Pedowitz, R. A. (2005). Lower body positive-pressure exercise after knee surgery. *Clinical Orthopaedics and Related Research*, *431*, 213-219. doi: 10.1097/01.blo.0000150459.92012.f7

Escamilla, R. F. (2001). Knee biomechanics of the dynamic squat exercise. *Medicine and Science in Sports and Exercise*, *33*, 127-141. doi: 10.1097/00005768-200101000-00020

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. *Medicine and Science in Sports and Exercise, 33,* 984-998. doi: 10.1097/00005768-200106000-00019

Fleming, B. C., Oksendahl, H., & Beynnon, B. D. (2005). Open- or closed-kinetic chain exercises after anterior cruciate ligament reconstruction? *Exercise & Sport Science*, *33*, 13-140. doi: 10.1097/00003677-200507000-00006

Fowles, G. R., & Cassiday, G. L. (2005). *Analytical Mechanics* (7th Ed.)., (pp. 218-224). Belmont, CA: Thomson Learning.

Fry, A., Smith, J., & Schilling, B. (2003). Effect of knee position on hip and knee torques during the barbell squat. *Journal of Strength & Conditioning Research*, *17*, 629-633. doi: 10.1519/1533-4287(2003)017<0629:EOKPOH>2.0.CO;2

González-Badillo, J. J., & Sánchez-Medina, L. (2010). Movement velocity as a measure of loading intensity in resistance training. *International Journal of Sports Medicine*, *31*, 347-352. doi: 10.1055/s-0030-1248333

Gullett, J., Tillman, M., Gutierrez, G., & Chow, J. (2009). A biomechanical comparison of back and front squats in healthy trained individuals. *Journal of Strength & Conditioning Research*, *23*, 284-292. doi: 10.1519/JSC.0b013e31818546bb

HÄkkinen, K., & Komi, P. V. (1983). Alterations of Mechanical Characteristics of Human Skeletal Muscle During Strength Training. *European Journal of Applied Physiology and Occupational Physiology*, *50*(2), 161-172. doi: https://doi.org/10.1007/BF00422155

Hall, S. J. (2012). *Basic Biomechanics* (6th Ed.)., (pp. 251-257). New York: McGraw-Hill.

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. *Medicine and Science in Sports and Exercise*, *21*, 613-618. doi: 10.1249/00005768-198910000-00019

Hemmerich, A., Brown, H., Smith, S., Marthandam, S. S., & Wyss, U. P. (2006). Hip, knee, and ankle kinematics of high range of motion activities of daily living. *Journal of Orthopaedic Research*, *24*, 770-781. doi: 10.1002/jor.20114

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. *Journal of Orthopaedic & Sports Physical Therapy*, *29*, 93-105. doi: 10.2519/jospt.1999.29.2.93

Jagodinsky, A., Fox, J., Decoux, B., Weimar, W., & Lu, W. (2015). Biomechanical comparison of frontal plane knee joint moment arms during normal and Tai Chi walking. Journal of Physical Therapy Science, 27, 2959-2962. doi: 10.1589/jpts.27.2959

Jason, J. (2011). *The effect of cadence on ground reaction forces during the push-up exercise* (Master's thesis). Publication Number: 1493031, ISBN: 9781124609935

Jidovtseff, B., Harris, N. K., Crielaard, J. M., & Cronin, J. B. (2011). Using the load-velocity relationship for 1RM prediction. *Journal of Strength & Conditioning Research*, *25*, 267-270. doi: 10.1519/JSC.0b013e3181b62c5f

Jonsson, P., & Alfredson, H. (2005). Superior results with eccentric compared to concentric quadriceps training in patients with jumper's knee: A prospective randomised study. *British Journal of Sports Medicine*, *39*, 847-850. doi: 10.1136/bjsm.2005.018630

Jovanović, M., & Flanagan, E. P. (2014). Researched applications of velocity based strength training. *Journal of Australian Strength and Conditioning*, *22*, 58-69.

Kibele, A., & Behm, D. G. (2009). Seven weeks of instability and traditional resistance training effects on strength, balance and functional performance. *Journal of Strength & Conditioning*, *23*, 2443-2450. doi: 10.1519/JSC.0b013e3181bf0489

kinematics of high-flexion activities of daily living performed by male muslims in the middle east. *Journal of Arthroplasty*, *26*, 319-327. doi: 10.1016/j.arth.2010.08.003

Kongsgaard, M., Aagaard, P., Roikjaer, S., Olsen, D., Jensen, M., Langberg, H., & Magnusson, S. P. (2006). Decline eccentric squats increases patellar tendon loading compared to standard eccentric squats. *Clinical Biomechanics*, *21*, 75-748. doi:10.1016/j.clinbiomech.2006.03.004

Leffler, J., Scheys, L., Plante-Bordeneuve, T., Callewaert, B., Labey, L., Bellemans, J., & Franz, A. (2012). Joint kinematics follow bi-compartmental knee replacement during daily life motor task. *Gait & Posture*, *36*, 460-4544. doi: 10.1016/j.gaitpost.2012.04.008

Li, G., Most, E., DeFrate, L., Suggs, J., Gill, T., & Rubash, H. (2004). Effect of the posterior cruciate ligament on posterior stability of the knee in high flexion. *Journal of Biomechanics*, *37*, 779-783. doi: 10.1016/j.jbiomech.2003.09.031

Macrum, E. C. (2008). *The Relationship Between Dorsiflexion Range of Motion and Lower Extremity Movement Patterns and Muscle Activation* (Unpublished master's thesis), The University of North Carolina, Chapel Hill.

Macrum, E., Bell, D. R., Boling, M., Lewek, M., & Padua, D. (2012). Effect of limiting ankle-dorsiflexion range of motion on lower extremity kinematics and muscle-activation patterns during a squat. *Journal of Sport Rehabilitation*, *21*, 144-150. doi:10.1123/jsr.21.2.144

Markolf, K. L., Gorek, J. F., Kabo, J. M., & Shapiro, M. S. (1990). Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *Journal of Bone and Joint Surgery*, *72*, 557-567. doi:10.2106/00004623-199072040-00014

Marshall, P. W., & Murphy, B. A. (2006). Increased deltoid and abdominal muscle activity during Swiss ball bench press. *Journal of Strength and Conditioning Research, 20*, 745-750. doi:10.1519/R-18085.1

Mattacola, C. G., & Dwyer, M. K. (2002). Rehabilitation of the ankle after acute sprain or chronic instability. *Journal of Athletic Training*, *37*, 413-429. ERIC Number: EJ665439

McCaw, S. T, & Melrose, D. R. (1999). Stance width and bar load effects on leg muscle activity during the parallel squat. *Medicine and Science in Sports and Exercise, 31*, 428-436. doi:10.1097/00005768-199903000-00012

Miller, J. P., Sedory, D., & Croce, R. V. (1997). Leg rotation and vastus medialis oblique/vastus lateralis electromyogram activity ratio during closed chain kinetic exercises prescribed for patellofemoral pain. *Journal of Athletic Training, 32*, 216-220. PMID: 16558452

Milletello, W. M., Beam, J. R., & Cooper, Z. C. (2009). A Biomechanical Analysis of the Squat Between Competitive Collegiate, Competitive High School, and Novice Powerlifters. *Journal of Strength and Conditioning Research, 23*(5), 1611-1617. DOI: 10.1519/JSC.0b013e3181a3c6ef

Morrissey, M. C., Harman, E. A., Frykman, P. N., & Han, K. H. (1998). Early phase differential effects of slow and fast barbell squat training. *American Journal of Sports Medicine*, *26*, 221-230. doi: 10.1177/03635465980260021101

Morrissey, M., Harman, E., & Johnson, M. (1995). Resistance training modes: Specificity and effectiveness. *Medicine and Science in Sports and Exercise*, *27*, 648-660. doi:10.1249/00005768-199505000-00006

Nagura, T., Dyrby, C., Alexander, E., & Andriacchi, T. (2002). Mechanical loads at the knee joint during deep flexion. *Journal of Orthopaedic Research*, *20*, 881-886. doi: 10.1016/S0736-0266(01)00178-4

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. *Journal of Orthopedic and Sports Physical Therapy, 25*, 307-315. doi: 10.2519/jospt.1997.25.5.307

Norwood, T. J., Anderson, S. G., Gaetz, B. M., & Twist, W. P. (2007). Electromyographic activity of the trunk stabilizers during stable and unstable bench press. *Journal of Strength and Conditioning Research, 21*, 343-347. doi: 10.1519/R-17435.1

Palmitier, R. A., An, K. N., Scott, S. G., & Chao, E. Y. (1991). Kinetic chain exercise in knee rehabilitation. *Journal of Sport Medicine*, *11*, 402-413. doi: 10.2165/00007256-199111060-00005

Piva, S. R., Goodnite, E. A., & Childs, J. D. (2005). Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy*, *35*, 793-801. doi: 10.2519/jospt.2005.35.12.793

Potvin, J. R., McGill, S. M., & Norman, R. W. (1991). Trunk muscle and lumbar ligament contributions to dynamic lifts with varying degrees of trunk flexion. *Spine*, *16*, 1099-1107. doi: 10.1097/00007632-199109000-00015

Purdam, C. R., Cook, J. L., Hopper, D. M., & Khan, K. M. (2003). Discriminative ability of functional loading tests for adolescent jumper's knee. *Physical Therapy in Sport*, *4*, 3-9. doi: 10.1016/S1466-853X(02)00069-X

Rahmani, A., Viale, F., Dalleau, G., & Lacour, J. R. (2001). Force/velocity and power/velocity relationships in squat exercise. *Eur J Appl Physiol*, *84*, 227-232. doi: 10.1007/PL00007956

Rajamohan, G., Kanagasabai, P., Krishnaswamy, S., & Balakrishnan, A. (2010). Effect of complex and contrast resistance and plyometric training on selected strength and power parameters. *Experimental Sciences*, *1*, 1-12. ISSN: 2218-1768

Rodgers, M. M. (1988). Dynamic biomechanics of the normal foot and ankle during walking and running. *Journal of the American Physical Therapy Association*, *66*, 1822-1830.

doi: 10.1093/ptj/68.12.1822

Sakamoto, A., & Sinclair, P. J. (2006). Effect of movement velocity on the relationship between training load and the number of repetitions of bench press. *Journal of Strength & Conditioning Research*, *20*, 523-527. doi: 10.1519/16794.1

Schoenfeld, B. J. (2010). Squatting kinematics and kinetics and their application to exercise performance. *Journal of Strength & Conditioning Research*, *24*, 3497-3506. doi:10.1519/JSC.0b013e3181bac2d7

Selburne, K. B., & Pandy, M. G. (1998). Determinants of cruciate-ligament loading during rehabilitation exercise. *Clinical Biomechanics*, *13*, 403-413. doi: 10.1016/S0268-0033(98)00094-1

Shoemaker, S. C., & Markolf, K. L. (1985). Effects of joint load on the stiffness and laxity of ligament-deficient knees. An in vitro study of the anterior cruciate and medial collateral ligaments. *Journal of Bone and Joint Surgery*, *67*, 136-146 doi: 10.2106/00004623-198567010-00017

Signorile, J. F., Kwiatkowski, K., Caruso, J. F., & Robertson, B. (1995). Effect of foot position on the electromyographical activity of the superficial quadriceps muscles during the parallel squat and knee extension. *Journal of Strength & Conditioning Research*, *9*, 182-187. doi: 10.1519/1533-4287(1995)009<0182:EOFPOT>2.3.CO;2

Starrett, K. (2013). *Becoming a supple leopard the ultimate guide to resolving pain, preventing injury, and optimizing athletic performance* (2nd Ed). Las Vegas, NV: Victory Belt.

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. *Clinical Biomechanics*, *15*, 176-187. doi: 10.1016/S0268-0033(99)00063-7

Vahdat, I., & Ghomsheh, F. T. (2018). The Effects of Task Execution Variables on Resultant Vertical Ground Reaction Force Acting on Foot Sole During Squat Lifting. *Journal of Bodywork and Movement Therapies*, *22*(3), 632-638. doi: https://doi.org/10.1016/j.jbmt.2017.10.010

van Eijden, T. M., Weijs, W. A., Kouwenhoven, E., & Verburg, J. (1987). Forces acting on the patella during maximal voluntary contraction of the quadriceps femoris muscle at different knee flexion/extension angles. *acta anatomica journal*, *129*, 310-314. doi:10.1159/000146421

Watanabe, Y., Tanimoto, M., Oba, N., Sanada, K., Miyachi, M., & Ishii, N. (2015). Effect of resistance training using bodyweight in the elderly: Comparison of resistance exercise movement between slow and normal speed movement. *Geriatr & Gerontol International*, *15*, 1270-1277. doi: 10.1111/ggi.12427

Westcott, W. L., Winett, R. A., Anderson, E. S., Wojcik, J. R., Loud, R. L., Cleggett, E., & Glover, S. (2001). Effects of regular and slow speed resistance training on muscle strength. *Journal of Sport Medicine and Physical Fitness*, *41*, 154-158. PMID: 1147355

Willson, J. D., & Kernozek, T. W. (1999). Plantar loading and cadence alterations with fatigue. *Medicine and Science in Sports and Exercise*, *31*, 1828-1833. doi: 10.1097/00005768-199912000-00020

Wilson, G. J., Murphy, A. J., & Pryor, J. F. (1994). Musculotendinous stiffness: its relationship to eccentric, isometric, and concentric performance. *Journal of Applied Physiology*, *76*(6), 2714-2719. doi: 10.1152/jappl.1994.76.6.2714

Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement* (4^{th} Ed.)., (pp. 107-116). Hoboken, NJ: John Wiley & Sons. doi: 10.1002/9780470549148

Witvrouw, E., Lysens, R., Bellemans, J., Cambier, D., & Vanderstraeten, G. (2000). Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study. *American Journal of Sports Medicine*, *28*, 480-489. doi:10.1177/03635465000280040701

Wu, G., & Hitt, J. (2005). Ground contact characteristics of Tai Chi gait. *Gait Posture*, *22*, 32-39. doi: 10.1016/j.gaitpost.2004.06.005

Young, M., Cook, J., Purdam, C., Kiss, Z., & Alfredson, H. (2005). Eccentric decline squat protocol offers superior results at 12 months compared with traditional eccentric protocol for patellar tendinopathy in volleyball players. *British Journal of Sports Medicine*, *39*, 102-105. doi: 10.1136/bjsm.2003.010587

Zhang, X., Guo, Y., An, M., & Chen, W. (2013). Analysis of kinematic data and determination of ground reaction force of foot in slow squat. *Acta Mechanica Sinica*, *29*, 143-148. doi:10.1007/s10409-013-0052-z

Zwerver, J., Bredeweg, S. W., & Hof, A. L. (2007). Biomechanical analysis of the single-leg decline squat. *British Journal of Sports Medicine*, *41*, 264-268. doi:10.1136/bjsm.2006.032482

APPENDIX A

INFORMED CONSENT FORM

TEXAS WOMAN'S UNIVERSITY

CONSENT TO PARTICIPATE IN SQUAT RESEARCH

Title: Effect of Stable and Unstable Squat on Knee Moment Arm, Orientation Angles and Resultant Joint Moment in Healthy Young College Students

Principal Investigator: Mohammad Hasan……..…………………….…. 940-536-4456
Research Advisor: Young-Hoo Kwon, Ph.D……………………………. 940-898-2598

Explanation and Purpose of the Research

You are being asked to participate in a research study at Texas Woman's University in the Biomechanics laboratory. The purpose of this study is to examine the difference between stable and unstable squat on lower extremity on the sagittal and frontal planes. The research hypotheses is that unstable squat would show different patterns of lower extremity joints than stable squat. You have been asked to participate in this study because you identified yourself as a potential participant that meets the inclusion criteria for this study.

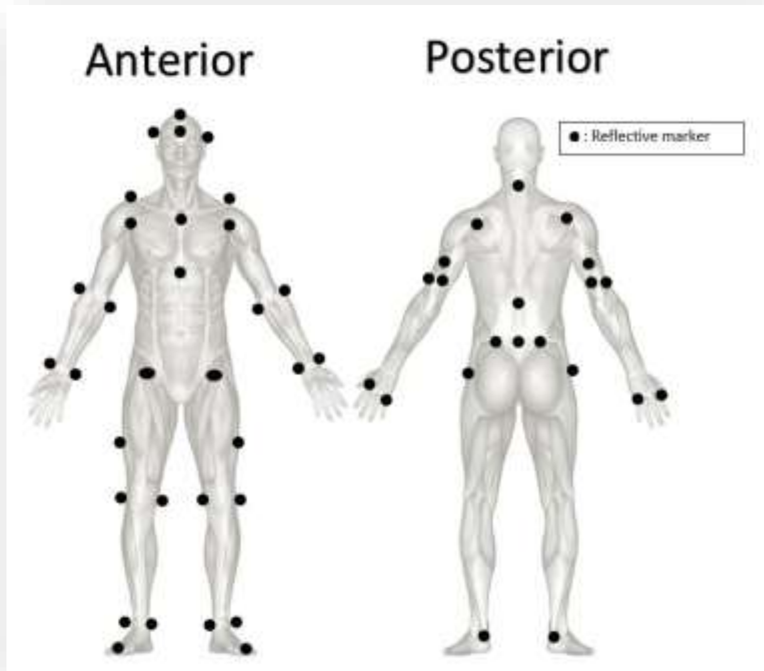
Description of Procedures

You will be asked to read and sign this informed consent prior to the initiation of the study in the PH 123, Biomechanics Laboratory in Texas Woman's University. You will then move to the Motion Analysis Laboratory (PH 124) and be asked to change into specific clothing for optical motion in a separate preparation room if needed.

You will have a warm-up period to make sure that you have adequate time to warm the connective tissue (specifically, lower body joints), thus reducing the possibility of injury during squat performance.

All experimental procedures will be conducted in the Motion Analysis Lab. A 10-camera optical motion capture system (Vicon) with a picture rate of 250 Hz will be used to measure lower extremity motion during stable and unstable squat. A static trial will be used to determine reflective markers relationship and calculate the joint center coordinates of the participants' body. In addition, a static trial allows for certain markers to be removed in the dynamic trials to minimize the negative influence of the markers on the participant's movement during data collection. In addition, reflective markers (10 mm diameter) will be placed on specific parts of your body. From these markers, each part (from lower body segments) is properly defined on the camera system to track the motion being recorded. The markers will have placed as follows: Four marker will be placed on the head, the trunk will have six markers, twenty-two markers will be placed on the arms, five markers will be placed on the pelvis, eight markers on the legs, and eight markers on the feet.

Initial: ……..



When the motion capture system is ready for data collection, you will be asked to perform a static trial (standing in T-pose with arms spread out laterally) to locate your joint centers. After the capture of the static trial is over, you will be asked to do the squat motion with two different conditions (stable and unstable squat). For the stable squat condition, each foot will be placed on one force plate (one force plate per foot) at about shoulder width apart. During the unstable squat the same procedure for the stable squat will be used, but the balance disk will be placed under each foot. You will take a rest whenever you need to minimize fatigue.

The total time commitment for this single-session data collection approximately 60 minutes including all preparation such as explaining the consent form, attaching markers on the body, and data collection.

Potential Risks

Loss of Confidentiality: You will be identified as a participant by a unique ID code. All computer files associated with you will be identified solely by this code and will not contain any identifying information. The Participant Master Identification Code Sheet will be kept separate from all other data collected and will be accessible only to the principal investigator and research assistants. No other identifying information will be collected. Upon completion of data collection sessions, Participant Master Identification Code Sheet will be destroyed by its erasure. As computer files will not contain any identifying information, erasure of computer files is not considered necessary to protect confidentiality after the destruction of the master-cross reference list. All files are recorded and stored directly to the computer; therefore, will be erased from the computer and/or DVDs will be destroyed three years from

Initial: ....

the conclusion of the study. There is a potential loss of confidentiality through all email transactions. Confidentiality will be protected to the extent that is allowed by the law.

Embarrassment: No other participants will be present during data collection sessions. The researchers will try to prevent any embarrassment issues that may occur prior to incident. You will be advised to let the researchers know at once if there is a problem or if you are uncomfortable. Each practitioner will be instructed to assist you in meeting your needs. Be the markers will be placed on the body by male (research team member). You have the right to stop the study at any point if you feel embarrassed.

Skin irritation due to skin preparation: Prior to the data collection, you will be asked whether you have any skin allergies. As an effect of removing the markers some people get skin irritation. That will be avoided by skin preparation to minimize risk by cleansing the area of contact. You will be asked if you have any skin sensitivity and if you are sensitive to such treatments you cannot be recruited. If skin irritation happened, alcohol prep swabs will be used to treat the affected area.

Fatigue: You will be allowed to rest any time if you feel tired. If you feel fatigued, you have the right to stop the study completely at any time.

Injury: Potential of injury will be minimized by allowing each participant time to warm-up. Warming-up is a one way to avoid injury. Moreover, if any participant feels uncomfortable during the data collection, they have the right to not continue in the study. In addition, if an injury should occur, all proper and necessary medical and first aid procedures will be followed as dictated by the type or extent of the injury.

Muscle soreness: Potential muscle and joint soreness will be minimized by asking you to stretch and warm-up at the beginning of the data collection session. Muscle soreness may happens for days after the data collection. To minimize the soreness, slow and gentle stretching of the sore area will relieve that tight feeling and diffuse the pain. Moreover, applying massage with hot/cold pack will shortening the duration of muscle soreness. If soreness persists, then you will have the right to stop the data collection completely.

Coercion: Participation in this study is voluntary, and you may withdraw at any time at your discretion without penalty.

The researchers will try to prevent any problem that could happen because of this research. You should let the researchers know at once if there is a problem and they will help you. However, Texas Woman's University does not provide medical services or financial assistance for injuries that might happen because you are taking part in this research.

Participation and Benefits

Participation in this study is voluntary and you are free to withdraw at any time without penalty. There is no monetary compensation for this study. If you would like to know the results of this study you can provide your mailing address, or email address, and they will be sent directly to you following completion.

Initial: ……..

Information about the study

You will be given a copy of this signed and dated consent form to keep. If you have any questions about the research study you should ask the researchers; their phone numbers are at the top of this form. If you have questions about your rights as a participant in this research or the way this study has been conducted, you may contact the Texas Woman's University Office of Research and Sponsored Programs at 940-898-3378 or via e-mail at IRB@twu.edu.

_____________________________ ___________________

Signature of Participant Date

*If you would like to know the results of this study tell us where you want them to be sent:

Email: ___________________________

or

Address:

____

____