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Does Restricting Anterior Movement of the Knees During a Barbell Back Squat Alter Lower Extremity Biomechanics?

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DOES RESTRICTING ANTERIOR MOVEMENT OF THE KNEES DURING A BARBELL BACK SQUAT ALTER LOWER EXTREMITY BIOMECHANICS?

by

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ABSTRACT

DOES RESTRICTING ANTERIOR MOVEMENT OF THE KNEES DURING A BARBELL BACK SQUAT ALTER LOWER EXTREMITY BIOMECHANICS?

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INTRODUCTION: The strength implications of the barbell back squat make it ideal for use in training programs, rehabilitation, and competition. Even though the back squat is an integral part of these programs, there are also concerns about injury risk due to improper biomechanics. Restricted squats (knees kept behind the toes) are noted to reduce joint loading at the knees but may not take into account added potential risks for the entire lower extremity. Unrestricted squats are more representative of natural movement patterns but may increase joint loading especially at the knees. Research has explored the biomechanics of back squats in elite, male populations, but has yet to investigate how back squat biomechanics differ between restricted and non-restricted squats in a female, recreationally-active population. PURPOSE: Therefore, the purpose is to determine how restricting the anterior movement of the knees during barbell back squats affects joint mechanics of the lower extremities in female recreational weightlifters. METHODS: 16 healthy, female, recreationally-active, weightlifters (mean $\pm$ SD, age= 25.6$\pm$ 4.2 yrs; height= 170.4 $\pm$ 8.3cm; weight= 63.8$\pm$ 8.3 kg) participated in this study. Biomechanical analysis of joint angles and moments were performed using a 3-D motion capture system and standard procedures (Motion Analysis Corporation, Santa Rosa, Ca). Participants performed 5 squats for each of the three squat conditions; natural (NS), knee over toe (KOT), and restricted (RS). The middle 3 squats were used for data processing. A repeated measures ANOVA was used to compare sagittal plane joint angles, lower extremity joint moments, net support moments, and the relative contribution of the individual joint moment to the net support moment, expressed as a percentage. An adjusted alpha value of $\alpha < .004$ determined statistical significance. RESULTS: Knee angle and flexion moment were smaller in RS condition and larger in the NS condition $F(2,30)=35.3, p<.0001$, $F(2,30)=18.8, p<.0001$. Hip extension moment was smallest in KOT and largest in the RS and NS conditions $F(2,30)=18.2, p<.0001$. Ankle angle was the smallest in RS and NS conditions and largest in the KOT condition $F(2,30)=75.8, p<.0001$. Trunk angle was largest in the RS condition $F(2,30)=42.5, p<.0001$. The net support moment was largest in the NS condition $F(2,30)=7.9, p=.002$ CONCLUSIONS: The primary findings of this study supported initial hypotheses that anterior restriction of the knees during a barbell back squat affects lower extremity biomechanics. There were clear differences in sagittal plane joint angles and joint moments seen across the NS, KOT, and RS conditions. The net support moment and the percent contribution of the joint moments also differed between squat conditions and provided valuable information about the distribution of the load across the joints among the three squat conditions. Findings also revealed that this population has natural squat mechanics that are most similar to squatting with the knees over the toes. This may suggest that individuals in this population, with a year of barbell back squat experience, self-optimize their natural squat mechanics. Alternatively, it is possible that the three squat conditions could all be appropriate

ways to squat, depending on the goals of the lifter. These three squats may be used as a way to decrease the load on individual joints while performing the barbell back squat. Training may also be important to decreasing the compensations seen in the RS condition, which may allow for lifters to squat in a safer manner without disproportionally increasing joint loading.

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CHAPTER 1: Introduction

Resistance training has been a significant part of health and fitness for over 4,000 years (Todd, J., 1995). As athletes have adapted their sport or need for general strength, equipment has changed along with the differing needs of the activity as well as the athlete themselves. The rise of the Strongman in the mid 1800s introduced a barbell-like apparatus to resistance training (Todd, J., 1995). Initially with fixed-weight and spherical ends, the barbell served as the best way to demonstrate strength. The barbell also represented a versatile object capable of supporting immense loads while still allowing for balanced and even lifting. Eventually, the need to adjust weight on either side of the barbell drove the adaption of the barbell into a form resembling current-day barbells and weight plates (Todd, J., 1995).

Along with the development of the barbell and importance of resistance training, there has been a significant rise in popularity of barbell sports. Barbell sports are a collection of resistance exercises, utilizing barbells, targeted at increasing coordination, flexibility, strength, and balance. Barbell exercises are versatile in nature and allowing for variations in load without an excessive need for equipment or weight machines. Additionally, barbell exercises are best at strengthening large muscle groups and often include stabilization and coordination benefits for virtually the entire body. For this reason, barbell exercises are often used as a supplement to specialized sports training. The strength, coordination, and flexibility gained through the use of barbell training translates well into performance in many other athletic activities (Calhoon, G., & Fry, A. C., 1999).

Participation in barbell sports and general weightlifting has risen dramatically over the past 30 years, becoming more prominent within every athletic domain (Calhoon, G., & Fry, A. C., 1999). Between 1998 and 2007, the number of people participating in weightlifting has grown by almost 65% (Burke, D. P., & Burke, D. T., 2017). An increase in participation in weightlifting may be attributed to known positive health benefits and may be part of an effort to combat the rising incidence of chronic illness and obesity (Burke, D. P., & Burke, D. T., 2017). Injury rates within elite weightlifting and powerlifting populations hovers between 1 and 4 injuries per 1,000 training hours (Keogh, J., Hume P.A., & Pearson, S., 2006; Raske, Å., & Norlin, R., 2002; Siewe, J. et al., 2011). Increased media coverage on barbell sports such as weightlifting in the Olympics, Powerlifting, and CrossFit have created additional interest in barbell sports. Furthermore, Title IX has given legal standing for the increase in women's participation in all forms of athletics (Hardin, M., & Greer, J. D., 2009; Kane, M. J., 1996). The increase of athletic programs at a collegiate level has spurred the need for supporting activities at lower levels, increasing opportunity and exposure of sports to women and girls. Therefore, women's participation in weightlifting activities has also grown exponentially despite the traditional view of weightlifting being more masculine in nature (Hardin, M., & Greer, J. D., 2009). However, the majority of research on weightlifting and barbell movements continues to be done in male populations.

In addition to supporting the performance of other athletic activities and sports, barbell exercises developed into sports of their own. Competitive weightlifting can be divided into two branches: weightlifting and powerlifting, both of which have become more prominent in the athletic sphere (Raske, Å., & Norlin, R., 2002). Weightlifting and powerlifting are highly reliant on strength and technical skill to properly execute maximal lifts and score the largest combined total (Raske, Å., & Norlin, R., 2002). Despite its name, powerlifting is a relatively low power sport when defined by the parameters of true power, force times velocity (Chiu, L., 2007). Powerlifting relies on maximal strength development over greater periods of time (Chiu, L., 2007). Powerlifting consists of three maximal lifts, the squat, the bench press, and the deadlift. During these three lifts, loads can exceed the bodyweight by up to five times (Raske, Å., & Norlin, R., 2002). Therefore, correct technique and form are crucial to reducing the overall risk of traumatic injury as well as injury over time. Technique standards for all of the powerlifting lifts have been relatively well studied within elite populations, lesser so in recreationally active and healthy populations. Elite populations may be favorited for several reasons including access, interest in maximizing performance, and understanding injury and injury risk factors.

Being the first lift in a powerlifting meet, as well as a popular movement in training and rehabilitation programs, the barbell back squat's simplicity and strength gaining implications make it an extremely versatile movement (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Myer, G. D. et al., 2014; Yavuz, H. et al., 2015). Barbell back squats demand the coordination of several joint complexes and major muscle groups to translate strength, mobility, and functionality to activities of daily living as well as sport (Chandler, T. J., & Stone, M. H., 1991; Myer, G. D. et al., 2014).

Though the barbell back squat is such an integral part of many training programs and sports, it has been thought to be synonymous with injury. Many of the injuries attributed to the barbell back squat may not be a product of the exercise itself, but rather from improper technique (Chandler, T. J., & Stone, M. H., 1991). In elite populations, injuries resulting from squatting or squat technique include and are not limited to knee osteoarthritis, patellar tendinitis, stress fractures, meniscal tears, and spondylolysis (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009; Raske, Å., & Norlin, R, 2002). The knees and lower back withstand the most stress during the barbell back squat and are often the two most vulnerable body parts to injury or discomfort due to incorrect or sub-optimal squatting technique (Kujala, U. M. et al., 1995; Raske, Å., & Norlin, R, 2002). The knee joints also sustain the most overuse injuries, which could lead to long term degradation of the joint and surrounding tissues (Raske, Å., & Norlin, R, 2002). Additionally, females may be at a higher risk for premature osteoarthritis from competition in power sports that utilize the barbell back squat (Kujala, U. M. et al., 1995). Females are also at increased risk of injuries in general, primarily at the knees. This may be due to a multitude of factors including conditioning status, hormonal and ligamentous laxity effects, and anatomy (Hutchinson, M. R., & Ireland, M. L., 1995). Conditioning status has been well documented as an injury risk factor among females, while increased laxity in key ligaments surrounding the knees may further increase injury risk when compared to their male counterparts (Hutchinson, M. R., & Ireland, M. L., 1995). Although the degree to which anatomy plays a role in injury risk is debated, anatomy and lower extremity alignment contribute directly to the forces and strain on the knee compartments, ligaments, and musculotendinous structures (Hutchinson, M. R., & Ireland, M. L., 1995). Females generally have a greater knee valgus and commonly have weak vastus medialis obliquus (VMO) muscles which may create an even larger predisposition to injuries of the knee (Hutchinson, M. R., & Ireland, M. L., 1995). An investigation of the mechanics of the barbell back squat in females is necessary to understand how injury risk factors may differ and if technique guidelines should be amended according to gender.

Currently, the NSCA guidelines for both men and women performing barbell back squats assert that a flawless squat is absent of both lateral and medial displacement of the knee, meaning that the knee is kept behind the vertical line of the toes and do not experience any moments of valgus during the squatting movement (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Lorenzetti, S, 2012; McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010; Myer, G. D. et al, 2014). There is an increased shearing force at the knee with excessive anterior translation of the knees over the toes (List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Myer, G. D. et al, 2014). Increased shearing forces can lead to deleterious changes in joint tissue health which may adversely affect joint congruity and may lead to injuries such as patellar tendentious or knee osteoarthritis (Escamilla, R. F., 2001; Lorenzetti, S. et al., 2012; Raske, Å., & Norlin, R, 2002). By keeping the knees behind the vertical line of the toes, the torque experienced by the knee joint is reduced significantly and becomes a force that is well within the capacity for healthy tissues, when compared to a squat where the knees pass in front of the toes (Kasim, P., 2007; Schoenfeld, B. J., 2010). Because injury rates are higher at the lower back as well, the NSCA guidelines also include the positioning of the trunk. The trunk should stay parallel to the tibia, while maintaining a slightly lordotic lumbar spine in an effort to reduce injury risk (Myer, G. D. et al, 2014).

There is some controversy on allowing anterior movement of the knees past the toes during barbell back squats. This originates from the natural movement patterns of both men and women, where slight forward motion of the knees in front of the toes during barbell back squats is common (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010). Though it is widely accepted that anterior knee translation leads to increased shear forces, enforcing restriction of the knees behind the toes may lead to technique and movement patterns that are not indicative of experienced and skilled lifters (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003). The inherent trade-off between keeping the knees behind the toes and the resulting changes in the overall squat technique might introduce compensations at other relevant joints such as the lumbar spine and the hips (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). These compensations could lead to positions or loading that increases tissue stress and ultimately injury. Forward knee movement in barbell back squats needs further examination to understand the impact on joint position and loading at all relative joints (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010).

The use of a single measure to quantify lower extremity loading as a whole is critical to understanding movements such as the barbell back squat that require the coordination of multiple joint complexes. A support moment is algebraic sum of the absolute value of individual joint kinetics to obtain a single measure of lower extremity function (Flanagan, S. P., & Salem, G. J., 2005; Hof, A. L., 2000; Hwang, S., Kim, Y., & Kim, Y., 2009; Winter, D. A., 1980). Support moments were first used in gait to quantify the function of the limb to resist collapse during stance phase (Winter, D. A., 1980). To calculate a support moment, joint moments are summed into a single number for analysis, which represents the lower extremity as a whole (Winter, D. A., 1980). From the net support moment, researchers can look at the relative contribution, or percentage, of the individual joint moments to maintaining posture and preventing collapse (Winter, D. A., 1980). The use of support moment in movements such as the barbell back squat can allow for individual contributions of the joints of the lower extremity to be examined separately and as a whole.

Therefore, it is important to work towards establishing evidence based technique guidelines that aim to minimize excessive joint loading while maintaining correct technique at all relative joints: the lumbar spine, the hips, the knees, and the ankles. Current gaps in literature highlight the need for additional research on barbell back squats. With an increase in participation of women in barbell sports and their underrepresentation in current literature, additional research in this population is needed. Additionally, existing literature on barbell back squats is focus on elite populations, ignoring recreationally active individuals without the proficiency to compete at an elite level. Lastly, a complete picture of restricted and unrestricted barbell squats needs to be painted, paying close attention to the possible compensatory changes that may be present with knee restriction at all relevant joints including the ankles, the knees, the hips, and the lumbar spine.

Statement of Purpose

The purpose of this study was to determine how restricting the anterior movement of the knees during barbell back squats affects joint mechanics of the lower extremities in female recreational weightlifters. The above purpose was met through the following specific aims:

Specific Aim One: To compare sagittal plane joint angles of the trunk, hip, knee, and ankle between three barbell back squat conditions, natural squatting, restricted squatting, and knee over the toe squatting.

Hypothesis: The sagittal plane joint angles of the restricted squat condition will be larger at the trunk, hips, and the knees, and smaller at the ankle, as compared to the knee over toe squat and natural squat conditions.

Specific Aim Two: To compare the net support moment (sum of the sagittal plane ankle, knee, and hip moments), between three barbell back squat conditions, natural squat, restricted squat, and the knee over the toe squat, and to describe the relative contribution of each joint moment to the overall support moment.

Hypothesis: There will no difference in the net support moment between squat conditions.

Specific Aim Three: To compare the sagittal plane joint moments of the hip, knee, and ankle between three barbell back squat conditions natural squatting, restricted squatting, and knee over the toe squatting.

Hypothesis: The joint moments of the hip and ankle will be larger in the restricted squat and the knee joint moment will be smaller in the restricted squat condition when compared to the natural squat condition and the knee over toe squat condition. The natural squat condition will have similar joint moments at the knee and hip to the knee over toe squat condition.

Delimitations of Study

There are a few delimitations related to the sample chosen for this study:

- Participants only included females between the ages of 18 and 30 who are recreationally active.
- Individuals with current pain, recent injury, or previous surgery in the past 12 months to the lower extremities were not be represented in this sample.
- Due to the specifics of the inclusion and exclusion criteria, results of this study are not otherwise generalizable outside this particular sample

Assumptions of Study

The following assumptions were made when completing this study:

- All lower-extremity segments are rigid bodies.
- All lower-extremity joints are frictionless.

- Full effort was given by participants during data collection.
- Participants answered questions regarding their physical activity and medical history truthfully.

Limitations of the Study

There are also several limitations to this study:

- Accuracy of movement in the transverse plane in 3D analysis.
- Not generalizable across genders
- Several participants are members of the same gym and may have been exposed to similar coaching on technique.

Significance of Study

With the growing popularity of functional barbell exercises, it is imperative to understand barbell back squat performance and the relevant forces at all relevant joints. This project was designed to help create a more complete picture of barbell back squat technique by taking into account the ankles, knees, hips, and lumbar spine. It is important to establish technique guidelines based on varying knee position and how each position affects the motion and forces across all relevant joints of the lower extremity. This project was also designed to increase the literature and understanding of squat technique and resultant forces in recreationally-trained females. Finally, this project and its findings can impact the strength training and rehabilitation domains by expanding the understanding of how barbell back squats can be used safely and effectively in all types of programs to increase strength, ambulation, lower extremity coordination, and performance, while reducing general injury risk.

CHAPTER 2: Review of the Literature

Introduction

Resistance exercises and training can be traced as far back as 4,000 years in the ancient Egyptian, Chinese, and Greek civilizations (Stone, M. H., Pierce, K. C., Sands, W. A., & Stone, M. E., 2006; Todd, J., 1995). The Greeks are often thought to be the first purveyors of modern weight training equipment (Todd, J., 1995). A famous Greek physician, Claudius Galen, in his pervasive medical text, *De Sanitate Tuenda,* described exercises that involved bearing weight upon the shoulders alluding to the use of a barbell-like apparatus in ancient times. His text may also have kept the idea of resistance training alive despite the fall of the Roman Empire and resulting decline in popularity of exercise (Todd, J., 1995). As Europe continued to cultivate resistance training, equipment continued to transform to fit the ever-changing needs of the athletes of the time. The rise of the Strongman in the mid 1800s re-introduced the barbell to resistance training (Todd, J., 1995). First, with spherical, fixed weight ends for Strongman shows, the barbell eventually evolved into plate loaded barbells that resemble the equipment utilized today (Todd, J.,1995). More recently, modern equipment such as barbells, weight plates, and lifting platforms have begun to crop up in gym facilities to support general interest and participation in weightlifting.

Participation

Weightlifting, including barbell sports, has become more increasingly more prominent in modern times as its popularity continues to sky rocket. Between 1998 and 2007, the number of people participating in weightlifting has grown by almost 65% (Burke, D. P., & Burke, D. T., 2017). Additionally, according to the US Bureau of Labor Statistics, weight lifting is the second most popular form of physical activity following walking (Woods R. A., 2017). Increased participation in these activities may be due to several factors. First, the alarming rise of obesity and chronic illness has encouraged a recent emphasis on the positive health benefits associated with strength training, and weightlifting and may help to explain part of the increase in participation (Burke, D. P., & Burke, D. T., 2017). Additionally, increased media coverage on weightlifting in the Olympics, Powerlifting, and CrossFit has continued to facilitate growth in barbell sports popularity and participation from elite to recreational skill levels.

However, the road to increased participation in weightlifting for women has not been quite as smooth of a transition. Historically, the definition of masculinity was synonymous with conceptions of athleticism and weight training, while traditional notions of females were in direct opposition of what it meant to be an athlete (Kane, M. J., 1996). Severely affected by gender norms and lack of exposure, the history of women and weightlifting is vague, as women were traditionally thought to be too weak or simply uninterested in sports deemed as 'masculine' as weightlifting (Hardin, M., & Greer, J. D., 2009). Since the passage of Title IX in 1972, women have had the legal basis to push for greater equality in athletics which has led to exponential growth of women's participation in all sports, including weightlifting and barbell sports (Hardin, M., & Greer, J. D., 2009; Kane, M. J., 1996).

With increased participation from athletes across genders and skill levels, exposure to injury risk factors associated with weightlifting activities and barbell sports has also increased

(Raske, Å., & Norlin, R., 2002). The injury rates in powerlifting and weightlifting activities hovers between 1 and 4 injuries per 1,000 training hours (Keogh J., Hume, P.A., & Pearson, S., 2006; Raske, Å., & Norlin, R., 2002; Siewe, J. et al., 2011). A large amount of these injuries have been attributed to overuse and technique (Calhoon & Fry, 1999; Raske & Norlin, 2002; Siewe et al., 2011). This has spurred the necessity to understand more about the role technique plays in injury incidence during weightlifting and barbell sport activity. Therefore, the purpose of this literature review is to describe the current literature related to weightlifting and barbell sports and their resulting injuries and technique guidelines, as specifically investigated through the barbell back squat.

Barbell Sports

Over the past 30 years, weightlifting and barbell sports have become increasingly prominent within the competitive athletic domain (Calhoon, G., & Fry, A. C., 1999). Barbell sports are simply training exercises designed to increase strength, flexibility, balance, performance, and coordination through the use of weights. These exercises are weighted via a barbell and weight plates that can be adjusted to accommodate different loading conditions. The versatility of the barbell allows for a wide range of functional exercises aimed at strengthening virtually every muscle in the body. Barbell sports have often been used to increase performance in various other activities because the strength and coordination gained in performing barbell exercises translates well to many other athletic activities (Calhoon, G., & Fry, A. C., 1999). Though barbells are often utilized to increase performance in other sports, competitive weightlifting with barbells has become a well-established sport in and of itself.

Competitive Weightlifting

Competitive weightlifting is divided into two subparts: Olympic weightlifting and powerlifting (Raske, Å., & Norlin, R., 2002). Both considered strength sports, Olympic weightlifting and powerlifting are highly dependent on technical skill and strength to achieve maximal lifts. The aim in both of these competitive sports is to lift the most weight, scoring the largest total weight possible over multiple lifts (Raske, Å., & Norlin, R., 2002). Though the aim and general methodology surrounding the two sports is similar in nature, powerlifting and Olympic weightlifting have notable differences in competitive standards which effect training and performance. Olympic weightlifting consists of two lifts; the snatch and the clean & jerk (Chiu, L., 2007). On the other hand, powerlifting includes the performance of three maximal lifts: the squat, the bench press, and the deadlift (Godawa, T. M., Credeur, D. P., & Welsch, M. A., 2012).

Olympic weightlifting relies on explosive strength and true power. The starting positions of the snatch and clean & jerk allow the athlete to complete the lift quickly and respond to stimulus faster when compared to the slower movements of powerlifting (Chiu, L., 2007). Weightlifting plays off a force, velocity relationship by introducing higher velocities to maximize force and therefore power within the lifts (Chiu, L., 2007). The two competitive lifts, the snatch and the clean & jerk, involve the barbell overhead, therefore requiring a different skill set than that of powerlifting (Chiu, L., 2007).

In contrast, despite its name, powerlifting is a relatively low-power sport (Chiu, L., 2007). Powerlifting relies on maximal strength development over greater periods of time to move a selected load (Chiu, L., 2007). The lesser reliance on explosive power and lack of overhead extension during powerlifting makes it possible to lift larger loads when compared to Olympic weightlifting. Loads in powerlifting can exceed bodyweight by up to five times (Raske, Å., & Norlin, R., 2002). Because of this, it is vital to maintain technique standards to reduce the overall risk of traumatic injury or injury over time. The order of lifts in competitive powerlifting is the squat, the bench press, then ending with the deadlift.

Powerlifting Movements

A competitive powerlifting meet will begin with the back squat. The lifter will remove a loaded barbell from a rack set to chest height. The bar will be loaded across the back, resting on the trapezius muscles (Escamilla, R. F., 2001; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). The lift attempt is started when the lifter begins knee flexion, while keeping the torso upright and the core tight (Myer, G. D. et al, 2014). The lifter will continue knee and hip flexion until the quadriceps are parallel to the floor. Extensors of the spine, hip, knee, and ankle must be strong enough to prevent the body from collapsing under the weight of the barbell, especially in the bottom position of the squat (Raske, Å., & Norlin, R., 2002). To finish the squat attempt, the lifter will then extend the knees and hips from the bottom position, returning to the starting position where both the knees and hips are fully extended (Myer, G. D. et al, 2014; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). The squat involves two of the most injury-prone body parts, the knees and lumbar spine (Kujala, U. M. et al., 1995; Raske, Å., & Norlin, R., 2002). Because of the injury rates to these areas, technique has been identified as one of the largest contributing factors to reducing injury risk (Chandler, T. J., & Stone, M. H., 1991; Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009). Technique standards continue to be somewhat contentious as to what the safest and most efficient squat technique entails.

Second, in a powerlifting meet, the athlete would complete the bench press. The bench press is executed by initially taking the barbell from a rack with the arms extended, while lying on a bench (Elliott, B. C., Wilson, G. J., & Kerr, G. K., 1989). In this position, the shoulder girdle must provide a steady base of support for the movement (Raske, Å., & Norlin, R., 2002). The bar is then lowered to the chest. The bar briefly pauses on the chest, then is followed by a symmetrical push from both arms and shoulders to return to the fully extended starting position using both the elbow flexors and horizontal flexors of the shoulders to act alternately in concentric and eccentric contraction patterns (Elliott, B. C., Wilson, G. J., & Kerr, G. K., 1989; Raske, Å., & Norlin, R., 2002). The more vertical the bar path, the greater force can be exerted directly onto the barbell, increasing the chances of a successful lift, especially under high loads (Elliott, B. C., Wilson, G. J., & Kerr, G. K., 1989). During the bench press, the shoulder girdle is put at increased risk for injury due to the high stress associated with the movement (Elliott, B. C., Wilson, G. J., & Kerr, G. K., 1989; Green, C. M., 2007; Raske, Å., & Norlin, R., 2002). Common injuries of the shoulder due to bench pressing include anterior shoulder instability, atraumatic osteolysis of the distal clavicle, and pectoralis major rupture (Green, C. M., 2007).

The last lift performed in a powerlifting meet is the deadlift. Two techniques exist to essentially bring the barbell from the ground to a standing position. In a conventional deadlift, the lifter begins with a narrow stance, with the arms passing outside the legs as the lifter squats down to grip the barbell on the floor (McGuigan, M. R., & Wilson, B. D., 1996). In contrast, in the sumo technique, the lifter assumes a much wider stance and grips the barbell with the arms coming between the legs (McGuigan, M. R., & Wilson, B. D., 1996). The sumo technique is often used by elite lifters as it is a more efficient lift, requiring the barbell to trace a shorter bar path (McGuigan, M. R., & Wilson, B. D., 1996). After gripping the barbell, the deadlift is executed by lifting the weight through the extension of the knees, hips, and back. The lift is completed when the barbell reaches mid-thigh and the knees are locked out and straight with the shoulders behind the bar (McGuigan, M. R., & Wilson, B. D., 1996). Much like the back squat, the deadlift requires the extensors of the ankle, hip, knee, and spine to keep the body erect despite the load of barbell (Raske, Å., & Norlin, R., 2002). The deadlift also has a few common injuries associated with the movement including muscular sprains and spondylosis (Raske, Å., & Norlin, R., 2002).

In all three movements of powerlifting, increasing adherence to technique by reducing excursions in the bar path is critical to lifting the largest loads (Raske, Å., & Norlin, R., 2002). Deviations in bar path can cause the lifter to have to change their technique by increasing the amount of compensatory movements the lifter must make to successfully complete the lift (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009). The minimization of deviations in the bar path and therefore, proper form, is crucial to not only successful lifts but also to injury prevention (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009; Raske, Å., & Norlin, R., 2002). A solid technical foundation is key for athletes to increase performance and longevity in the sport (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009).

Previously Examined Populations in Powerlifting

Previous research on technique and injury risk factors in powerlifting populations has been disproportionally elite in nature and left a glaring gap in the literature. This may be due to several factors including interest in maximizing performance, understanding injury and injury risk factors, and general access to a study population.

Elite powerlifting populations are often the most interested in maximizing performance and staving off injury due to the competitiveness of the sport. This competitive nature allows for a research angle on performance at the highest possible level. Elite powerlifters also provide a good base for studying how injuries occur as well as how they may affect performance afterwards. Longitudinal studies in elite powerlifting populations have contributed to much of what is known about the long-term effects of powerlifting and injuries (Raske, Å., & Norlin, R., 2002). General access to elite powerlifters at competitions held under the International Powerlifting Federation is often greater than recreational populations. To be considered recreationally-active, as laid out by the Center for Disease Control and the American College of Sports Medicine, an individual needs to participate in 30 minutes or more of moderate activity at least 5 days a week or vigorous activity at least 3 days per week (Martin, S. B., Morrow Jr, J.

R., Jackson, A. W., & Dunn, A. L., 2000). By focusing on purely elite athletes, research is skewed towards the extreme and does not accurately represent how other populations, such as a recreational population, experiences the same movements and injuries.

The Back Squat

The barbell back squat's relative simplicity and its strength implications make it ideal for use in training programs, rehabilitation, and competition (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Myer, G. D. et al., 2014; Yavuz, H. et al., 2015). It is estimated that over 200 muscles are active during squat performance allowing the movement to gradually strengthen nearly every muscle group in the lower extremities (Schoenfeld, B. J., 2010; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). Barbell back squats necessitate the coordination of these major muscle groups and translate strength, mobility, and functionality into activities of daily living (Chandler, T. J., & Stone, M. H., 1991; Myer, G. D. et al., 2014). The strength gained through back squatting also translates into other sporting activities such as running, jumping, sprinting, and when done correctly, can help aide in the increased stability and protection of the knee joint from injury (Chandler, T. J., & Stone, M. H., 1991; Escamilla, R. F., 2001; Escamilla R. F. et al., 1998). It is for these reasons that strength and rehabilitation programs have adapted the barbell back squat as an essential part of their varied programs. Further research would aide in the understanding of barbell back squats and the use for this movement within sport, training, and rehabilitation fields.

Injury Implications and Squat Technique

All uses of the barbell squat, independent of loading conditions, require technique guidelines to be followed to ensure safety and success of the movement, as inadequate squat technique may predispose athletes to injury (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009). The incidence of injury associated with the barbell back squat and other weightlifting activities is between 1 and 4 injuries per 1,000 training hours (Keogh, J., Hume, P.A., & Pearson, S., 2006; Raske, Å., & Norlin, R, 2002; Siewe, J. et al., 2011). Chandler & Stone (1991) assert that the injuries attributed to squats may not result from the exercise itself, but rather from improper technique, pre-existing structural abnormalities, fatigue, or excessive training. The most important of these factors is squat technique. Among elite Powerlifters, who utilize the back squat as a competition lift, incorrect form can lead to a multitude of injuries. These injuries include and are not limited to knee osteoarthritis, patellar tendinitis, stress fractures, meniscal tears, and spondylolysis (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009; Raske, Å., & Norlin, R, 2002). Females and individuals with high body mass indexes (BMIs) have shown increased prevalence of premature osteoarthritis from competition in powersports that utilize the back squat (Kujala, U. M. et al., 1995). This may be attributed to the increased patellofemoral stress experienced during the barbell back squat, as the knees and lower back withstand the most stress during the movement and are often the two most vulnerable body parts to injury or discomfort from incorrect or sub-optimal squatting technique (Kujala, U. M. et al., 1995; Raske, Å., & Norlin, R, 2002).

The types of forces present during squatting activities is important to note as excessive forces can decrease effectiveness of the exercise as well as expose the lifter to injury. Shear forces are present when two forces act parallel to each other causing the objects to slide over one another (Austin, G. P., & Jacobs, M. L., 2003). For example, as the knee flexes, the femur rolls and glides over the tibial surface. This motion and the resultant shear force is controlled by the musculature surrounding the knee as well as the ligaments supporting the joint (Schoenfeld, B. J., 2010). Shear forces can cause injuries to the articulating surface of the joint as well as the surrounding muscle, ligament, and tendon tissues if the exerted forces exceed the capacity of the tissues (Schoenfeld, B. J., 2010). Large, repetitive shear forces can damage the articulating surfaces of the joint over time, causing a multitude of injuries (Schoenfeld, B. J., 2010). Compressive forces are present when two forces push or press on an object making it thicker and shorter (Austin, G. P., & Jacobs, M. L., 2003). This is often seen in the knee joint during squatting activities as the distal femur pushes down on the tibiofemoral joint (Schoenfeld, B. J., 2010). Finally, torque is an unbalanced force with a point of application other than the center of an object resulting in rotation around a fixed axis (Austin, G. P., & Jacobs, M. L., 2003). Because of the unbalanced nature of these forces, excessive joint torque can lead to injury in tissues surrounding joint complexes such as the knee, as they fight to resist the forces acting upon them (Schoenfeld, B. J., 2010). The body's tissues have capacity to with stand shear, compressive, and torsional forces up to a certain point. Once these capacities are surpassed, the risk of traumatic injury to the tissues themselves increases significantly (Schoenfeld, B. J., 2010). This is important to note when examining squat technique as it may be advantageous to minimize shear, compressive, and torsional forces as tactic to reduce injury risk.

Currently, the squat technique and form guidelines are most clearly defined by the National Strength and Conditioning Association (NSCA). These guidelines are established to reduce injury risk and give athletes a fundamental understanding of the overall movement. Myer and colleagues (2014) state that a flawless squat is absent of knee displacement both medially and laterally. Any excessive anterior translation of the knees over the toes is purported to increasing shearing forces on the knee joint (List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Myer, G. D. et al, 2014). Increased shearing forces on the knee joint have been found to cause deleterious changes in the joint tissues which may affect joint congruity and may ultimately lead to injuries such as patellar tendentious or knee osteoarthritis (Escamilla, R. F., 2001; Lorenzetti, S. et al., 2012; Raske, Å., & Norlin, R, 2002). Due to the increased injury risk associated with anterior movement of the knees past the toes and the resultant increase in shear forces, the NSCA suggests that the preferred style of squats would restrict the knees behind the vertical line of the toes throughout the entirety of the movement (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Lorenzetti, S, 2012; McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010; Myer, G. D. et al, 2014).

Factors Influencing Squat Performance

Experience, load, and gender have the ability to alter squatting mechanics and may contribute to an increase in injury risk factors. It has been theorized that skill and understanding of the back squat is essential to developing and maintaining proper squat technique and may be critical to minimizing injury risk (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009). Consequently, the development of technical maturity through practice and gained experience is essential to improving overall squat performance. Miltello and colleagues (2009) found that among Powerlifters, novice Powerlifters with less than six months of training experience, exhibited mechanics indicative of poor squatting technique and often lack the technical maturity and strength to correct improper form. Novice lifters also demonstrated a lack control during the decent and larger knee angles during all phases of the squat, which increases compressive joint forces and therefore, increases inherent injury risk (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009). It can be suggested that competent squatting technique may be correlated with experience of the lifter as experience is crucial in developing strength and correct movement patterns and therefore decreasing lifter injury risk. The influx of popularity in barbell sports and increased use of barbell back squats in various applications, has increased the necessity for further research, in recreationally-active populations, to limit the injury implications poor technique and lack of experience may have.

Squat technique may be further altered due to the various loads required in training programs. When working at higher percentages of a one repetition max (1RM), technique is often varied with heavier loads, as a lifter compensates to complete the lift. A load intensity between 40-70% of 1RM may increase trunk lean and decrease the curvature of the lumbar spine (List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Schoenfeld, B. J., 2010). This may result directly in increased intradiscal pressure, vertebrae compression, and increased pressure on the tibiofemoral and patellofemoral joints, which in turn, increases injury risk and may alter compensatory mechanics of the squat (List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). Squat technique is important to fine-tune at lower percentages of a 1RM to ensure technical competency and safety when attempting lifts close to a 1RM.

Gender may also play a large role in the variation of squat mechanics and inherent injury risk factors. Currently, the literature is heavily skewed towards men, with relatively few studies focused on the unique biomechanics of squats in females. Females are at increased risk of injuries primarily at the knees and may be at increased risk for common injuries such as patellar femoral pain (PFP), ACL sprains and tears, patellar tendinitis, and stress fractures because (Hutchinson, M. R., & Ireland, M. L., 1995). This increased risk of injury at the knees may be due to a multitude of factors including conditioning status, hormonal and ligamentous laxity effects, and anatomy (Hutchinson, M. R., & Ireland, M. L., 1995). For many females, baseline conditioning levels are often lower than their male counterparts, and increased injury risk, particularly to the knees, during athletic activity has been well documented (Hutchinson, M. R., & Ireland, M. L., 1995). In addition to conditioning status, hormonal and ligamentous laxity may have effects on inherent injury risk in women. Females tend to have increased ligamentous laxity and flexibility compared to males which may increase the chances of ligament sprains, patellar subluxations, and other ligamentous injuries (Hutchinson, M. R., & Ireland, M. L., 1995). Joints tend to grow thicker and stronger in direct response to increased stresses and strains placed on them, making for a tighter and more stable joint complex, but increased laxity may have a negative effect on the stability of the joint (Dunn, B. et al., 1984; Hutchinson, M. R., & Ireland, M. L., 1995). This laxity may further increase injury risk, primarily in undertrained females. Without this crucial training and correct loading, females and their joint complexes are at increased risk of injury (Hutchinson, M. R., & Ireland, M. L., 1995). Although the degree to which anatomy plays a role in injury risk is debated, anatomy and lower extremity alignment contribute directly to the forces and strain on the knee compartments, ligaments, and musculotendinous structures (Hutchinson, M. R., & Ireland, M. L., 1995). Females generally have a lower center of gravity, wider pelvis, shorter legs, and greater knee valgus when compared to males (Hutchinson, M. R., & Ireland, M. L., 1995; Powers, C. M., 2010). Based on the increased femoral anteversion due to pelvis shape, coupled with common dysplasia or weakness in the vastus medialis obliquus (VMO) on the medial side of the knee, women have an even larger predisposition to injuries of the knee (Hutchinson, M. R., & Ireland, M. L., 1995; Powers, C. M., 2010). When back squat mechanics are examined in female populations, they tend to exhibit a more coordinated squatting pattern, less effected by load and changing joint angles (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010). Yet, females may be susceptible to increased forward motion in the knees during the back squat over their male counterparts (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010; Powers, C. M., 2010). This may be due to laxity or anatomical differences in the joints and pelvis that become more evident when squats are preformed (Hutchinson, M. R., & Ireland, M. L., 1995). Females also commonly demonstrate decreased hip strength and increased knee valgus angles and moments during drop landing and single-leg squat tasks, which are reported to be strong predictors of knee injury (Hutchinson, M. R., & Ireland, M. L., 1995; Nakagawa, T. H., Moriya, E. T., Maciel, C. D., &

Serrao, F. V., 2012; Powers, C. M., 2010). Similar mechanical demands are present during double-leg squats and warrant further research to identify if these specific movement patterns and their resulting injury risk factors are present in the mechanics of barbell back squats in females.

Knee Restriction During Back Squats

In addition to following the NSCA guidelines for back squat technique, the notion of restricting the knees behind the toes stems from the increase in forces experienced at pertinent tissues of the knee complex. Even slight movement of the knees past the vertical plane of the toes can increase shear forces that may become deleterious over time (Escamilla, R. F., 2001; Lorenzetti, S. et al., 2012). This forward translation of the knees may not only increase the shear forces on the patellar tissues but may also influence the way loads are translated through the cruciate ligaments. As the tibia moves forward, sliding anteriorly on the femur during knee flexion, the cruciate ligaments are strained. The main objective of these ligaments is to control and counteract excessive anterior movement of the tibia on the femur (Schoenfeld, B. J., 2010). Excessive tibiofemoral shear forces can be injurious to the cruciate ligaments due to forces exceeding the ligaments capacity (Escamilla, R. F., 2001). This can result in strains, sprains, or even tears of the cruciate ligaments (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998). In addition to being injurious to cruciate ligaments, anterior movement of the knees over the toes has been found to be damaging to overall joint congruity and existing tissues through the use of joint modeling (Escamilla, R. F., 2001; Lorenzetti, S. et al., 2012; Raske, Å., & Norlin, R, 2002). Given that shear forces are increased as the knees move past the toes, attempts should be made to avoid significant forward knee translation to protect the tibiofemoral joint as well as the cruciate ligaments (Schoenfeld, B. J., 2010).

Unrestricted Back Squats

Counter arguments for leniency on anterior movement of the knees past the toes take into consideration natural movement patterns as well compensatory technique changes that may be associated with knee restriction. Both males and females show natural movement patterns that include slight forward motion of the knees in front of the toes during barbell back squats (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010). This may result in larger shear forces that can have somewhat damaging effects on the knee joint, but these forces have been measured to be only .67 times bodyweight during back squats (Escamilla R. F. et al., 1998). When that is compared to activities such as slow running, where forces can be upwards of 1.0 times bodyweight, the shear forces experienced at the knee, as it anteriorly passes the toes during the back squat, become somewhat negligible (Escamilla R. F. et al., 1998). In addition, these shear forces have also been tested far below the capacity for the cruciate ligaments, decreasing the concern for injury to lifters whose knees pass slightly in front of the toes (Escamilla, R. F., 2001).

Though it is widely accepted that anterior knee translation leads to increased shear forces, enforcing restriction of the knees behind the toes may lead to technique and movement patterns that are not indicative of experienced and skilled lifters (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003). The inherent trade-off between keeping the knees behind the toes and the resulting changes in the overall squat technique might increase injury risk at other relevant joints such as the lumbar spine and the hips (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). The resultant forces experienced by the lumbar spine and hips with the restriction of the knees may be disproportionately increased (Kasim, P., 2007). The spine is already the most vulnerable of the joints during squatting. The lumbar spine is better equipped to handle compressive forces rather than shear forces (Schoenfeld, B. J., 2010). To decrease the shear forces on the spine, a normal lordotic curve should be maintained with the spinal column held rigid throughout the squatting movement. This is something that is not always observed when the knees have restricted motion, especially in a loaded condition (Meakin, J. R., Smith, F. W., Gilbert, F. J., & Aspden, R. M., 2008; Schoenfeld, B. J., 2010). Unrestricted barbell back squats take into consideration the lower extremity as whole, instead of only focusing on the knee as an injury site.

Support Moment

Examining the lower extremity as a whole is critical to understanding movements such as the barbell back squat that require the coordination of multiple joint complexes. This can be studied through the use of a single measure, the net support moment. A net support moment is the algebraic sum of the absolute value of individual joint kinetics to obtain a single measure of lower extremity function (Flanagan, S. P., & Salem, G. J., 2005; Hof, A. L., 2000; Hwang, S., Kim, Y., & Kim, Y., 2009; Winter, D. A., 1980).

First studied in gait, Winter (1980) asserted that the basic function of the lower limb during the stance phase of gait is to resist collapse and generate sufficient extension for push off. Collapse of the limb requires flexion of the entire lower extremity including the knee, the hip, and the ankle (Winter, D. A., 1980). In order to prevent this collapse of any relevant joints during stance, a net moment must be present at joint complexes such as the hip, the knee, and the ankle (Winter, D. A., 1980). This allows for each individual joint to contribute to overall lower limb support. In addition, the ability of each joint to extend the lower extremity can be easily quantified (Winter, D. A., 1980). It has been proposed that the support moment shows less variability than any of the joint moments separately (Winter, D. A., 1980).

To calculate a support moment, the individual net joint moments, in the sagittal plane, for the hip, knee, and ankle are determined using inverse dynamics (Flanagan, S. P., & Salem, G. J., 2005; Winter, D. A., 1980). The absolute value of these net joint moments are then summed into a single number for analysis, which represents the lower extremity as a whole (Winter, D. A., 1980). From the net support moment, researchers can then look at the relative contribution or percentage of the individual joint moments to maintaining posture and preventing collapse (Winter, D. A., 1980). Speed of movement can affect the summation accuracy of the support moment, but this is considered negligent in slower moving activities such as walking and squatting (Flanagan, S. P., & Salem, G. J., 2005; Hof, A. L., 2000).

The use of support moments in movements other than gait, such as a barbell back squat can be beneficial for several reasons. A support moment takes into account each individual joint center involved in maintaining rigidity and support, while also establishing a single measure from which individual joint contributions can be derived (Flanagan, S. P., & Salem, G. J., 2005). A support moment can also help to identify asymmetries between limbs or specific joints, which can limit the effectiveness of exercises such as the barbell back squat, especially in a rehabilitation setting (Roos, P. E., Button, K., & van Deursen, R. W., 2014; Winter, D. A., 1980). Currently, there is extremely limited research using the support moment to quantify lower extremity function in double leg and barbell back squats. The use of a support moment in this context may further increase understanding of how barbell back squats effect lower extremity kinetics, as well as how individual joint contributions may change due to altered squat technique.

Summary

Due to the recent increase in participation, especially in barbell sports and the lack of research on females, it is important to know more about barbell back squats and technique in females. Previous research has recognized poor squat technique as a leading contributor to injury (Chandler, T. J., & Stone, M. H., 1991; Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009). Most of these studies have also identified the knees as the primary joint of interest as a majority of the injuries resulting from performing squats are sustained to the knee complex (Kujala, U. M. et al., 1995; Raske, Å., & Norlin, R., 2002). Anterior movement of the knees past the toes during barbell back squats has historically been blamed for the incidence of associated injury due to the increased shear forces the knee joint experiences (List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Myer, G. D. et al, 2014). On the other hand, arguments for leniency on this anterior movement come from natural movement patterns as well as the consideration of all joint forces of the entire lower extremity (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). Because of this controversy, the knee movement in back squats requires further examination to understand the impact on joint coordination and how knee position during squatting affects all relative joints (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010). To study the lower extremity as a whole during barbell back squats, it is important to use a single measure for comparison, such as the support moment. A support moment can help to identify asymmetries between squat conditions or specific joints that may limit the effectiveness of the barbell back squat (Roos, P. E., Button, K., & van Deursen, R. W., 2014; Winter, D. A., 1980). Therefore, it is important to examine technique guidelines and make adjustments that aim to minimize injury risk while maintaining correct technique standards at all relative joints; the lumbar spine, the hips, the knees, and the ankles.

Literature Gap

Current literature gaps highlight the necessity for further research into barbell back squats. The increasing participation of women in barbell sports makes the understanding of technique in this population crucial to ensuring injury prevention and optimal performance. Females are highly underrepresented in current literature and additional research may contribute to overall understanding of technique, as well as the unique technique implications for injury prevention. Additionally, much of the existing data on barbell back squatting patterns and resulting technique are based in elite Olympic weightlifting and powerlifting populations, excluding recreationally-active individuals. Because of the popularity of both sports and barbell exercises, further research is needed to establish similar data within populations of healthy, active subjects, without the expertise to compete at an elite level. The use of support moment to quantify the relative contributions of the hip, the knee, and the ankle is critical to understand the barbell back squat as a whole. Using the overall net joint moment of the lower extremity will help to identify possible asymmetries between squatting conditions. This may also aide in the understanding of technique based on the entire lower extremity, which is not currently represented well in the literature. Lastly, the restriction method to keep the knees behind the toes needs to be further investigated and studied to better understand the biomechanics of the lower extremity joints. Both physical and visual restriction have been used, leaving results somewhat inconclusive of how each technique may play into relevant joint angles and how these joint angles change the way forces are translated through joint centers during barbell back squats. Therefore, it is important to investigate how squat mechanics during restricted and non-restricted barbell back squats differ in recreationally trained females.

CHAPTER 3: Methods

Experimental Design and Setting

This experiment was conducted using a repeated measures design in a research laboratory setting. The three conditions that were tested are the natural back squat (NS), restricted back squat (RS) and the knee over toe back squat (KOT). Measurements included sagittal plane kinematics of the ankles, knees, hips, and trunk, and sagittal plane moments of the hip, knee, and ankle joint.

Participants

Sixteen healthy, female, recreationally-active, weightlifters (mean $\pm$ SD, age= 25.6$\pm$ 4.2 yrs; height= 170.4 $\pm$ 8.3cm; weight= 63.8$\pm$ 8.3 kg) participated in this study. Participants for this study were recruited from three primary locations. The first location was the University of Wisconsin- Milwaukee campus. Students and associated members of UWM were recruited for this study through the posting of flyers around the recreation and fitness centers as well as community boards in the Health Sciences buildings. Secondly, recruitment took place at BrewCity CrossFit where athletes from both the CrossFit gym and the Milwaukee Barbell Club were eligible for participation to ensure diversity within the sample population. Lastly, participants were recruited from the Wisconsin Athletic Club (WAC). Flyers were posted throughout the gyms and individual classes were informed about the study.

The participants consisted of females between the ages of 18 and 35. This age range was identified due to the recruitment area and availability of participants on a college campus and at local gyms. Females were also selected as the population for interest for several reasons. First, females are underrepresented in current literature on barbell sports and movements. It was particularly important to further understand how this specific population utilizes these lifts and what injury risks factors may be associated with barbell squat performance. Additionally, females are increasingly susceptible to increased injury risk, primarily at the knees (Hutchinson, M. R., & Ireland, M. L., 1995). During the barbell back squat, females may also be susceptible to increased forward motion in the knees, increasing known risk factors for injury (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010). Participants were also selected because they were recreationally- active with barbell back squat experience. At least one year of barbell back squat experience was required of each participant in order to ensure technical squatting competency (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010; Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). Additionally, participants were currently utilizing the barbell back squat in their regular fitness program.

Individuals were considered eligible for participation by meeting the following criteria: Female, age 18-35 years, recreationally- active, with at least a year of barbell back squat experience. To be considered recreationally-active, as laid out by the Center for Disease Control and the American College of Sports Medicine, an individual needed to be currently participating in 30 minutes or more of moderate activity at least 5 days a week or vigorous activity at least 3 days per week (Martin, S. B., Morrow Jr, J. R., Jackson, A. W., & Dunn, A. L., 2000). Each participant was also required to be currently using the barbell back squat within their current fitness regimen.

Individuals were not eligible for participation in this study if they had any current injury, had sustained a lower extremity injury in the past 6 months or had undergone any lower extremity surgery within the past 12 months. Additionally, pregnancy and any disorders or previous injuries that may cause pain during squatting or other physical activity made a participant ineligible to partake in the study. Lastly, any participant with three or more deficits, during the back squat screening, using an adapted checklist based of *The Back Squat Assessment* from Myer, G. D. and colleagues (2014), were not used in this sample.

A power analysis was performed for this study based on similar studies. With a power of 80% and a significance level of $p < .05$, the total number of participants needed was 15. This is in agreement with similar studies where the number of participants was between 7 and 12 (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Lorenzetti, S. et al., 2012).

Instrumentation

The three-dimensional marker trajectories were recorded using Cortex (Motion Analysis Corporation, Santa Rosa, Ca) motion analysis system along with 10 digital cameras (Eagle cameras; Motion Analysis Corporation). The video was collected at the standard 200 Hz frequency. Calibration was based on previous studies performed in the lab as well as the manufacturer's recommendations. Ground reaction force data was gathered at a rate of 1000

Hz using two force plates (AMTI, Newton MA). Marker and ground reaction force data was collected and synchronized using a motion capturing software (Visual 3D, C-Motion, Germantown, MD).

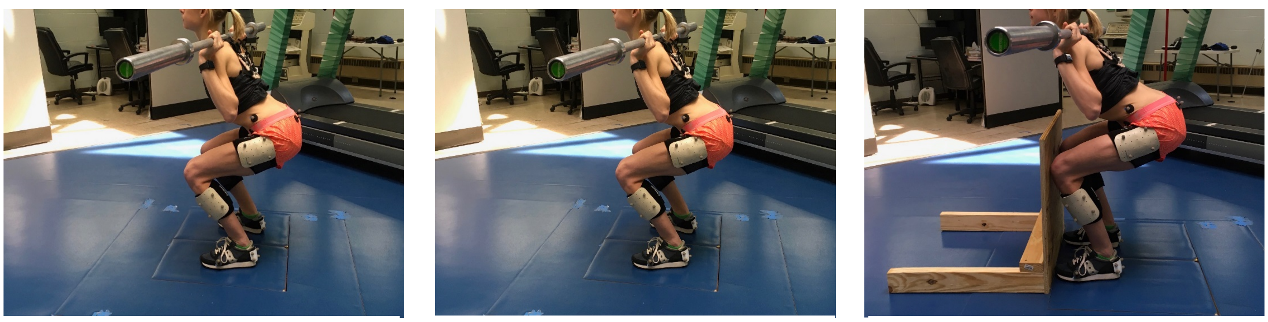
The equipment that was needed for the barbell back squat is as follows. For warm-up and squat screening, the barbell was used to create the same stimulus as the testing trials. For all squat trials, a 44lb, Olympic standard barbell was used (WodBar 5.0, Get RXd, Houston, TX). Physical knee restriction was implemented using a vertical, supported wood board measuring 60cm by 60cm.

Procedures

Each participant was provided with information about the study, the goals of the investigation, as well as what they could expect and the tasks they would be performing. IRB consent was then obtained. Participants were asked to wear a tight-fitting tank-top or t-shirt and tight-fitting shorts and neutral shoes were provided by the lab. Each participant then performed a dynamic warm-up consisting of 2 rounds of 20 jumping jacks, 10 air squats, and 10 lunges (5 each side) to prepare for the testing session. Current squat technique was then assessed using the adapted version of *The Back Squat Assessment* and the 44lb barbell and was evaluated by a researcher experienced in weightlifting (Myer, G. D. et al, 2014). This assessment determined the competence of the participant's current squat technique. The participant performed 3 squats to ensure that no gleaming squat errors were present before the testing took place. Any participant with 3 or more deficits on the back squat screening assessment were deemed ineligible. Markers were placed on the participant and calibration of the motion analysis system will took place. For tracking purposes, markers were placed bilaterally at the 1st and 5th metatarsal heads, lateral and medial malleoli, medial and lateral epicondyles of femur, greater trochanters, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), iliac crests, and the acromioclavicular (AC) joints. Clusters of markers were placed on the lateral surface of the thigh, lateral surface of the shank, between the scapulae, and the calcaneus as marked by the heel of the shoe. After calibration, markers on the greater trochanters, iliac crest, medial and lateral epicondyles of femur, lateral and medial malleoli, acromioclavicular joints, and 1st and 5th metatarsal heads were removed to allow for the squat trials to take place.

Each participant performed the three conditions in the same order (Figure 1). First, the participant squatted naturally. Secondly, the participant performed the knees over toes squat, ensuring that the heels stayed on the ground. Lastly, the participant performed the restricted squat. Familiarization time was given to the participant for each condition to limit the effect of task learning. The barbell was placed on the back, across the trapezius muscles of the participant, where adjustments for comfort can be made to the rack position. The bar was not removed or repositioned between squat conditions. Instructions and feedback regarding technique and form was given to the participant during any of the trials. The participant performed one set of 5 continuous squats for each condition. After the first set of the natural squats was completed, the participant familiarized themselves with knee over toe condition. After familiarization, the participant performed the knee over toe squat. Lastly, the participant familiarized themselves with the restricted squat condition, then performed one set of five continuous restricted squats. Participants were asked to perform their squats in a slow and controlled manner, and feedback on speed of the movement during trials was given. The participant kept the barbell in the back racked position for the duration of the trials to increase load consistency. Testing stopped if pain occurred during squatting or if the participant elected to end testing themselves.

Figure 1- Squat Conditions



Knee Over Toe Squat | Natural Squat | Restricted Squat

An acceptable squat started with the hips and knees fully extended. The feet were placed at the participant's discretion for comfort. The participant squatted downwards, keeping chest erect and the heels planted on the floor. The participant continued to squat until the thighs became parallel with the floor or they were unable to squat lower while mainlining their balance or heels on the floor. The squat trial ended when the participant returned to their starting position and completed 5 repetitions.

Data Processing

Using the Visual 3D software, the collected kinematic data was processed and analyzed. A low-pass fourth order Butterworth filter and cutoff frequency of 12 Hz was used to filter marker trajectories, and a cutoff frequency of 50 Hz for the ground reaction force data. The standing calibration taken prior to the squat trials was used to calculate joint kinematics using the local coordinate systems of the trunk, pelvis, thigh, and shank angles and Cardan angles. Calculation of hip, knee, and ankle joint angles was done using a joint coordinate system approach (Grood, E. S., & Suntay, W. J., 1983). The kinematic measures that were extracted for analysis were the relative sagittal plane joint angles of the self-reported dominant limb (limb used to kick a ball for distance). Internal joint moments were normalized to body weight in kilograms. The kinetic measures that were extracted were the knee, hip, and ankle forces that were then used to calculate joint moments using inverse dynamics. The middle three squats from each condition were averaged and analyzed.

The net support moment was derived from the algebraic sum of the absolute value of the joint moments at the point of greatest knee flexion across the middle three squats of each condition. The net support moment was normalized so that individual contributions of the hips, the knees, and ankles could be identified as a percentage of the overall net support moment.

Statistical Analysis

A repeated measures ANOVA was used to compare the dependent variables between three squat conditions; NS, KOT, and RS. The dependent variables were the sagittal angles (trunk, hip, knee, and ankle) and the moments (hip extension, knee extension, and ankle plantarflexion) at the point of max knee flexion and the net support moment (NSM) and percentage of contribution of the hip (%H), knee (%K), and ankle (%A). To account for the multiple comparisons and protect against Type I error, the Bonferroni correction was used to adjust the p-value to $p<.004$. Tukey's post hoc test was used to identify significant differences among the squat conditions.

CHAPTER 4: Manuscript

Introduction

Participation in barbell sports and general weightlifting has increased significantly over the past 30 years (Calhoon, G., & Fry, A. C., 1999). Between 1998 and 2007, the number of people participating in weightlifting and weightlifting activities has grown by almost 65% (Burke, D. P., & Burke, D. T., 2017). Additionally, according to the US Bureau of Labor Statistics, weightlifting is the second most popular form of physical activity following walking (Woods R. A., 2017). This increase in popularity may be due to several factors including sport exposure through the media, known positive strength and health benefits, and the role of weight lifting in fighting the epidemic of chronic illness and obesity (Burke, D. P., & Burke, D. T., 2017). Despite the historical notion of masculinity, weightlifting and barbell sports have become increasingly popular among females as well (Hardin, M., & Greer, J. D., 2009). Barbell sports have also often been used to increase performance in various other activities as the strength and coordination gained in performing barbell exercises translates well to many other athletic activities (Calhoon, G., & Fry, A. C., 1999).

The barbell back squat is in integral part of weight lifting and barbell sports alike, increasing in popularity with the rising overall participation in weight lifting. A popular movement in training and rehabilitation programs, the simplicity and strength implications of the barbell back squat make it a particularly versatile and useful movement (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Myer, G. D. et al., 2014; Yavuz, H. et al., 2015). The barbell back squat coordinates several joint complexes as well as major muscle groups which translates well into strength, mobility, and functionality (Chandler, T. J., & Stone, M. H., 1991; Myer, G. D. et al., 2014). The strength gained through back squatting also translates into other sporting activities such as running, jumping, sprinting, and when done correctly, can help aide in the increased stability and protection of the knee joint from injury (Chandler, T. J., & Stone, M. H., 1991; Escamilla, R. F., 2001; Escamilla R. F. et al., 1998).

Though commonly used in sport and training programs, barbell back squats have often been thought to be synonymous with injury. Injury incidence has been reported in elite populations hovering between 1 and 4 injuries per 1,000 training hours (Keogh, J., Hume, P.A., & Pearson, S., 2006; Raske, Å., & Norlin, R, 2002; Siewe, J. et al., 2011). Injuries stemming from improper squatting technique can include knee osteoarthritis, patellar tendinitis, stress fractures, meniscal tears, and spondylolysis (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009; Raske, Å., & Norlin, R, 2002). It has been theorized that the injuries sustained from performing the barbell back squat may be attributed to poor technique and mechanics rather than the movement itself (Chandler, T. J., & Stone, M. H., 1991). As investigated through elite, predominately male populations, the lower back and the knees have been found to be particularly vulnerable to increased stress and injury (Kujala, U. M. et al., 1995; Raske, Å., & Norlin, R, 2002). Improper or sub-optimal technique may further increase the joint loading, particularly at the knees and lower back (Kujala, U. M. et al., 1995).

While more females are participating in barbell sports, most of the research has been done in male populations. Understanding squat mechanics in females is necessary because it is known that lower extremity mechanics differ between males and females, which could alter joint loading and ultimately affect injury (Hutchinson, M.R., & Ireland, M. L., 1995). The little research on females shows that they may be at a higher risk for premature osteoarthritis from competition in power sports that utilize the barbell back squat (Kujala, U. M. et al., 1995). Females may also be susceptible to increased forward motion in the knees during the back squat (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010; Powers, C. M., 2010). Because of the increased risk of injury, additional research on barbell back squat mechanics is necessary to increasing the understanding of the movement as a whole.

Currently, the barbell back squat technique is most clearly defined for both males and females by the National Strength and Conditioning Association (NSCA). These guidelines were established to reduce injury risk and give athletes a fundamental understanding of the movement. Myer and colleagues (2014) state that a flawless squat is absent of knee displacement both medially and laterally. Any excessive anterior translation of the knees over the toes is purported to increasing shearing forces on the knee joint (List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Myer, G. D. et al, 2014). Increased shearing forces on the knee joint have been found to cause deleterious changes in the joint tissues which may affect joint congruity and may ultimately lead to injuries such as patellar tendentious or knee osteoarthritis (Escamilla, R. F., 2001; Lorenzetti, S. et al., 2012; Raske, Å., & Norlin, R, 2002). Due to the increased shear force associated with anterior movement of the knees past the toes, the NSCA suggests that the preferred style of squats would restrict the knees behind the vertical line of the toes throughout the entirety of the movement (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Lorenzetti, S, 2012; McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010; Myer, G. D. et al, 2014). These guidelines also include cues for trunk position. The trunk should stay parallel to the tibia while maintaining a slightly lordotic spine (Myer, G. D. et al, 2014). Maintaining this trunk position during the duration of the exercise helps to reduce unwanted spinal loading and decreases the risk for overall injury.

Though it is widely accepted that anterior knee translation leads to increased shear forces, enforcing restriction of the knees behind the toes may lead to technique and movement patterns that are not indicative of experienced and skilled lifters (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003). Counter arguments for leniency on anterior movement of the knees past the toes takes into consideration natural movement patterns as well compensatory technique changes that may be associated with knee restriction. The inherent trade-off between keeping the knees behind the toes and the resulting changes in the overall squat technique might increase injury risk at other relevant joints such as the lumbar spine and the hips by shifting the load to these joints (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; List, R., Gülay, T., Stoop, M., & Lorenzetti, S., 2013; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). Additionally, both males and females show natural movement patterns that include slight forward motion of the knees in front of the toes during barbell back squats (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010).

Because of the current debate on the safety of anterior movement of the knees over the toes, examining the lower extremity as a whole is critical to understanding a movement such as the barbell back squat that requires the coordination of multiple joint complexes. This can be studied through the use of a single measure, the net support moment. A net support moment is the algebraic sum of the absolute value of individual joint kinetics to obtain a single measure of lower extremity function (Flanagan, S. P., & Salem, G. J., 2005; Hof, A. L., 2000; Hwang, S., Kim, Y., & Kim, Y., 2009; Winter, D. A., 1980). These net joint moments are then summed into a single number for analysis, which represents the lower extremity as a whole (Winter, D. A., 1980). From the net support moment, researchers can look at the relative contribution or percentage of the individual joint moments to maintaining posture and preventing collapse (Winter, D. A., 1980). The use of a support moment to describe the barbell back squat is useful to understand how lower extremity kinetics are affected during barbell back squats, as well as how individual joint contributions may change due to altered squat technique.

No study to date has examined squat mechanics in a knee over toes squat and a restricted squat in a recreationally-active, female population. Therefore, the purpose of this study was to determine how restricting the anterior movement of the knees during barbell back squats affects joint mechanics of the lower extremities in female, recreational weightlifters. It was hypothesized that the sagittal plane joint angles of the restricted squat condition will be larger at the trunk, hips, and knees, and smaller at the ankle than the natural squat condition and knee over toe squat condition. A secondary hypothesis was that the net support moment will not differ between squat conditions. A tertiary hypothesis was that the joint moments of the hip and ankle will be larger in and the knee joint moment will be smaller in the restricted squat condition than in the natural squat condition or the knee over toe squat condition and that the natural squat condition will have similar joint moments at the knee and hip to the knee over toe squat condition.

Methods

Participants

Sixteen healthy, female, recreationally-active, weightlifters (mean $\pm$ SD, age= 25.6$\pm$ 4.2 yrs; height= 170.4 $\pm$ 8.3cm; weight= 63.8$\pm$ 8.3 kg) participated in this study. The demographics of the participants are listed in Table 1. Individuals were considered eligible for participation by meeting the following criteria: Female, age 18-35 years, recreationally- active, with at least a year of barbell back squat experience. To be considered recreationally-active, as laid out by the Center for Disease Control and the American College of Sports Medicine, an individual needed to be currently participating in 30 minutes or more of moderate activity at least 5 days a week or vigorous activity at least 3 days per week (Martin, S. B., Morrow Jr, J. R., Jackson, A. W., & Dunn, A. L., 2000). Each participant was also required to be currently using the barbell back squat within their current fitness regimen. The IRB protocol was approved prior to the start of testing.

Table 1- Participant Demographics

DEMOGRAPHIC	MEAN ± SD
AGE (YRS)	25.6 ± 4.2
HEIGHT (CM)	170.4 ± 8.3
WEIGHT (KG)	63.8 ± 8.3
TRAINING AGE (YRS)	3.3 ± 1.8
DAYS PER WEEK EXERCISING	4.7 ± 1.4
DAYS PER MONTH SQUATTING	3.2 ± 2.2
AVERAGE WEIGHT USED DURING SQUATTING (KG)	55.9 ± 29.5

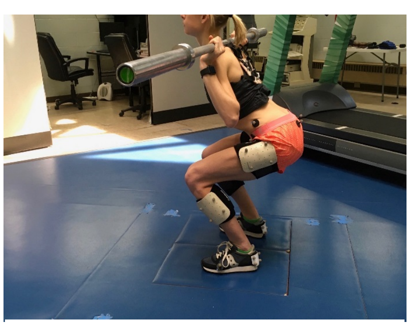
Individuals were not eligible for participation in this study if they had any current injury, had sustained a lower extremity injury in the past 6 months or had undergone any lower extremity surgery within the past 12 months. Additionally, pregnancy and any disorders or previous injuries that may cause pain during squatting or other physical activity made a participant ineligible to partake in the study. Lastly, participants were screened by a trained researcher with experience in squat technique using an adapted checklist based of *The Back Squat Assessment* from Myer, G. D. and colleagues (2014). Participants with three or more deficits during this assessment were not included in the study. None of the screened participants had enough deficits to be excluded from this study.

Barbell Back Squat Movement

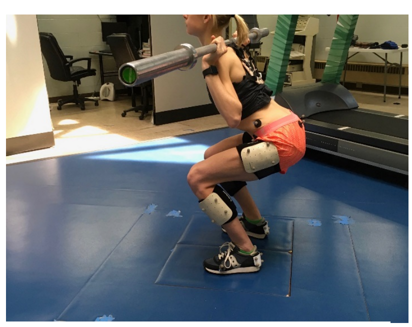
The high rack barbell back squat was performed with an unloaded barbell (44lbs) placed across the back, resting on the trapezius muscles (Escamilla, R. F., 2001; Fry, A. C., Smith, J. C., &

Schilling, B. K., 2003; Lorenzetti, S. et al., 2012; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015) (Figure 2). The feet were placed about shoulders width apart at the participant's discretion for comfort. A researcher observed each squat and informed the participant if the movement was not correct. Three squat conditions were tested. They were a natural barbell back squat (NS), a knee over toe barbell back squat (KOT) , and a restricted barbell back squat (RS) (Figure 2). The natural squat was the participant's preference for squatting. In the knee over toe condition, the participant was asked to squat with the knee moving anteriorly over the toe without the heel lifting off the ground. Lastly, in the restricted condition, the knees were restricted behind the toes by a vertical, supported wooden board measuring 60cm by 60cm. The participants were asked to perform each condition with a two second count down and a two second count up. The NS condition consisted of the participant squatting downwards until the hip crease was at the same level as the superior aspect of the knee and the thighs were parallel with the floor. During the KOT and RS conditions, the participant was asked to squat downwards until balance could not be maintained or until the heels did not stay in contact with the floor (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003).

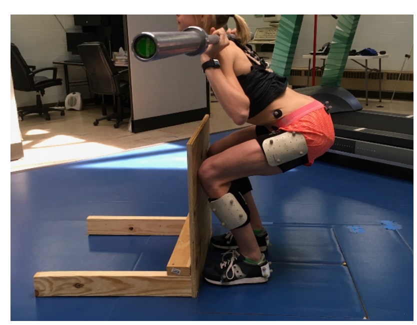
Figure 2- Squat Conditions



Knee Over Toe Squat



Natural Squat



Restricted Squat

Procedures and Data Collection

After informed consent was obtained, the participant performed a dynamic warm-up and current squat technique was assessed using an adapted version of *The Back Squat Assessment* and a standard, Olympic 44lb barbell (Myer, G. D. et al, 2014). The participant self-selected their dominant limb (leg to kick a ball for distance), which was used for data analysis purposes. For 3D biomechanical recording, markers were placed bilaterally at the 1st and 5th metatarsal heads, lateral and medial malleoli, medial and lateral epicondyles of femur, greater trochanters, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), iliac crests, and the acromioclavicular (AC) joints. Clusters of markers were placed on the lateral surface of the thigh, lateral surface of the shank, between the scapulae, and the calcaneus as marked by the heel of the shoe. After calibration, markers on the greater trochanters, iliac crests, medial and lateral epicondyles of femur, lateral and medial malleoli, acromioclavicular joints, and 1st and 5th metatarsal heads were removed to allow for the squat trials to take place. Three dimensional marker trajectories were recorded using the Cortex motion analysis and 10 digital cameras (Motion Analysis Corporation, Eagle Cameras, Santa Rosa, Ca). The video was collected at a standard 200 Hz. Ground reaction force data was gathered at a rate of 1000 Hz using two force plates (AMTI, Newton MA). Marker and ground reaction force data was collected and synchronized using a motion capturing software.

Three different squat conditions were tested in the same order, loaded with a 44lb Olympic standard barbell: the natural squat, the knee over toe squat, and the restricted squat. Familiarization time for each condition was given until the participant verbally stated that they were comfortable with the movement. Five constitutive repetitions of each condition were collected, and the middle three repetitions were used for data processing.

Data Processing

Using the Visual 3D software (Visual 3D, C-Motion, Germantown, MD), the collected kinematic and force data were processed and analyzed. A low-pass fourth order Butterworth filter and cutoff frequency of 12 Hz was used to filter the marker trajectories, and a cutoff frequency of 50Hz for the ground reaction force data. The standing calibration taken prior to the squat trials was used to calculate joint kinematics using local coordinate systems of the trunk, pelvis, thigh, and shank angles and Cardan angles. Calculation of hip, knee, and joint angles was done using a joint coordinate system approach (Grood, E. S., & Suntay, W. J., 1983). The kinematic measures that were extracted for analysis were the relative sagittal plane joint angles of the dominant limb. Inverse dynamics were used to calculate internal joint moments of the knee, hip, and ankle forces at the point of greatest knee flexion. Internal joint moments were normalized to body weight in kilograms. The trunk segment angle was determined relative to vertical in the global coordinate system. The net support moment was derived from the algebraic sum of the absolute value of the joint moments at the point of greatest knee flexion. Relative contributions of the hips, the knees, and ankles were represented as a percentage of the overall net support moment.

Statistical Analysis

A repeated measures ANOVA was used to compare the dependent variables between three squat conditions; NS, KOT, and RS. The dependent variables were the sagittal angles (trunk, hip, knee, and ankle) and the moments (hip extension, knee extension, and ankle plantarflexion) at the point of max knee flexion and the net support moment (NSM) and percentage of contribution of the hip (%H), knee (%K), and ankle (%A). To account for the multiple comparisons and protect against Type I error, the Bonferroni correction was used to adjust the p-value to $p<.004$. Tukey's post hoc test was used to identify significant differences among the squat conditions.

Results

There were several significant findings in this study. The significant findings for the joint angles, net support moment, joint moments, and relative joint contributions to the net support moment are summarized in Table 2. As predicted, trunk flexion angle in the RS condition was significantly larger than in the KOT condition $F(2,30)=42.4$ $p<.0001$. Trunk flexion was also significantly different between the RS condition and the NS condition, $F(2,30)=42.5$, $p<.0001$. There was no difference between hip flexion in any of the three conditions, $F(2,30)=5.9$, $p=.006$. Contrary to the hypothesis, knee flexion angle of the RS condition was smaller than both the NS condition and the KOT condition, $F(2,30)=35.3$, $p<.0001$. The joint angles at greatest knee flexion of the ankle, knee, hip, and trunk of each condition are represented visually below in Figure 3.

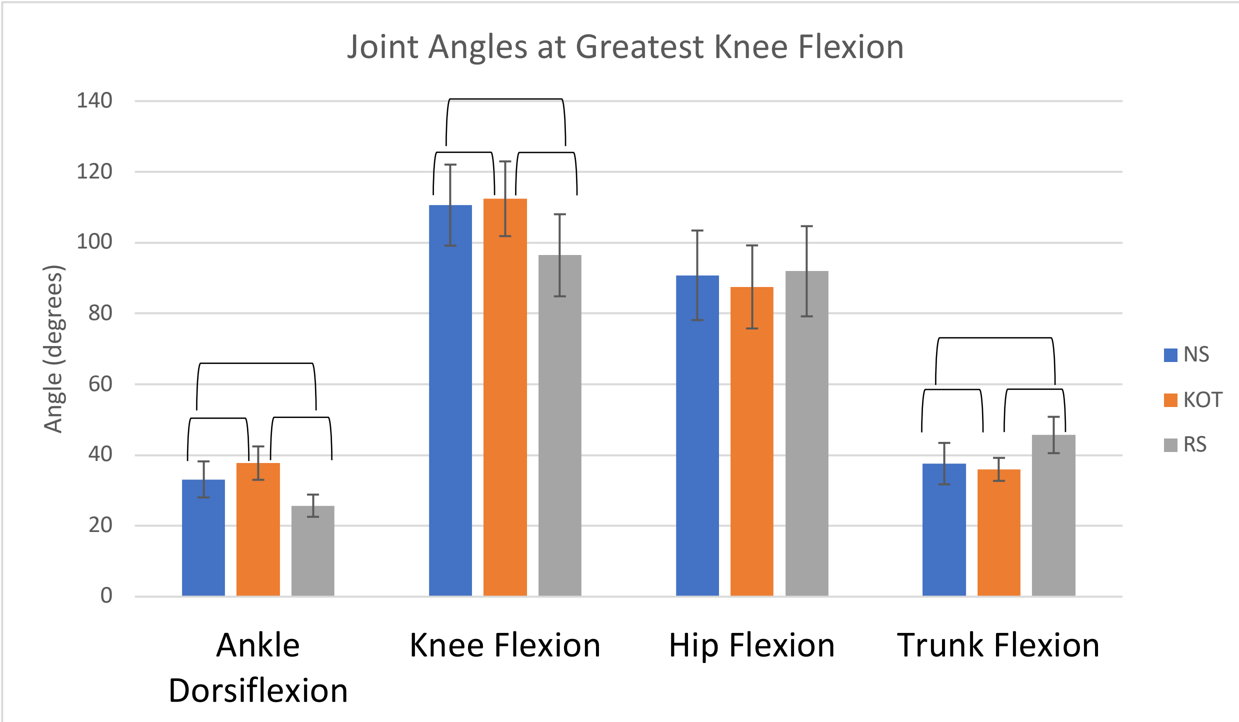


Figure 3- Joint Angles at Greatest Knee Flexion (Degrees)-Bars indicate a significant difference based on Tukey's post hoc test (p<.004).

The second hypothesis of the study was not supported. The NSM was larger in the NS condition than in the other two conditions, $F(2,30)=7.9$, $p=.002$. The individual joint contributions to each support moment are listed in Table 2. The largest of the ankle contribution came from the KOT condition. The largest of the knee contribution came from the KOT and NS conditions. The largest contribution of the hip came from the RS condition. The individual contributions of the ankle, knee, and hip of each condition are represented visually below in Figure 4.

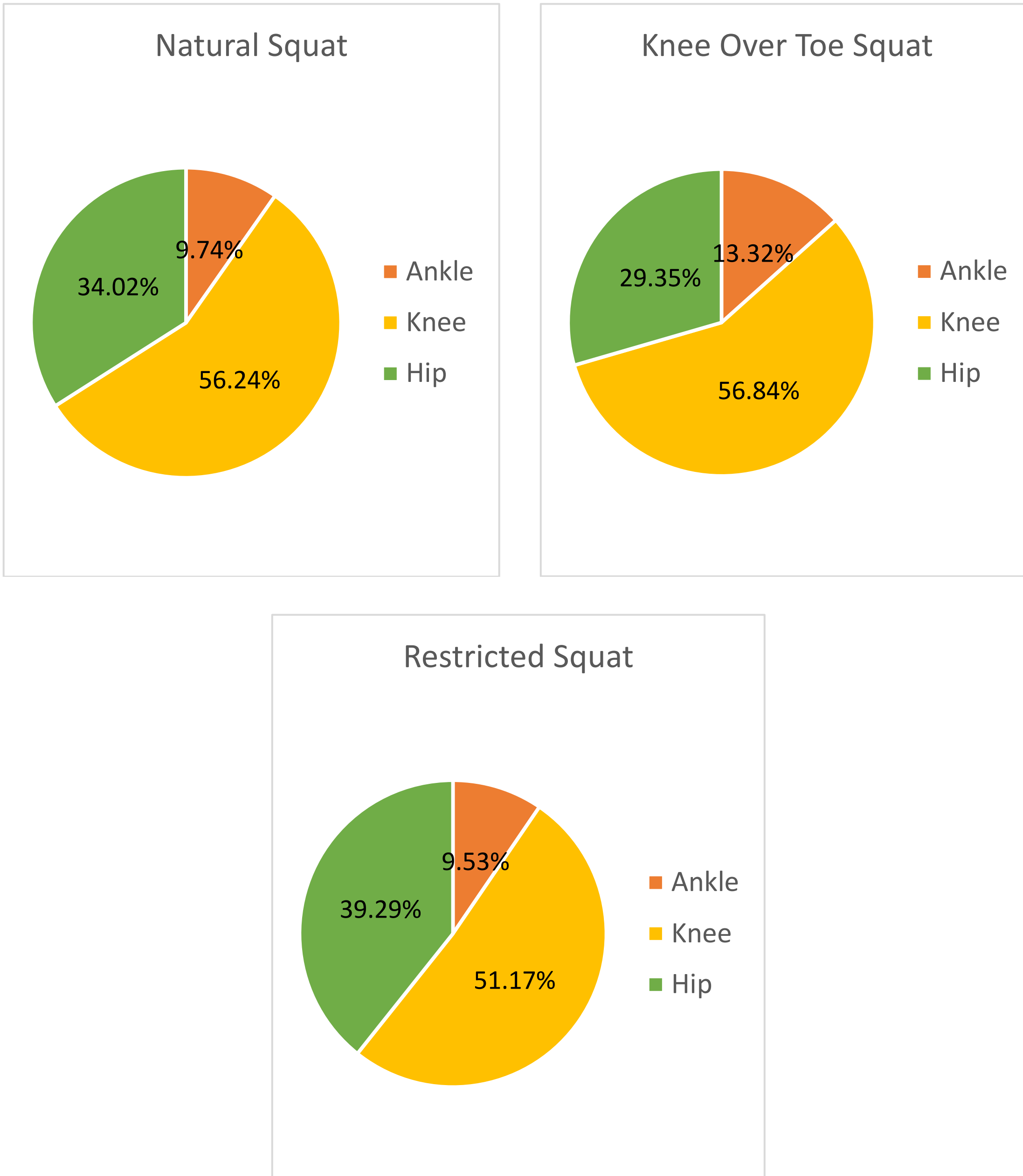


Figure 4- Individual Joint Contributions of the Natural Squat, Knee Over Toe Squat, and the Restricted Squat

In agreement with the last hypothesis, hip extension moment of the RS condition was significantly larger than in the KOT condition, $F(2,30)=18.2$, $p<.0001$. The hip extension moment of the RS condition was similar to NS condition which did not support the hypothesis that the hip extension joint moment would be similar between the KOT condition and the NS condition, $F(2,30)=18.2$, $p=.841$. The knee extension moment of the RS condition was smaller than both the KOT and NS conditions, $F(2,30)=18.7$, $p<.0001$, $F(2,30)=18.7$, $p<.0001$. In disagreement with this hypothesis, the ankle plantar flexion moment of the KOT condition was similar to the ankle plantar flexion moment in the RS condition and NS condition, $F(2,30)=5.0$, $p=.014$, $F(2,30)=5.0$, $p=.031$, respectively. The joint moments at greatest knee flexion of the ankle, knee, and hip of each condition are represented visually below in Figure 5.

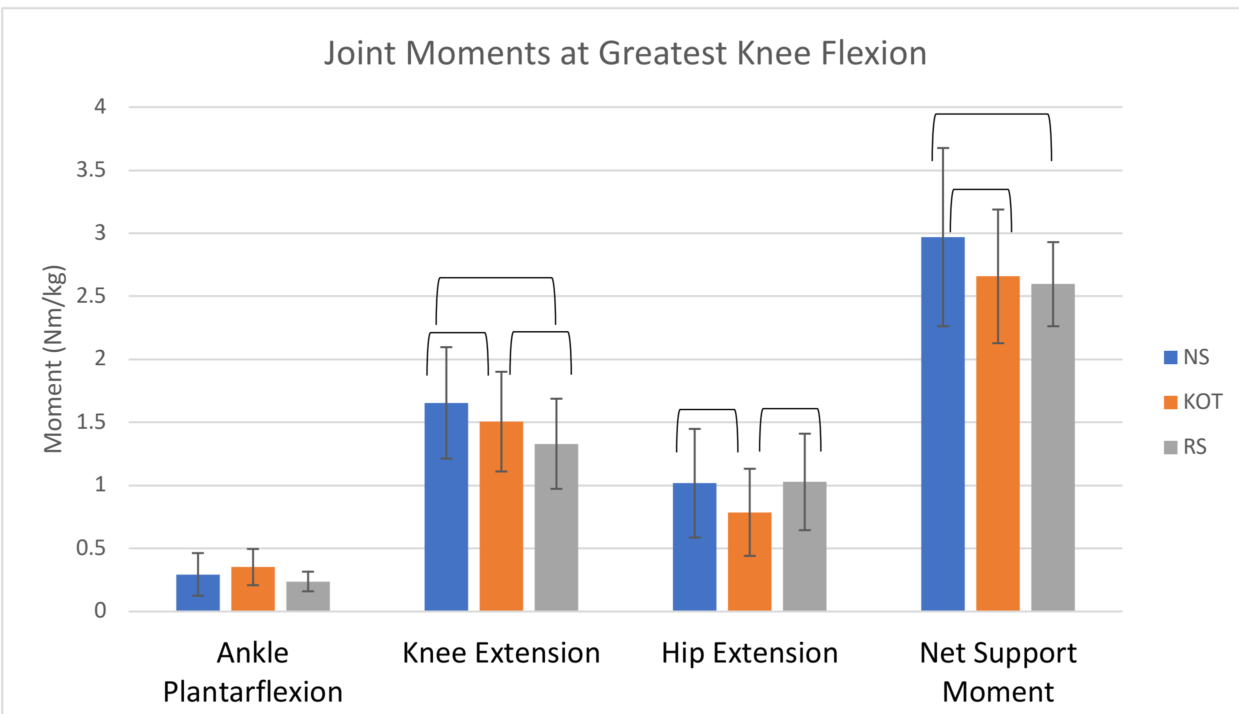


Figure 5- Joint Moments at Greatest Knee Flexion (Nm/kg)- Bars indicate a significant difference based on Tukey's post hoc test (p<.004).

Table 2- Summary of Findings- Bars indicate significance based on Tukey's post hoc test p<.004

Variable	Natural (mean ± SD)	Knee Over Toe (mean ± SD)	Restricted (mean ± SD)
Dorsiflexion Angle	33.1 ± 5.1	37.7 ± 4.7	25.7 ±3.1
Knee Flexion Angle	-110.6 ± 11.4	-112.4 ± 10.6	-96.5 ± 11.6
Hip Flexion Angle	90.8 ± 12.7	87.5 ± 11.7	91.9 ± 12.7
Trunk Flexion Angle	-37.6 ± 5.8	-35.9 ± 3.2	-45.7 ± 5.1
Net Support Moment (NSM)	2.9 ± 0.7	2.7 ± 0.5	2.6 ± 0.3
Ankle Plantar Flexion Moment	-0.3 ± 0.2	-0.4 ± 0.1	-0.2 ± 0.1
Knee Extension Moment	1.7 ± 0.4	1.5 ± 0.4	1.3 ± 0.4
Hip Extension Moment	-1.0 ± 0.4	-0.8 ± 0.3	-1.0 ± 0.4
Ankle Contribution to NSM	9.7% ± 4.0	13.3% ± 4.7	9.5% ± 4.4
Knee Contribution to NSM	56.2% ± 10.3	56.8% ± 10.9	51.2% ± 11.5
Hip Contribution to NSM	34.0% ± 11.1	29.3% ± 10.9	39.3% ± 12.8

Discussion

The primary findings of this study supported initial hypotheses that anterior restriction of the knees during a barbell back squat effects lower extremity biomechanics. There were clear differences in sagittal plane joint angles and joint moments seen across the NS, KOT, and RS conditions. The net support moment and the percent contribution of the joint moments also differed between squat conditions and provided valuable information about the distribution of the load across the joints among the three squat conditions.

Natural Squat Mechanics

Although research has shown that anterior movement of the knees over the toes increases shearing forces which may be injurious to joint tissues, the NS showed that recreational weightlifters in this sample had mechanics that included slight forward motion of the knees past the toes. These findings support the notion that females are subject to natural squatting patterns that include slight anterior movement of the knees past the toes (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010). This was determined due to the knee kinematics and position at greatest knee flexion and further supported by the kinetics that showed that highest demand was on the knee joint, resulting in the largest knee moment, which contributed greatly to the overall NSM. The natural squat reduced joint loading at the hip by lessening the hip contribution and resulting forces. The lesser contribution of the hip and therefore lesser hip extension moment help reduce forces that could be potentially deleterious to the hip joint over time (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998; Fry, A. C., Smith, J. C., & Schilling, B. K., 2003; Kasim, P., 2007; Lorenzetti, S. et al., 2012; Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S., 2015). Additionally, the trunk stayed erect and resisted forward lean during the NS. The ability of the trunk to stay erect during this squatting style may decrease strain of the lower back, especially when the barbell is loaded (Meakin, J. R., Smith, F. W., Gilbert, F. J., & Aspden, R. M., 2008; Schoenfeld, B. J., 2010). Overall, this squat pattern may be an unconscious effort by the lifter to optimize the movement and forces of the lower extremity in an effort to protect the lower back as well as the hips from undue stress and injury.

When compared with the findings from Lorenzetti and colleagues (2012), who examined the mechanics of unrestricted 60° back squats in males, the results of this study were comparable. Despite methodological differences, Lorenzetti and colleagues (2012) found that the average moments of the knee and hip were 1.2 Nm/kg and 1.1 Nm/kg, respectively, when roughly normalized to body weight. These joint moments may be slightly smaller due to the fact that the participants in the study did not squat to parallel.

Natural and Knee Over Toe Squat Mechanics

As hypothesized, most individuals had natural squatting patterns that most closely resembled the KOT squat mechanics. This has been well established in previous literature of skilled male lifters that note that natural squat mechanics often include slight anterior movement of the knees past the toes (McKean, M. R., Dunn, P. K., & Burkett, B. J., 2010). Both the NS and the KOT conditions showed larger internal joint forces at the knee complex. This may be linked to the increased movement of the knees past the toes. Previous literature has also noted that these resulting forces at the knees as they move over the toes are still being far below the capacity of the patellar tissues and cruciate ligaments and are particularly small when compared to other athletics activities such as running (Escamilla, R. F., 2001; Escamilla R. F. et al., 1998). These two conditions also allowed for the trunk to stay erect, reducing the chance of injury at the lower spine, and creating a body shape that is more indicative of skilled lifters (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003). The forward motion of the knees during the KOT was facilitated by an ankle strategy. This increased movement at the ankle may increase the risk of injury at pertinent tissues such as the Achilles tendon complex. Overall, of the three conditions, the KOT and NS looked the most similar in their squat mechanics.

Restricted and Knee Over Toe Squat Mechanics

Differences between the knee over toe and restricted squatting conditions can be seen as virtually every joint of the lower extremity. The movement of the knee past the toe in the KOT was facilitated at the ankle, while the physical restriction of the knees did not allow for this type of ankle movement in the RS condition. The idea behind anterior knee restriction is to reduce the injury risk factors that are common with high moments experienced at the knee as the knee crosses the vertical plane of the toe (Escamilla, R. F., 2001; Lorenzetti, S. et al., 2012; Raske, Å., & Norlin, R, 2002). The knee moment was, in fact, reduced with the restriction of the knees. The findings of the current study agree with findings from Lorenzetti and colleagues (2012), that performing restricted squats decreases the moment at the knee. This was because the knee flexion angle was significantly reduced. The reduced knee flexion mirrored the findings from Fry and colleagues (2003), that found a smaller knee flexion angle from a static model when the motion of the knee was restricted. The decrease of the knee angle shows the inability of the lifter to achieve similar knee flexion and may be attributed to the lack of comfort with the movement and reduced range of motion necessary to counterbalance the movement restriction, or reduced knee extensor strength needed to achieve greater knee flexion. This decrease in knee flexion may also not be practical in a setting where physical knee restriction cannot be provided. Compensatory changes to the lumbar spine became apparent in the RS condition. These compensatory changes, as previously examined, could increase the injury risk at an already vulnerable area, the lumbar spine (Kasim, P., 2007). With the increase in the trunk angle seen in the RS condition, the lumbar spine may experience shear forces to the extent not seen in the knee over toe condition. Since the lumbar spine is more adept at handling large compressive forces and not large shearing forces, squatting in a manner that increases these injurious shearing forces at the lumbar spine may not be the optimal (Schoenfeld, B. J., 2010). Furthermore, the increased trunk lean is not indicative of skilled, experienced weightlifters (Fry, A. C., Smith, J. C., & Schilling, B. K., 2003) and therefore novice lifters should be carefully monitored for the presence of increased trunk lean. If this pattern is present, it creates an opportunity for early movement re-training to improve technique and reduce potential injurious positions and loads.

Overall, the findings of this study marked major differences between the KOT and RS conditions. These differences were seen at practically every joint of the lower extremity, including the trunk. Each condition had different compensatory motions of the joints in order to facilitate squatting movements that placed emphasis on protecting different injury-prone areas.

Training Experience

On average, the participants had a training age of about 3 years. The training age refers the cumulative amount of time an individual has spent training for a particular sport, or in this case a particular movement. Training age has been previously noted as a way to distinguish experienced lifters from novice lifters. A training age of 3 is classified as experienced and squat technique is often far less variable than in novice lifters with less that 6 months of experience (Miletello, W. M., Beam, J. R., & Cooper, Z. C., 2009). However, training age does not explain coaching and the effect it may have on squat technique. Participants were asked whether they had previously been coached to keep their knees behind their toes during barbell back squats. A post hoc analysis showed no significant differences in movement between those who were coached to keep the knees behind the toes and those who were not coached to do so. This may further indicate self-optimization of squat technique.

Additionally, participants were asked the locations where they most frequently trained the back squat. The culture and practices of training and coaching may differ from one location to the next. The answers fell into three categories; BrewCity CrossFit, the Wisconsin Athletic Club, and UWM. A post hoc analysis of these gym categories found no significant difference between where the participant squatted most frequently and their squatting mechanics, suggesting that there was not a confounding factor of gym training practices of techniques.

Support Moment

Though it was hypothesized that the net support moments would be the same between all three squatting conditions, the results of this study did not support that notion. The net support moments should be the same, no matter the differences at individual joints. In theory, as one joint lessens its overall contribution to the net support moment, another joint moment of the lower extremity must increase to counteract this change. The net support moment should be the same because the ground reaction force is based off of the force, mass equation (F=MA). Under perfect conditions, the mass and acceleration would have stayed constant throughout the conditions. In reality, the mass remained constant throughout all the conditions, but the acceleration increased during the natural squat condition leading to larger joint moments and therefore a larger net support moment. It has been previously noted the speed of movement can affect the net support moment as joint moments increase with increased speed (Flanagan, S. P., & Salem, G. J., 2005; Hof, A. L., 2000). The effect of speed was considered negligible in slower movements, such as the back squat (Flanagan, S. P., & Salem, G. J., 2005; Hof, A. L., 2000). This discrepancy may be a product of comfort in the natural squat condition and the slower movement of the restricted and knee over toe conditions may have been because the lifter had to decrease speed in order to follow condition instructions correctly. Because the speed of the squatting motion was not controlled for, it could have affected the summation of the net support motion. In the current study, a post-hoc analysis of the velocity of the center of mass between squat conditions as a method of assessing movement speed was completed. No significant difference was found between squat conditions. It is possible that while center of mass velocity differences may not have been statistically different, a small difference could have affected the support moment. A limitation of this study was not only the lack of control of the speed of the motion, but also the unweighted nature of the barbell back squats.

Practical Applications

Within a healthy, recreationally-active, population, mechanics of the natural squat show slight anterior movement of the knees past the toes with an erect trunk. It may be advantageous to allow for slight movement of the knees past the toes during barbell back squats in healthy individuals. This is in concurrence with the findings in Fry and colleagues (2003) and Lorenzetti and colleagues (2012). This may suggest that individuals in this population, with a year of barbell back squat experience, self-optimize their squat mechanics. By allowing slight anterior movement of the knees past the toes, the lifter can control compensatory movements at the other joints of the lower extremity.

Alternatively, it is possible that the three squat conditions could all be appropriate ways to squat, depending on the goals of the individual lifter. Populations using the barbell back squat as a way to increase strength and athleticism may prefer to squat naturally unless pain occurs. Opposingly, when recovering from injury, additional considerations may be taken to select the correct squat form to match the injury. Those who would like to reduce the loads translated through the knees should choose to perform the restricted barbell back squat, while those with concerns or injuries of the hip and lower back should choose to perform knee over toe squats.

Training and NSCA Guidelines

Though the RS showed compensatory changes due to knee restriction, these changes aren't necessarily a reason to forgo knee restricted squatting. Corrections may be applied, through training, allowing for an individual to reap the reduced injury risk benefits of restricted squatting at the knee, while also managing the risk factors for injury at the other relevant joints. By identifying movement deficiencies when the knees are restricted, a training plan can be set in place. Training quadricep strength and core strength may allow for a lifter may be able to minimize the trunk lean observed during the RS condition and injury risk implications that come with a forward leaning trunk. Additionally, with mobility work, a lifter may also be able to squat to parallel while maintaining the knees behind the toes. NSCA guidelines may be possible to follow without the fear of compensation by simply identifying compensations and training to reduce them through strength and flexibility.

Future research would be needed to further understand squat mechanics in populations with pathological conditions effecting the lower extremity as well as populations with less experience in using the barbell back squat. Literature would also benefit from the addition of a training study designed to reduce compensations seen in restricted squats. Additionally, the effect of load on natural, knee over toe, and restricted squat mechanics may give further insight into the injury reduction applications of varying squat technique.

Limitations

There are several limitations of this study. First, due to the sample, these results are not generalizable across genders. Secondly, the speed of the movement was not kept consistent throughout all three conditions. Lastly, the barbell represented a fairly light load and these results may not be generalizable to squat mechanics with heavier loads on the barbell.

Conclusions

In conclusion, this study found that, recreational-weightlifters, with a year of barbell back squat experience have squat mechanics that allow for slight movement of the knees in front of the toes and do not follow the current NSCA guidelines. The knee over toe condition had more excessive movement, especially at the ankle, when compared to the natural squat and the restricted squat. As previously identified, compensatory changes were reflected in nearly every lower extremity joint including the trunk during the restricted condition. The changes seen between the squat conditions may suggest that individuals self-optimize their natural squat mechanics. Using a net support moment, the description of the individual joint contributions is easier quantify and visually identify, proving a useful tool for studying movements of the lower extremity. Furthermore, the three squat conditions may be used interchangeably depending on the goals of the lifter or rehabilitation status and the necessity to reduce load or stress on certain joints. Additionally, training to reduce compensations may be the best way to utilize the restricted squat and reduce known injury risk factors at the knees as well as the rest of the lower extremity.

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APPENDICIES

Appendix A:
Background Questionnaire

Background Questionnaire

1. How often do you exercise?
   a. 1 day per week
   b. 2 days per week
   c. 3 days per week
   d. 4 days per week
   e. 5+ days per week

2. How long do you exercise at one time?
   a. 30 minutes
   b. 45 minutes
   c. 60 minutes
   d. 75 minutes
   e. 90 minutes

3. What kind of activities/exercise do you participate in? (Mark all that apply)
   a. Weightlifting
   b. Running
   c. CrossFit
   d. Yoga
   e. Recreational Sports
   f. Cycling
   g. Pilates
   h. Other: ___________________

4. How long have you been using the barbell back squat?
   a. < 6 months
   b. 6-12 months
   c. 12-24 months
   d. 24-48 months
   e. 48+ months

5. How often do you use the barbell back squat in your current fitness routine?
    a. 1-2 times per month
    b. 3-4 times per month
    c. 1-2 times per week
    d. 2+ times per week

6. What are your reasons for using the barbell back squat? (Mark all that apply)
    a. Strength
    b. Physical fitness
    c. Enjoyment
    d. Training for another activity
    e. Rehab from an injury
    f. Other: ________________

7. Approximately how much weight do you squat on average?
    a. < 45lbs
    b. 45-50lbs
    c. 50-100lbs
    d. 100-150lbs
    e. 150-200lbs
    f. 200+ lbs

8. Have you been coached to keep your knees behind your toes while squatting?
    a. Yes
    b. No
    c. Unsure

9. Which barbell back squat variation do you prefer?
    a. High rack barbell back squat
    b. Low rack barbell back squat
    c. Unknown/ No preference

10. On a scale of 1-5, how important is squat technique during your training?

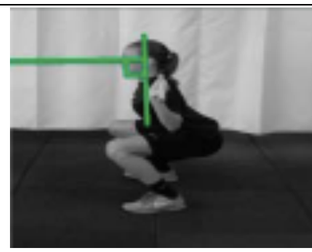
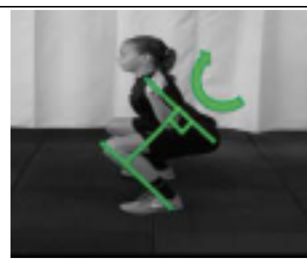
1 2 3 4 5

1-Not at all important
3- Somewhat important
5-Very important

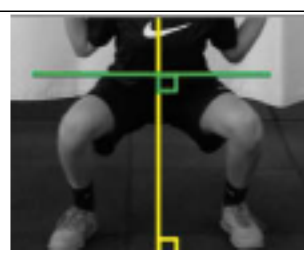
APPENDIX B:
Barbell Back Squat Screening Assessment

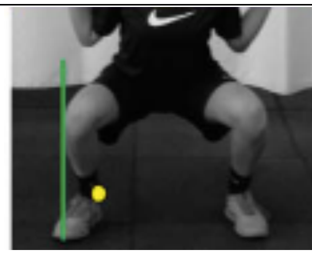
Barbell Back Squat Screening Assessment

Domain One: Upper Body

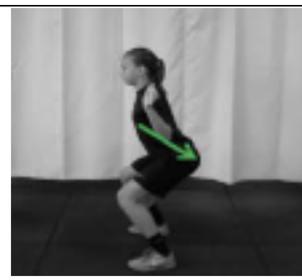
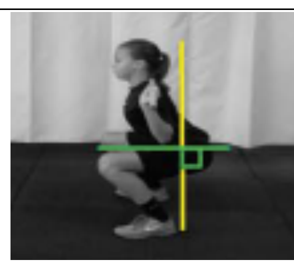
Criteria	Description	Correct	Deficit	Comments
Head Position	Line of neck is perpendicular to the ground and gaze is aimed forward.			
Thoracic Position	Chest is held upward, and shoulder blades are retracted.			
Trunk Position	Trunk is parallel to tibia, while maintaining slightly lordotic lumbar spine.			

Domain Two: Lower Body

Criteria	Description	Correct	Deficit	Comments
Hip Position	Line of hips is parallel to ground in frontal plane throughout squat			

Frontal Knee Position	Lateral aspect of knee does not cross medial malleolus for either leg.			
Foot Position	Entire foot remains in contact with the ground.			

Domain Three: Movement Mechanics

Criteria	**Description**	**Correct**	**Deficit**	**Comments**
Decent	Utilizes hip-hinge strategy at a controlled, constant speed throughout descent. Torso remains upright.			
Depth	At apex of depth, the tops of the thighs are at least parallel to the ground.			
Ascent	Shoulders and hips rise at the same, constant speed to return to start			

	position. Decent: Ascent timing ratio is at least 2:1.			

Total Deficits: ________________ ☐ Eligible ☐ Ineligible

APPENDIX C:
Phone Screening Script

Phone Script Screening & Medical History Questionnaire

(To be read by the research assistant) To make sure that you are eligible for this study, I need to ask you several questions about your past medical lower extremity history. Is this okay with you? I'll read each question carefully and please try to answer to the best of your ability. If you don't understand a question, please ask. This information will not be recorded or used for research purposes unless you are eligible, and consent to be in the study. I just ask that you answer each question as honestly as possible.

1. General Screening Criteria All Potential Participants

First, I'm going to ask you some general questions about you, your health, and your physical activity level.

☐ Yes	☐ No	Are you between the ages of 18 and 35 years old?
☐ Yes	☐ No	Are you currently utilizing the barbell back squat in your current fitness routine?
☐ Yes	☐ No	Do you currently participate in moderate level exercise at least three days per week?
☐ Yes	☐ No	Are you fully cleared to participate in regular training and activity?

If answer is "Yes" to all above, continue to section 2.
If answer is "No" to any, continue to section 4.

2. **Medical History Screening Criteria** All Potential Participants

I'm going to ask you some specific questions about your medical history. If you need further explanation in order to answer the question, please ask.

☐ Yes	☐ No	Do you have a history of any lower extremity surgery or fracture in the past 12 months?
☐ Yes	☐ No	Do you have a history of neurological pathologies that can affect ability to squat?
☐ Yes	☐ No	Do you have a history of any back injuries that can affect squatting (i.e. Scoliosis, Spondylitis, Sciatic Pain)?
☐ Yes	☐ No	Do you have a history of hip or lumbar (low back) referred pain?
☐ Yes	☐ No	Do you have a history of head injury or vestibular disorder within the last 6-months that can affect balance and training?
☐ Yes	☐ No	Do you have a medical condition that may impair your balance performance (i.e. concussion, neurological impairments, etc.)?
☐ Yes	☐ No	Are you pregnant or do you have reason to believe that you may be pregnant?

If answer is "No" to all above, continue to section 3.
If answer is "Yes" to any, continue to section 4.

3. **Injury Screening Criteria** <u>All Potential Participants</u>

I'm now going to ask you some questions about any injury history to make sure you qualify for this study.

☐ Yes ☐ No	Are you currently experiencing any pain during squatting?
☐ Yes ☐ No	Are you currently experiencing a musculoskeletal or neurological condition (i.e. anterior knee pain, iliotibial band syndrome, patellar tendonitis, patellofemoral pain syndrome) or any knee ligamentous or other non-contractile tissue injury)?

If answer is "No" to all above, continue to section 5.
If answer is "Yes" to any, continue to section 4.

4. Screening Failures

I am sorry to inform you that you do not qualify for our study. We thank you for your time and interest in this study. Please let me know if you have any further questions.

5. Screening Successes

I am pleased to inform you that you may qualify for our study. If you are still interested in participating, we will now need to schedule you for a testing session. This session will take approximately an hour to an hour and a half during which time your final eligibility will be determined, and data collection will be obtained. During this session, you will be asked to perform some strength testing and you will be asked to perform running tasks while a camera system tracks your movement. All of the procedures of this study are outlined in the consent form. Would you like me to e-mail you a copy of it?

If you are still interested in participating in this study, please let me know so that we can schedule a time to get you in for testing.

Schedule for Testing:

What days work best for you?
What times work best for you? AM, Midday, PM?

Prior to data collection, we will have you fill out a quick survey regarding your training history and reasons for utilizing the barbell back squat after the consent form is signed and before data collection.

Do you have any other questions about the study?

Include *the directions to campus.*
Include directions on what clothes to wear.

Appendix D:
Informed Consent Form

Study title	Does Restricting Anterior Movement of the Knees During a Barbell Back Squat Alter Lower Extremity Biomechanics?
Researcher[s]	Jennifer Earl Boehm, PhD, ATC, FNATA and Lucy Koshewa. University of Wisconsin- Milwaukee. Department of Kinesiology- Integrated Health Care and Performance.

We're inviting you to participate in a research study. Participation is completely voluntary. If you agree to participate now, you can always change your mind later. There are no negative consequences, whatever you decide.

What is the purpose of this study?
The purpose of this study is to determine how restricting the anterior movement of the knees during barbell back squats affects joint mechanics of the lower extremities in female recreational weightlifters.

What will I do?

- In our lab:
    - You'll complete a survey about your past medical history, injury history, what you do for exercise, and your experience will barbell back squats. (5 minutes)
    - We'll have you warm up for activity then we will screen your current back squat form for large technical errors. (10 minutes)
    - We'll place reflective markers and reflective clusters onto your legs and hips to build a 3-D video of your squatting (5 minutes)
    - We'll measure and record your squatting mechanics on the force plates in three separate conditions; natural squatting, knees over the toes, and restricted squatting. One set of 5 squats per condition will be recorded. (20-30 minutes)

Risks

Possible risks	**How we're minimizing these risks**
Some questions may be very personal or upsetting	You can skip any questions you don't want to answer.
Mild Muscle Soreness	We will allow for proper and adequate warm up before any physical activity and testing and also provide time and direction for proper cool down after the testing session is complete.
Reoccurrence of injury or new injury occurs during the testing process	We will allow for proper and adequate warm up before any of the testing begins, along with proper cool down after the study is done to help decrease the risk of injury. You can stop at any time or if injury occurs. You will also

	be given referrals to local clinics in case medical advice/ attention is needed.
Breach of confidentiality (your data being seen by someone who shouldn't have access to it)	• All identifying information is removed and replaced with a study ID. • We'll remove all identifiers within the data after 1 year following the completion of the study. • We'll store all electronic data on a password-protected, encrypted computer. • We'll store all paper data in locked room (END 132) separate from any the participant key and informed consent containing identifiable information. • We'll keep your identifying information separate from your research data, but we'll be able to link it to you by using a study ID. We will destroy this link after we finish collecting and analyzing the data.

There may be risks we don't know about yet. Throughout the study, we'll tell you if we learn anything that might affect your decision to participate.

Other Study Information

Possible benefits	• Better understanding of squatting mechanics • Possible use of different types of squats to reduce injury risk at specific joints or overall
Estimated number of participants	15 participants
How long will it take?	Approximately an hour to an hour and a half
Costs	None
Compensation	None
Future research	De-identified (all identifying information removed). Your data won't be used or shared for any future research studies.
Recordings / Photographs	Standard video cameras will be used to record the side view of the participants during all squatting conditions. This will be used alongside data analysis.
Removal from the study	If you do not feel comfortable being recorded, you will be removed from the study due to the necessity of the video for data analysis. If you give the wrong or misguided information about your past medical history, you will be removed from the study.

What if I am harmed because I was in this study?

If you're harmed from being in this study, let us know. If it's an emergency, get help from 911 or your doctor right away and tell us afterward. We can help you find resources if you need psychological help. You or your insurance will have to pay for all costs of any treatment you need.

Confidentiality and Data Security

We'll collect the following identifying information for the research: Signature of Consent Form This information is necessary to allow us to perform the study and have evidence that you agreed to all of the risks, benefits, knowledge of the study, and participation of the study.

Where will data be stored?	• Data obtained during the 3-D video will be stored on safe and controlled file in Enderis 132 lab computer. • Data recorded on paper will be stored in safe, locked file that is located in Enderis 132 separate from collected data.
How long will it be kept?	12 Months

Who can see my data?	**Why?**	**Type of data**
The researchers	To analyze the data and conduct the study	The questionnaire, kinetic and kinematic measures will be collected. You will be given a Study ID that will prevent any of the information from being associated with you and your name will be removed from all of the information collected.
The IRB (Institutional Review Board) at UWM The Office for Human Research Protections (OHRP) or other federal agencies	To ensure we're following laws and ethical guidelines	The questionnaire, kinetic and kinematic measures will be collected. You will be given a Study ID that will prevent any of the information from being associated with you and your name will be removed from all of the information collected.
Anyone (public)	If we share our findings in publications or presentations	All of your measures, results, and questionnaire answers will be used during the presentation of publication of the study, but they will be associated with the study ID given. Your name will not be used in any of the information. All results will include

		information that has been will be aggregated together.

Contact information:

For questions about the research	Lucy Koshewa Dr. Jennifer Earl-Boehm	(720) 839-1146 lkoshewa@uwm.edu Pavilion 378 (414) 229-3227 jearl@uwm.edu Pavilion 367
For questions about your rights as a research participant	IRB (Institutional Review Board; provides ethics oversight)	414-229-3173 / irbinfo@uwm.edu
For complaints or problems	Lucy Koshewa Dr. Jennifer Earl-Boehm	(720) 839-1146 lkoshewa@uwm.edu Pavilion 378 (414) 229-3227 jearl@uwm.edu Pavilion 367
	IRB	414-229-3173 / irbinfo@uwm.edu

Signatures

If you have had all your questions answered and would like to participate in this study, sign on the lines below. Remember, your participation is completely voluntary, and you're free to withdraw from the study at any time.

____

Name of Participant (print)

____ ____________

Signature of Participant Date

____

Name of Researcher obtaining consent (print)

____ ____________

Signature of Researcher obtaining consent Date

Appendix E:
IRB Protocol Form

IRBManager Protocol Form

NOTE: If you are unsure if your study requires IRB approval, please review the UWM IRB Determination Form.

Instructions: Each Section must be completed unless directed otherwise. Incomplete forms will delay the IRB review process and may be returned to you. Enter your information in the **colored boxes** or place an **"X"** in front of the appropriate response(s). If the question does not apply, write **"N/A."**

SECTION A: Title

A1. Full Study Title: Does Restricting Anterior Movement of the Knees During a Barbell Back Squat Alter Lower Extremity Biomechanics?

SECTION B: Study Duration

B1. What is the expected start date? *Data collection, screening, recruitment, enrollment, or consenting activities may not begin until IRB approval has been granted. Format: 07/31/2011*

04/01/2018

B2. What is the expected end date? *Expected end date should take into account data analysis, queries, and paper write-up. Format: 07/05/2014*

04/01/2019

SECTION C: Summary

C1. Write a brief descriptive summary of this study in Layman Terms (non-technical language):

This study will be looking at female recreational weightlifters who utilize the barbell back squat in their current fitness routine. The barbell back squat has the versatility to be used in strength training, rehabilitation, and sport. The barbell back squat has historically been associated with causing injury, but many of these injuries can be attributed to improper technique rather than the back squat itself. The knee joint has the highest incidence of injury due to the barbell back squat and because of this, technique has been identified as one of the largest contributing factors to reducing injury risk. Several studies have identified that forward movement of the knees past the toes increases knee joint forces, contributing to an increased injury risk. The restriction of the forward movement of the knees over the toes may decrease forces at the knee joint but may cause compensatory changes in squat mechanics at other lower extremity joints. All participants will complete a previous medical history and training history questionnaire as well as a squat screening to check for competent squat form. The participants will then be asked to complete 3 barbell back squat conditions; natural squats (what they would use normally), unrestricted squats (knees in front of the toes), and restricted squats (knees restricted behind toes). 3-D joint, segment angle, support moment, and force data will be collected for each back squat condition. This study will help determine how forces, joint angles, and support moments differ between different types of back squats and which back squat may be the most advantageous to reduction of injury risk.

C2. Describe the purpose/objective and the significance of the research:

The purpose of this study is to determine how restricting the anterior movement of the knees during barbell back squats affects joint mechanics of the lower extremities in female recreational weightlifters. The significance of this study is far reaching, having implications in clinical rehabilitation, strength training, as well as sport and performance. It will not only add to the barbell back squat literature and current debate on squat technique, but it will also introduce a female population into the discussion. It will help to increase the knowledge of how barbell back squat technique effects recreationally- active individuals and the understanding of the barbell back squat at all relevant joints of the lower extremity.

C3. Cite the most relevant literature pertaining to the proposed research:

Fry, A. C., Smith, J. C., & Schilling, B. K. (2003). Effect of knee position on hip and knee torques during the barbell squat. The Journal of Strength & Conditioning Research, 17(4), 629-633.

List, R., Gülay, T., Stoop, M., & Lorenzetti, S. (2013). Kinematics of the trunk and the lower extremities during restricted and unrestricted squats. *The Journal of Strength & Conditioning Research*, *27*(6), 1529-1538.

Lorenzetti, S., Gülay, T., Stoop, M., List, R., Gerber, H., Schellenberg, F., & Stüssi, E. (2012). Comparison of the angles and corresponding moments in the knee and hip during restricted and unrestricted squats. *The Journal of Strength & Conditioning Research*, *26*(10), 2829-2836.

Miletello, W. M., Beam, J. R., & Cooper, Z. C. (2009). A biomechanical analysis of the squat between competitive collegiate, competitive high school, and novice powerlifters. *The Journal of Strength & Conditioning Research*, *23*(5), 1611-1617.

Myer, G. D., Kushner, A. M., Brent, J. L., Schoenfeld, B. J., Hugentobler, J., Lloyd, R. S., ... & McGill, S. M. (2014). The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Strength and conditioning journal*, *36*(6), 4.

Raske, Å., & Norlin, R. (2002). Injury incidence and prevalence among elite weight and power lifters. *The American journal of sports medicine*, *30*(2), 248-256.

Schoenfeld, B. J. (2010). Squatting kinematics and kinetics and their application to exercise performance. The Journal of Strength & Conditioning Research, 24(12), 3497-3506.

SECTION D: Subject Population

Section Notes…

- D1. If this study involves analysis of de-identified data only (i.e., no human subject interaction), IRB submission/review may not be necessary. **Please review the UWM IRB Determination Form for more details.**

D1. Identify any population(s) that you will be specifically targeting for the study. Check all that apply: (Place an "X" in the column next to the name of the special population.)

	Existing Dataset(s)		Institutionalized/ Nursing home residents recruited in the nursing home
X	UWM Students of PI or study staff		Diagnosable Psychological Disorder/Psychiatrically impaired
X	UWM Students (but not of PI or study staff)		Decisionally/Cognitively Impaired

X	Non-UWM students to be recruited in their educational setting, i.e. in class or at school		Economically/Educationally Disadvantaged
	UWM Staff or Faculty		Prisoners
	Pregnant Women/Neonates		International Subjects (residing outside of the US)
	Minors under 18 and ARE NOT wards of the State		Non-English Speaking
	Minors under 18 and ARE wards of the State		Terminally ill
	Other (Please identify):		

D2. Describe the subject group and enter the total number to be enrolled for each group. For example: teachers-50, students-200, parents-25, student control-30, student experimental-30, medical charts-500, dataset of 1500, etc. Then enter the total number of subjects below. Be sure to account for expected drop outs. For example, if you need 100 subjects to complete the entire study, but you expect 5 people will enroll but "drop out" of the study, please enter 105 (not 100).

Describe subject group:	**Number:**
Recreationally- active women	15
TOTAL # OF SUBJECTS:	15
TOTAL # OF SUBJECTS	

(If UWM is a collaborating site for a multi institutional project):	

D3. For each subject group, list any major inclusion and exclusion criteria (e.g., age, gender, health status/condition, ethnicity, location, English speaking, etc.) and state the justification for the inclusion and exclusion criteria:

1. **Inclusion Criteria**
   a. Female sex (self-identified)
   b. 18-35 years old
   c. Recreationally active (moderate exercise at least 3 days per week)
   d. Currently using barbell back squat in current fitness program
   e. One year of experience in using the barbell back squat
   f. Currently not under any physical training restrictions
2. **Exclusion Criteria**
   a. Currently experiencing a musculoskeletal or neurological condition affecting the lower extremity
   b. Previous lower extremity surgery in past 12 months
   c. Previous lower extremity injury in past 6 months
   d. One or more deficits in the barbell back squat screening
   e. Currently experiencing pain during squatting
   f. Pregnancy

SECTION E: Study Activities: Recruitment, Informed Consent, and Data Collection

Section Notes…

- Reminder, all recruitment materials, consent forms, data collection instruments, etc. should be attached for IRB review.
- The IRB welcomes the use of flowcharts and tables in the consent form for complex/ multiple study activities.

In the table below, chronologically describe all study activities where human subjects are involved.

- In **column A**, give the activity a short name. Please note that Recruitment, Screening, and consenting will be activities for almost all studies. Other activities may include: Obtaining Dataset, Records Review, Interview, Online Survey, Lab Visit 1, 4 Week Follow-Up, Debriefing, etc.

- In **<u>column B</u>**, describe who will be conducting the study activity and his/her training and/or qualifications to complete the activity. You may use a title (i.e. Research Assistant) rather than a specific name, but training/qualifications must still be described.
- In **<u>column C</u>**, describe in greater detail the activities (recruitment, screening, consent, surveys, audiotaped interviews, tasks, etc.) research participants will be engaged in. Address **where**, **how long**, and **when** each activity takes place.
- In **<u>column D</u>,** describe any possible risks (e.g., physical, psychological, social, economic, legal, etc.) the subject may ***reasonably*** encounter. Describe the **safeguards** that will be put into place to minimize possible risks (e.g., interviews are in a private location, data is anonymous, assigning pseudonyms, where data is stored, coded data, etc.) and what happens if the participant gets hurt or upset (e.g., referred to Norris Health Center, PI will stop the interview and assess, given referral, etc.).

A. Activity Name:	**B. Person(s) Conducting Activity**	**C. Activity Description (Please describe any forms used):**	**D. Activity Risks and Safeguards:**
Recruitment	Lucy Koshewa (LK): UWM MS Kinesiology student, CPR/First aid certified. Jennifer Earl Boehm, PhD, ATC (JEB). Licensed athletic trainer, CPR/First aid certified. 15 years experience	Recruitment will occur on the University of Wisconsin-Milwaukee campus and in the community. Flyers (Appendix A) including the study title, purpose, inclusion/exclusion criteria, study activities, and researcher contact information will be posted around UWM Campus. Community flyers will be posted with the local recreational/ fitness associations such as BrewCity CrossFit and Milwaukee Barbell Club that are near campus. The study personnel will also post	No risk

	conducting human subjects research	the study flyer on social media groups (i.e. Facebook, Twitter, etc.)	
Screening	LK	**Initial screening** will be done via phone where the investigator will ask potential participant several questions (Appendix B: Phone Screening Questionnaire). The questions will ask about the potential participants current fitness routine, medial history, and health conditions related to the inclusion/exclusion criteria. All questions will help determine if the participant meets the inclusion criteria of the current study. If they qualify during initial screening, they will be scheduled for final screening/initial testing in the UWM Musculoskeletal Injury Biomechanics Laboratory (MIBL). **Final screening** The participant will be asked to warm-up for activity by completing 2 rounds of 20 jumping jacks, 10 body weight squats, and 5 lunges per leg. Then the participant will be given a weighted barbell bar (44 lbs) to	No risk

		place across their shoulders in standard high bar back squat position. The participants experience with performing this type of exercise ensures they will perform it safely. Participants will complete 3-5 squat repetitions while the investigator rates their movement quality on a standardized checklist. (Appendix C) This will ensure that the participant has competent squat form and can complete the back squat safely during testing.	
Obtaining Consent	LK	Study personnel will provide a verbal and written explanation (Appendix D) of what the study is about, what the participant will be doing, and any risks or benefits that the participant might experience. The patient will be told that they will be able to withdraw from the study at any time and they will not be punished for not completing the study. After questions have been answered, written consent will be asked.	No Risk

		Participants will be given a of the consent form for their records.	
Background Questionnaire	LK	A background questionnaire (Appendix E) will be given to the participant after the consent form and knowledge of the study is signed. The questions will consist of training history, training habits, and current fitness routine. The data is being collected to gain further knowledge about the participant and their training style while utilizing the barbell back squat. The information obtained will be used during the data analysis as a secondary analysis to provide further insight into why squat mechanics may differ between conditions.	No Risk
Squatting Biomechanics	LK	Participants will change into laboratory provided shoes and clean, tight-fitting shorts and t-shirt or tank top for each session to maintain clothing consistency.	Minimal risk. May experience minor skin irritation from the medical-grade adhesive used in the marker adhesives. May experience mild muscle soreness with squatting task, similar to physical activity

		Squatting biomechanical data will be collected using a high-resolution video camera system, the Motion Analysis Eagle System. Single reflective markers will be placed over several trunk and lower extremity landmarks on both sides of the body using adhesive tape and elastic wrap. Plastic clusters of four markers will be placed over the lateral aspect of the thigh and shin attached to a Velcro strap wrapped around the thigh and shin. A spray tape adhesive, commonly used for athletic training purposes, may also be used to hold some of the clusters in place. An additional cluster will be between the scapulas on the back via an elastic strap harness around the participant's torso. The last cluster will be attached to the heel of the participant's shoe. These markers and clusters will help to establish joint centers and anatomical axes during the standing and moving trials. These	Minimal risk of injury due to physical activity

markers are non-invasive and are used to track the motion of the participant's body via high-speed cameras. Only the image of the reflective markers is visible by the cameras. A standing calibration trial will be recorded for three seconds while the participant stands in the center of the view of the cameras.

Squatting Conditions.

All squats will be performed with a metronome and a cadence of 3 seconds down, 2 seconds up. Instructions for each condition are as follows:

1. Natural Squat "Perform a squat with your natural movement. Keeping your heels on the floor, squat downwards until your thighs become parallel with the ground. Then return to standing"
2. Unrestricted Squat "Perform a squat with your knees as far in front of your toes as you can without pain

		and without their heels coming off the floor. Squat downwards until your thighs become parallel with the ground. Then return to standing" 3. Restricted Squat "Perform a squat with your knees touching the board in front of you. Keeping your heels on the floor, squat downwards until your thighs become parallel with the ground. Then return to standing" Participants will be allowed practice trials of each condition until they are able to perform the task competently. Dynamic trials will then be recorded (Appendix F) while the participant completes all three squatting conditions, one set of 5 reps per condition, with 1 minute of rest between conditions.	

E2. Explain how the data will be analyzed or studied (i.e. quantitatively or qualitatively) and how the data will be reported (i.e. aggregated, anonymously, pseudonyms for participants, etc.):

Data will be analyzed quantitatively.

Ground reaction force data from the force plates will be utilized and converted to joint moments of the hip, knee, and ankle via inverse dynamics. These joint moments will be used in the analysis of each squat condition and will be compared between conditions within the participant. The joint moments of each squatting condition will also be summed into the net support moment for the movement. The net moment will then be compared across conditions within the participant.

Joint angles will be calculated from the sagittal plane biomechanical data. Joint angles of the hip, knee, and ankle will be calculated using a joint coordinate system approach. Joint angles of the hip and knee will be determined by the relative position of the pelvis, thigh, and lower leg segments. Trunk angle will be determined relative to the pelvis.

A 2-D video of all successful trials of the three squat conditions will be taken. This video will be used to descriptively explain trends that may arise within the data after processing.

Statistical analysis of the study will be a one-way repeated measures ANOVA.

The independent variables will be the three squat conditions; natural squatting, unrestricted squatting (knees over toes), and restricted squatting (knees behind toes). The dependent variables will be sagittal joint angles of the hip, knee, and ankle, joint moments of the hip, knee, and ankle, and net support moment. All dependent variables will be compared within the participant. The significance level will be set at $\alpha < 0.05$.

Data will be aggregated when reported and will not contain any identifiable information.

SECTION F: Data Security and Confidentiality

Section Notes…

- Please read the IRB Guidance Document on Data Confidentiality for more details and recommendations about data security and confidentiality.

F1. Explain how study data/responses will be stored in relation to any identifying information (name, birthdate, address, IP address, etc.)? Check all that apply.

[_X_] Identifiable - Identifiers are collected and stored with study data.
[__] Coded - Identifiers are collected and stored separately from study data, but a key exists to link data to identifiable information.
[_X_] De-identified - Identifiers are collected and stored separately from study data without the possibility of linking to data.
[__] Anonymous - No identifying information is collected.

If more than one method is used, explain which method is used for which data.

IDENTIFIABLE:
The informed consent document will contain the participant's name. The participant key will contain the participant's name and the ID code used to save participant data. These items will be stored in a locked cabinet separate from all data collection items in order to provide an indirect link between identifiable information and coded data. At the conclusion of the study, only coded information will be retained. The participant key will be destroyed 2 years following conclusion of the study. **Videos do not contain any sensitive information and will be saved on a University-owned, encrypted computer or server with password-protected access.**

CODED:
All data on the "data collection sheet" will be coded with an ID code (letter and number) that is uniquely associate with each participant. The ID code will not contain any partial identifiers and no identifiers will be stored with the data. The only way to identify participants would be use of the participant key (Appendix G), which will be stored in a locked cabinet within a locked room, separate from all data. Videos will only be saved by participant ID and will not contain any identifiable information.

F2. Will any recordings (audio/video/photos) be done as part of the study?

[X_] Yes
[__] No [SKIP THIS SECTION]

If yes, explain what activities will be recorded and what recording method(s) will be used. Will the recordings be used in publications or presentations?

Standard video cameras will be used to record the side view of the participant's squat trials. This video will be used to descriptively explain trends that may arise within the data. The videos will be used during data processing and will be saved on a University-owned, encrypted computer or server with password-protected access.

F3. In the table below, describe the data storage and security measures in place to prevent a breach of confidentiality.

- In **column A**, clarify the type of data. Examples may include screening data, paper questionnaires, online survey responses, EMG data, audio recordings, interview transcripts, subject contact information, key linking Study ID to subject identifiers, etc.
- In **column B**, describe the storage location. Examples may include an office in Enderis 750, file cabinet in ENG 270, a laptop computer, desktop computer in GAR 420, Qualtrics servers, etc.
- In **column C**, describe the security measures in place for each storage location to protect against a breach of confidentiality. Examples may include a locked office, encrypted devices, coded data, non-networked computer with password protection, etc.
- In **column D**, clarify who will have access to the data.
- In **column E**, explain when or if data will be discarded.

A. Type of Data	B. Storage Location	C. Security Measures	D. Who will have access	E. Estimated date of disposal
Informed Consent	END 132	Stored in a locked room (END 132) separate from collected data.	LK, JE	**03/01/2028**
Participant Key	END 132	Stored in a locked room (END 132) separate from collected data.	LK, JE	**03/01/2019**
Screening & Injury History Forms	END 132	Stored in a locked room (END 132) separate from any the participant key and informed consent containing identifiable information.	LK, JE	**03/01/2028**
3-D Video Analysis	END 132	**Password-protected computer, encrypted devices & files**	LK, JE	**03/01/2028**
2-D Video Analysis	END 132	**Password-protected computer, encrypted devices & files**	LK, JE	
Paper Questionnaires	END 132	Stored in a locked room (END 132) separate from any the participant key and informed consent containing identifiable information.	LK, JE	**03/01/2018**

F4. Will data be retained for uses beyond this study? If so, please explain and notify participants in the consent form.

Study data and consent forms will be retained for 10 years following the completion of the study for the purpose of having comparisons for future studies.

SECTION G: Benefits and Risk/Benefit Analysis

Section Notes…

- Do not include Incentives/ Compensations in this section.

G1. Describe any benefits to the individual participants. If there are no anticipated benefits to the subject directly, state so. Describe potential benefits to society (i.e., further knowledge to the area of study) or a specific group of individuals (i.e., teachers, foster children).

There are no direct benefits to participants of this study. The information obtained from this study will help to further examine the biomechanical differences between restricted, un-restricted, and natural barbell back squats and how these differences may help reduce known injury risk factors.

G2. Risks to research participants should be justified by the anticipated benefits to the participants or society. Provide your assessment of how the anticipated risks to participants and steps taken to minimize these risks (as described in Section E), balance against anticipated benefits to the individual or to society.

Minimal risk is anticipated during participation in this study. The most common risk is muscle discomfort or soreness, similar to what would be experienced with moderate exercise. This risk will be reduced by allowing participants to warm up prior to movement testing. Additionally, both the PI and Co-PI are trained in first and CPR/AED use should an injury occur. If an injury occurs, the participant will be referred to the Norris Student Health Center, or to emergency care, as needed.

Psychological risks to participants are no more than those experienced in everyday life. Participants may discontinue their participation at any time.

SECTION H: Subject Incentives/ Compensations

Section Notes…

- H2 & H3. The IRB recognizes the potential for undue influence and coercion when extra credit is offered. The UWM IRB, as also recommended by OHRP and APA Code of Ethics, agrees when extra credit is offered or required, prospective subjects must be given the choice of an equitable, non-research alternative. The extra credit value and the non-research alternative must be described in the recruitment material and the consent form.
- H4. If you intend to submit to Accounts Payable for reimbursement purposes make sure you understand the UWM "Payments to Research Subjects" Procedure 2.4.6 and what each level of payment confidentiality means **(click here for additional information).**

H1. Does this study involve incentives or compensation to the subjects? For example cash, class extra credit, gift cards, or items.

[__] **Yes**
[_X_] **No [SKIP THIS SECTION]**

H2. Explain what (a) the item is, (b) the amount or approximate value of the item, and (c) when it will be given. For extra credit, state the number of credit hours and/or points. (e.g., $5 after completing each survey, subject will receive [item] even if they do not complete the procedure, extra credit will be award at the end of the semester)**:**

H3. If extra credit is offered as compensation/incentive, please describe the specific alternative activity which will be offered. The alternative activity should be similar in the amount of time involved to complete and worth the same number of extra credit points/hours. Other research studies can be offered as additional alternatives, but **a non-research alternative is required**.

H4. If cash or gift cards, select the appropriate confidentiality level for payments (see section notes):

[__] **Level 1** indicates that confidentiality of the subjects is not a serious issue, e.g., providing a social security number or other identifying information for payment would not pose a serious risk to subjects.

- For payments over $50, choosing Level 1 requires the researcher to collect and maintain a record of the following: The payee's name, address, and social security number, the amount paid, and signature indicating receipt of payment (for cash or gift cards).
- When Level 1 is selected, a formal notice is not issued by the IRB and the Account Payable assumes Level 1.
- Level 1 payment information will be retained in the extramural account folder at UWM/Research Services and attached to the voucher in Accounts Payable. These are public documents, potentially open to public review.

[__] **Level 2** indicates that confidentiality is an issue, but is not paramount to the study, e.g., the participant will be involved in a study researching sensitive, yet not illegal issues.

- Choosing a Level 2 requires the researcher to maintain a record of the following: The payee's name, address, and social security number, the amount paid, and signature indicating receipt of payment (for cash or gift cards).
- When Level 2 is selected, a formal notice will be issued by the IRB.
- Level 2 payment information, including the names, are attached to the PIR and become part of the voucher in Accounts Payable. The records retained by Accounts Payable are not considered public record.

[__] **Level 3** indicates that confidentiality of the subjects must be guaranteed. In this category, identifying information such as a social security number would put a subject at increased risk.

- Choosing a Level 3 requires the researcher to maintain a record of the following: research subject's name and corresponding coded identification. This will be the only record of payee names, and it will stay in the control of the PI.
- Payments are made to the research subjects by either personal check or cash. Gift cards are considered cash.
- If a cash payment is made, the PI must obtain signed receipts.
- If the total payment to an individual subject is over $600 per calendar year, Level 3 cannot be selected.

If Confidentiality Level 2 or 3 is selected, please provide justification.

SECTION I: Deception/ Incomplete Disclosure (INSERT “NA” IF NOT APPLICABLE)

Section Notes…

- If you cannot adequately state the true purpose of the study to the subject in the informed consent, deception/ incomplete disclosure is involved.

I1. Describe (a) what information will be withheld from the subject (b) why such deception/ incomplete disclosure is necessary, and (c) when the subjects will be debriefed about the deception/ incomplete disclosure.

N/A

IMPORTANT – Make sure all sections are complete and attach this document to your IRBManager web submission in the Attachment Page (Y1).

Appendix F:
Raw Data

	AA-NS	AA-KOT	AA-RS	KA-NS	KA-KOT	KA-RS	HA-NS	HA-KOT	HA-RS	TA-NS	TA-KOT	TA-RS
001	25.28721	37.73753	26.32596	-83.5315	-98.7305	-82.6857	77.29806	72.09497	76.66239	-43.822	-36.470	-47.19
002	45.64692	46.12323	31.95086	-121.617	-128.281	-104.306	95.38645	94.64708	101.5467	-41.087	-37.759	-51.90
003	30.79943	38.54763	24.8282	-118.79	-110.952	-99.1158	100.0644	85.07243	94.21277	-46.201	-38.995	-53.898
004	32.4649	34.61501	27.39247	-102.757	-97.912	-93.71	91.0114	87.34773	95.29659	-43.889	-42.718	-49.557
005	32.32738	35.9662	26.93696	-112.023	-116.842	-95.3896	107.639	107.1426	106.0805	-33.282	-33.539	-41.215
006	33.29146	44.94488	23.4768	-111.065	-131.404	-101.459	85.09632	87.96881	92.40946	-36.497	-34.346	-50.439
007	39.97121	43.05685	31.28913	-125.891	-120.653	-104.569	68.33998	72.99587	69.39146	-28.641	-33.034	-37.164
008	32.82302	36.26364	22.5521	-90.538	-93.0113	-69.4574	74.74963	68.43228	69.41452	-36.939	-34.524	-38.877
009	23.36118	27.48594	19.92861	-120.713	-114.456	-116.261	103.3155	92.64245	103.7693	-44.021	-38.076	-43.390
011	32.85721	40.25508	26.71573	-120.684	-117.104	-99.3685	97.76268	84.98856	90.13699	-42.528	-39.394	-48.805
012	37.05751	39.17313	25.23151	-105.642	-104.898	-79.5142	84.78246	83.23451	82.14451	-38.570	-36.892	-42.555
013	33.2188	35.01174	23.98089	-102.986	-110.074	-91.8133	82.2869	84.14437	86.00144	-37.803	-39.222	-48.588
014	34.76233	31.25731	27.57235	-116.115	-111.233	-110.249	81.57779	84.2239	95.71801	-25.851	-34.547	-41.871
015	32.32738	35.9662	26.93696	-112.023	-116.842	-95.3896	107.639	107.1426	106.0805	-33.282	-33.539	-41.215
016	32.53407	38.28355	23.51232	-110.016	-119.733	-101.335	109.0634	105.5948	111.5614	-36.248	-30.926	-51.517
017	31.44372	39.05664	22.57769	-115.462	-106.529	-98.5318	86.65015	82.48392	90.53639	-32.866	-31.511	-42.705

DOES RESTRICTING ANTERIOR OF THE KNEES DURING A BARBELL BACK SQUAT ALTER LOWER EXTREMITY BIOMECHANICS?

	AM-NS	AM-KOT	AM-RS	KM-NS	KM-KOT	KM-RS	HM-NS	HM-KOT	HM-RS
001	-0.20664	-0.307272	-0.18836	1.32736633	1.438291	1.14666067	-0.833342	-0.6443247	-0.945228
002	-0.64827	-0.705585	-0.22120	2.440673	2.464983	2.13721367	-0.760387	-0.86707	-0.782263
003	-0.16271	-0.273403	-0.21494	1.61131367	1.43650167	1.348811	-1.406125	-1.0574147	-1.2566497
004	-0.38542	-0.393147	-0.28979	1.496287	1.517026	1.53554533	-0.761605	-0.5480017	-0.7419023
005	-0.27882	-0.286572	-0.19475	1.683058	1.355864	1.073765	-1.7817	-1.3881603	-1.6486263
006	-0.21734	-0.378486	-0.23474	1.26005333	1.258412	1.00562133	-1.077899	-0.6416617	-1.113129
007	-0.64571	-0.489824	-0.37790	2.031504	1.52487067	1.48967533	-0.826026	-0.3415963	-0.5670743
008	-0.16659	-0.259561	-0.38712	0.94774867	0.86668767	0.779704	-0.553818	-0.4845637	-0.5741877
009	-0.15692	-0.248919	-0.12996	1.622076	1.675516	1.534438	-1.151815	-0.6478857	-0.9433807
011	-0.12565	-0.19659	-0.18135	2.009699	1.95411	1.77199033	-0.396117	-0.28303	-0.5311853
012	-0.38741	-0.492142	-0.21684	1.611796	1.6087513	1.29589633	-1.089693	-1.058133	-1.318067
013	-0.16987	-0.213268	-0.23844	1.28426	1.30224267	1.078422	-0.846465	-0.867243	-1.224506
014	-0.46593	-0.376845	-0.31678	2.53866667	1.71766667	1.603687	-1.304018	-0.925804	-0.9988087
015	-0.27882	-0.286572	-0.19475	1.683058	1.355864	1.073765	-1.7817	-1.3881603	-1.6486263
016	-0.14472	-0.186881	-0.30232	1.82320366	1.809634	1.53463967	-0.370681	-0.3921847	-0.6179107
017	-0.26739	-0.543262	-0.12006	1.10601867	0.81106733	0.875198	-1.34057	-1.0537377	-1.531671

DOES RESTRICTING ANTERIOR OF THE KNEES DURING A BARBELL BACK SQUAT ALTER LOWER EXTREMITY BIOMECHANICS?

	SM-NS	**SM-KOT**	**SM-RS**	**%A-NS**	**%K- NS**	**%H- NS**	**%A-KOT**	**%K- KOT**	**%H-KOT**
001	2.36735633	2.38988767	2.280257	0.08729034	0.56069562	0.35201404	0.12857173	0.60182368	0.26960458
002	3.849332	4.0376385	3.14068433	0.16841156	0.63405105	0.19753739	0.17475202	0.61050116	0.21474681
003	3.180153	2.76732	2.82040367	0.05116557	0.50667803	0.4421564	0.09879727	0.51909489	0.38210784
004	2.64331967	2.458175	2.56724	0.14581198	0.56606358	0.28812444	0.15993464	0.61713507	0.22293029
005	3.743583	3.03059667	2.91714967	0.07448078	0.4495848	0.47593442	0.09455971	0.44739177	0.45804853
006	2.55529433	2.27856	2.35349367	0.08505556	0.49311475	0.42182968	0.16610769	0.5522839	0.28160841
007	3.503246	2.35629133	2.434659	0.18431915	0.57989191	0.23578894	0.20787936	0.64714861	0.14497203
008	1.66816	1.61081267	1.74101933	0.09986652	0.56814015	0.33199333	0.16113688	0.53804374	0.30081938
009	2.930815	2.57232133	2.607788	0.05354267	0.55345561	0.39300172	0.0967685	0.65136341	0.25186809
011	2.531474	2.43373	2.484527	0.04963801	0.79388491	0.15647708	0.08077724	0.80292802	0.11629474
012	3.088905	3.15902633	2.83080333	0.12542168	0.52180174	0.35277658	0.15578914	0.50925544	0.33495542
013	2.30059967	2.38275367	2.54136833	0.0738393	0.55822837	0.36793233	0.08950485	0.54652845	0.3639667
014	4.308617	3.020316	2.91928233	0.10813965	0.58920685	0.3026535	0.12477017	0.56870429	0.30652554
015	3.743583	3.03059667	2.91714967	0.07448078	0.4495848	0.47593442	0.09455971	0.44739177	0.45804853
016	2.380766	2.59400333	2.45487133	0.07849616	0.76580549	0.15569835	0.07204347	0.69762208	0.15118896
017	2.71398167	2.408067	2.52693433	0.09852425	0.40752621	0.49394954	0.22560087	0.33681261	0.43758652

	%A- RS	%K- RS	%H- RS
001	0.08260838	0.50286466	0.41452696
002	0.07043295	0.68049299	0.24907406
003	0.07621001	0.47823332	0.44555667
004	0.11288089	0.59813081	0.2889883
005	0.06676323	0.36808704	0.56514973
006	0.0997425	0.42728874	0.47296877
007	0.15522064	0.611862	0.23291735
008	0.2223569	0.44784339	0.32979971
009	0.04983892	0.58840596	0.36175512
011	0.0729923	0.71321033	0.21379737
012	0.07660016	0.45778395	0.46561589
013	0.0938236	0.42434699	0.48182941
014	0.10851525	0.54934289	0.34214185
015	0.06676323	0.36808704	0.56514973
016	0.12315146	0.62514057	0.25170796
017	0.04751423	0.34634774	0.60613803

Appendix G:
Participant Demographics

Participant Number	Age (yrs)	Height (cm)	Weight (kg)
001	22	183	82.8
002	24	165	48.1
003	28	173.4	73.9
004	26	166.1	63.3
005	27	171.2	57.8
006	22	171	59.3
007	26	155	70
008	21	153	61
009	32	168.4	69
011	33	174.3	55.7
012	19	165	61.3
013	20	173	71.2
014	25	176.1	62.7
015	26	181	58.1
016	30	171.8	58.8
017	29	179.2	68.1

Appendix H:
Questionnaire Answers

Participant Number	Q #1	Q# 2	Q# 3	Q# 4	Q# 5	Q# 6	Q# 7	*Q# 8	Q# 9	Q# 10	**Training Site
001	D	C	A,B	D	C	A,B	C	1	A	4	3
002	E	E	A,B,E,F	E	A	A,B,C,D	E	2	A	4	3
003	C	C	A,B,C	E	B	A,B,C	E	2	A	5	2
004	E	B	A,B,C,D	D	C	A,B,C	E	2	A	5	1
005	E	C	A,B,F	E	C	A,B	C	1	C	4	2
006	C	B	A,D	B	B	A	A	1	A	5	3
007	E	E	A,C	E	D	A,B,C	F	2	C	5	1
008	C	C	A,B,D,E	C	B	A,B,C	C	2	C	2	3
009	E	D	A,B,F	E	A	A,B,C	E	2	C	5	2
011	E	C	A,H	E	D	A,B,C	C	2	A	5	2
012	C	E	A,F,H	B	B	A,B	C	1	C	4	3
013	D	D	A,F	C	B	A,B,C	E	2	C	4	1
014	E	C	A,B,C	E	B	A,B,C	E	1	A	5	1
015	E	C	A,B,C	B	C	A,B,C	D	2	C	5	1
016	D	E	B,C	B	C	A,B,D	C	1	C	5	1
017	C	C	A,B,C,D,E	B	A	A,B	C	1	A	5	1

**Question 8- 1 for yes, 2 for no or unsure, ** Training Site 1= BrewCity CrossFit, 2= Wisconsin Athletic Club, 3= UWM*