Valgus Knee Displacement while Performing a Back Squat at Decreased Velocities

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ABSTRACT

Introduction: The back squat has been related to injuries of the anterior cruciate ligament, medial collateral ligament, and the menisci. This study investigated the relationship between back squat velocity and medial knee displacement (MKD), a movement that could potentially result in knee injury. It was hypothesized that performing back squats at slower velocities would result in less MKD and lower activation of the medial gastrocnemius (MG) and adductor longus (AL) muscles. **Methods**: A total of 10 men between the ages of 20 and 40 participated in the study. Participants performed an estimated 1-repetition maximum (1-RM) protocol and weights of 55-65-75-85% 1-RM were calculated as well as at a 35% velocity reduction. Participants performed eight trials consisting of two back squats at each 1-RM percentage and at the two different velocities. Full-body kinematics and surface electromyography (EMG) were measured bilaterally. Knee displacement was defined as the ratio between the mediolateral distance of the knee lateral condyles and malleoli, followed by a subtraction of the inter-malleoli distance. Speed and weight variables were examined to determine if there would be a difference in medial knee displacement and muscle activation. **Results:** Knee displacement was larger during normal squat speed ($p < 0.001$) and decreased with weight ($p < 0.003$). In slower squats at higher weights, there was increased activation of the medial gastrocnemius ($p < 0.037$) and adductor longus ($p < 0.007$) muscles. **Conclusion:** These results suggest inward knee movements and increased muscle activity of the MG and AL occur at higher weights in slower squat speeds.

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INTRODUCTION

A squat begins with the individual in an upright position with the knees and hips fully extended. The movement is broken down into two parts; the descent and the ascent. During the descent the individual squats down in a continuous motion until a desired squat depth is obtained. The ascent is a continuous motion back to the upright position (Escamilla, 2001). The squat is often thought of as a bipedal exercise movement, however, it is also essential to activities of daily living. Tasks such as sitting, picking objects off the ground, ascending or descending stairs (unipedal), and getting up from the ground all feature a portion or a complete squatting movement (Lorenzetti et al., 2018 and Myer et al., 2014). The squat in an exercise setting can be performed four ways: an unweighted squat, back squat, front squat, and overhead squat. In this study, the back squat will be examined. In the back squat, the barbell is placed on the back around the level of the acromion. The back squat movement is an important exercise for building strength in the lower body. There are many different techniques to the back squat which vary in terms of stance width, foot angle, hip depth, barbell placement, and load. All of these variations have been shown to have different forces placed on hip and knee joints, as well as different muscle activations (Schoenfeld, 2010, and Escamilla, 2001).

Literature Review

Muscle Activity during the Back Squat

The predominant muscles used in a squat exercise are those of the lower body. The back squat requires the use of the hip extensors and flexors, knee extensors, hip adductors and abductors, and the ankle extensors (Foley et al., 2017, Dionisio et al., 2008, Macrum et al., 2012, and Padua et al., 2012). These muscles being gluteus maximus, gluteus medius, vastus lateralis, vastus medialis, rectus femoris, biceps femoris, semitendinosus, medial and lateral attachment of the gastrocnemius, and soleus. However, to perform the movement safely, many assistive muscles also contribute to the task. For example, muscles of the torso contract isometrically in order to keep it rigid. Altogether, there are approximately 200 muscles activated during the back squat (Solomonow et al., 1987).

Different foot placements can be used when performing the back squat. In a wide stance back squat the feet are generally placed shoulder width apart or wider. During the wide stance squat, there is a greater flexion at the hip and less flexion at the knees. This foot placement produces a greater moment arm at the hip, which requires more action of the hip flexors and extensors, such as the gluteus maximus and hamstring muscles. The final foot placement is more of a natural stance where the feet are placed approximately hip-width apart. During this foot placement, there is less anterior lean of the torso at the hip and greater flexion at the knee. This produces a greater moment arm at the knee thus requiring more muscle action about the knee flexors and plantar flexors: the quadriceps and gastrocnemius respectively.

As can be seen by the number of lower body muscles being recruited, it is easy to see why the back squat is a common exercise and rehabilitation movement (Schoenfeld, 2010). In addition, research supports that performing a closed-chain exercise movement, like the back squat, may be more beneficial than performing an open-chain exercise movement for rehabilitation of the knee joint as there is more muscle activation (Signorile et al., 1994). Furthermore, Palmitier (1991) and Escamilla et al., (1998) have demonstrated that the leg extension exercise increases forces on the anterior cruciate ligament (ACL).

Risk of Injury during a Back Squat

Because the back squat is a multi-joint movement and involves some of the major joints of the body, one can see why there would be concerns regarding injuries. When performed correctly, the back squat can be safe, and injuries uncommon (Schoenfeld, 2010). However, when not executed properly, a back squat can cause injuries to muscle and ligamentous sprains, ruptured intervertebral discs, spondylolysis, and spondylolisthesis (Vakos et al., 1994).

During this experiment, medial knee displacement (MKD) will be examined. MKD is observed in the frontal plane when the knees move towards the midline of the body. It is important to recognize that MKD and knee valgus angle are similar in nature, but not always the same. MKD is the linear movement of the knee joint in the frontal plane, while knee valgus angle concerns the frontal angle between the thigh and shank segments. Therefore, if the knees are outside of the ankles and moving in the direction of the midline without going inside the knees, then it is not a valgus knee angle.

Excessive MKD has been shown to cause a series of problems at the knee joint. It has been linked to ACL injuries (Hewett et al., 2005), meniscus damage (Elias et al., 2004), knee osteoarthritis (Mizuno et al., 2001), patellar femoral syndrome (Holden et al., 2015) and medial collateral ligament (MCL) sprain (Hull, 1996). Another factor to consider is the depth at which the squat is performed. Many individuals perform a back squat by dropping well below 90 degrees of knee flexion, which has been shown to place more pressure on the menisci (Shybut et al., 2015).

Interventions to Prevent MKD

Foley et al. (2017) state that many exercise trainers employ a method that may help alleviate MKD by using a banded loop around the distal thigh as a tactile cue to push the knees laterally. During this experiment, they tested the effects of a band loop on the kinematics and muscle activity of the lower extremity (gluteus maximus and medius, vastus lateralis, and biceps femoris) during a back squat. The results indicated that there was increased muscle activation; however, it did not change MKD after a one-time exposure. Contrary to this study, Collins et al. (2017) showed that a band loop increased medial knee collapse during an overhead barbell squat movement. It should be noted that these studies tested two different squat movements, back squat and overhead squat respectively, other than the angle of the upper body and the arms being overhead, the lower body musculature is the same, or at the very least very similar.

In Padua et al. (2012), the effects of heel lifts during a squat were examined. Placing a heel lift caused a decrease of the ankle dorsiflexion angle. Due to having less ankle dorsiflexion, this produced more activity in the tibialis anterior and gastrocnemius muscles, which resulted in greater medial knee displacement. This could be a clue that the lower leg has greater contribution to excessive MKD than the hip adductors. Marcum et al. (2012) tested this aspect by placing a wedge under the forefoot of participants. As this increased dorsiflexion they too saw in an increase in MKD.

Current Research on MKD

Slater and Hart (2017) examined the effects of different squat positions on muscle activations of the legs. During this experiment, participants were asked to perform three different types of squats 1) a standard squat with knees in line with the toes 2) squats with the knees collapsing medially, and 3) squats while lifting the heels off the floor. This resulted in increased activation of the gastrocnemius and the hip adductor muscles, which they determined may be the result of MKD.

In Bell et al., (2011), muscle activity was measured during MKD. All participants were required to perform the squat in a standardized manner before being placed in separate groups based on their performance. This can be important, as how they were required to perform the squat may have altered the muscle activity. During our own learned and practiced technique, we are going to have a specific movement pattern, thus a sequence of muscle activity that is unique to the individual (Schmidt and Lee, 1999). Therefore, it could be beneficial to let participants use their preferred squat technique in order to collect accurate muscle activity.

Velocity of the Squat

The velocity of the squat has been measured many times to determine its effect on the knee ligaments (Klein, 1967 and Meyers, 1971). Forces on the knee joint can be as high as 8000 N (Schoenfeld, 2010), however, these forces are well within the acceptable range (Escamilla, 2001). Myer et al. (2014), state that the squat movement should be performed at a constant speed throughout the movement.

Whether velocity of the back squat has any effect on excessive MKD is unknown at this point. In the force-velocity relationship of a concentric muscle action, as velocity increases, muscle force decreases and vice versa. The opposite is true during an eccentric muscle action (Sale, 1986). Therefore, there is a possibility that if the squat movement is performed too quickly, it does not allow for optimal muscle force production to prevent excessive MKD.

Objective and Hypothesis

Powerlifting and Olympic weightlifting athletes employ a lifting technique called tempo squats. This entails the athletes to break the squat into multiple phases, such as the descent, bottom of the squat, and ascent. During these phases, they would descend at a specific speed, pause at the bottom for a specific amount of time and ascend, again at a specific speed. The times for each phase can vary, an example of this would be a two second descent, two second pause at the bottom, and finally a one second ascent. Through this researcher's observations, it has been speculated that during these tempo squats individuals' knees were not exhibiting signs of excessive MKD.

Therefore, due to the limited information on velocity and the back squat, it is the purpose of this study to examine if velocity has an effect on MKD. This could help individuals incur fewer potential injuries, as well as aid rehabilitation specialists to educate and properly rehabilitate injured clients. It is possible that during the slowing down of the movement, participants would be better able to control the knees during the back squat.

As stated by Slater and Hart (2017) and Bell (2011) the gastrocnemius and hip adductors seem to be the culprit causing excessive MKD. Due to the gastrocnemius and hip adductors attachment to the medial aspect of the knees, it is plausible to expect this displacement to occur. It is hypothesized that by slowing down the movement, it will result in a greater distance between the knees and will be associated with lower muscle activation of the gastrocnemius and adductor longus muscles.

METHODS

Participants

Ten males between the ages of 20-40 years old (age: 30.8 +/- 6.6 years, weight: 81 +/- 11.9 kg, height: 1.74 +/- 0.06 m) volunteered for this experiment. The inclusion criteria for this experiment required that the back squat be a regular part of the participants exercise routine for a minimum of two years. Females tend to show a higher degree of Q-angle (quadriceps angles), which is the valgus stress acting upon the knee joint. A healthy Q-angle is that of 10 degrees. Men typically range from 10-14 degrees, while females from 15-17 degrees (Hamill, Knutzen, & Derrick, 2015). Therefore, since the effects Q-angle was not a focus of this study, only males were selected. The participants completed a Physical Activity Readiness Questionnaire for Everyone (PAR-Q+) to ensure they were free of any musculoskeletal and neurological injuries. The participants attended one session lasting 2-2.5 hours to complete the experiment. Study volunteers signed a written informed consent prior to participation and were given the opportunity to discuss any question or concerns. The study was reviewed and approved by the University and Prince Edwards Island's Research Ethics Board.

Protocol

Upon arrival of the participants, the Canadian Society for Exercise Physiology (CSEP) estimated 1-RM protocol was completed (Baechle et al., 2008). The steps for the protocol are as follows. 1) For the warm-up, the participants used a stationary bicycle and were instructed to maintain 70-80 rpm for five minutes. 2) The participants selected a starting weight they believed they could lift ten times with no loss of form. 3) Review of the technique was such that squats would be successful if there was no excessive rounding of the back or excessive MKD. It should be noted that at this point, the participants warmed-up the back squat movement with progressively increasing weights until the starting weight was reached. 4) If ten repetitions were completed with ease, more weight was added, and the process repeated until 6-10 repetitions were completed where there is no loss of form, and the participant would not be able to perform another repetition. 5) The process would not take more than three sets (excluding warm up). 6) Once the final set was performed the 1-RM was determined using the formula: 1-RM = Weight lifted / [%1-RM value from Table 1 / 100]. Example: 7 repetitions completed at 50kg. 1-RM = 50 / (83/100) = 60kg.

Table 1. CSEP one-repetition maximum protocol

Reps completed	1	2	3	4	5	6	7	8	9	10
%1RM	100	95	93	90	87	85	83	80	77	75

Once the estimated 1-RM was determined, four percentages of this value were calculated; 55-65-75-85% respectively. The participants then performed one repetition at each percentage. This was used to determine the baseline velocity of each squat to calculate a 35% reduction in velocity. Following this, the skin areas to be fixed with electromyography (EMG) surface electrodes were shaved on the participants, and antiseptic alcohol swabs were used to clean the area. 3D motion capture markers were also be placed on anatomical landmarks. At this point, the eight trials were performed by the participants. The eight trials consisted of performing one repetition at each percentage but at two different velocities. The trials were performed in random order and adequate rest periods were provided to prevent participant fatigue.

Movement Technique

To avoid unnatural squatting movements throughout the study, participants were allowed to perform the task using their preferred technique. Depth of the back squat was not measured, however, during the practice trials, the participants were advised that they were required to squat to a depth that their femur was at least parallel to the ground but could go deeper if they so choose. During the trials, if depth was not maintained the trial would be repeated. To prevent any equipment assisting MKD, the participants were not allowed to wear Olympic style weightlifting shoes, knee wraps/sleeves, or weightlifting belts.

Data Acquisition

For the purpose of this study, the focus of the results was the displacement of the knee, and the muscle activity of the muscles on the right leg only.

Kinematic Data

Full-body 3-dimensional kinematic data were recorded using an optoelectronic motion capture system (Optotrak 3D Investigate, Northern Digital Inc., Waterloo, ON) at 100Hz. There were a total of 15 markers used: a 3-marker rigid body placed on the chest, at the level of the xiphoid, two 3-marker rigid bodies placed on the anterolateral right and left thighs, individual markers placed on the lateral malleoli, the 5th metatarsals and the halluces bilaterally. To provide a full-body representation using rigid bodies, virtual landmarks were used. For the trunk rigid body, the virtual landmarks consisted of the right and left acromioclavicular joints, and the left and right anterior superior iliac spine. For the thigh rigid bodies, the virtual landmarks were the greater trochanters, medial and lateral epicondyles bilaterally. Medial knee displacement was defined as the ratio between the mediolateral distance between the lateral condyles of the knee and malleoli, followed by the subtraction of the inter-malleoli distance. Values above zero in (figure 1) indicate that the distance between the knees is larger than that of the ankles. Kinematic data was filtered offline using a second-order, zero-lag, low-pass Butterworth filter with a cutoff frequency of 7 Hz.

Electromyographic Data

Muscle activity was recorded using an electromyography (EMG) system (Trigno, Delsys Inc., Natick, Mass, USA) at a sampling rate of 2000Hz. Surface electrodes were placed on seven muscle locations bilaterally. These included the medial and lateral heads of the gastrocnemius (MG, LG), gluteus maximus (GM), gluteus medius (GMe), semitendinosus (ST), vastus medialis (VM), and adductor longus (AL). The sensors were placed on the body according to the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) standards (Stegeman, D., Hermans, H., 2007). Peak muscle activity was determined using a moving-average window of 2.5 ms in each activation profile and was represented as a magnitude in millivolts (mV). All EMG data was filtered offline by first removing low frequency noise using a zero-lag, fourth order Butterworth filter with a high-pass cutoff of 30 Hz, followed by a band-stop Butterworth filter to remove 60 Hz electrical interference, and finally rectified and low-pass filtered using a zero-lag, fourth order Butterworth filter with a cutoff of 10 Hz to obtain a smoothed profile.

Statistical Analysis

The variables of interest were: 1) peak knee displacement, and 2) peak EMG muscle activation of the 14 muscles. A two-way repeated measures ANOVA was used to identify statistical differences between squat speeds and weights. Post-hoc statistical analyses were performed using a Tukey statistical test. Statistically significant differences were identified at a p-value of < 0.05.

RESULTS

Knee Displacement

Figure 1 illustrates a representative participant performing a squat trial at 65 percent of their 1-RM at normal speed. This demonstrates the mediolateral displacement of the knees in relation to the ankles throughout the entire movement. We can see that at no point during the movement that the knees travel inside of the ankles. In figure 2, the group averaged relationships of the knees and ankles of all participants are shown. It was determined that the knees were further apart during the normal squat speed ($F_{(1,9)} = 53.035$, $p < 0.001$) and decreased as weight increased ($F_{(3,27)} = 7.453$, $p < 0.003$). Post-hoc testing indicated this difference was statistically significant only during the 55 and 85 percent trials.

Muscle Activity

Hip Extensors

Figures 3a and 3b indicate the muscle activity of the gluteus maximus and semitendinosus, respectively. There was a statistically significant increase in muscle activity of the gluteus maximus with squat weight, however, only when comparing the 55 and 85 percent trials ($F_{(3,27)} = 19.509$, $p < 0.001$). There was no statistically significant difference when comparing between speeds. When examining semitendinosus muscle activity, there was no statistically significant difference when comparing between speeds or weights ($p > 0.05$).

Hip Adductor and Abductor

Figures 4a and 4b illustrate muscle activity of the adductor longus and gluteus medius, respectively. As indicated by an interaction effect, there was increase muscle activity of the adductor longus during slower squats and increase muscle activity as the weights increased ($F_{(3,27)}$ = 5.741, $p < 0.007$). However, there was no statistically significant difference in gluteus medius activity ($p > 0.05$).

Knee Extensor

Figure 5 indicates that there was a statistically significantly greater vastus medialis activity when squatting with higher weights ($F_{(3,27)}$ = 10.521, $p < 0.001$) but did not differ between speeds.

Plantar Flexors

Finally, figures 6a and 6b illustrate muscle activity of the medial gastrocnemius and lateral gastrocnemius, respectively. There was a statistically significant increase in activity of the medial gastrocnemius in the slow squat weight as shown by an interaction effect ($F_{(3,27)}$ = 4.033, $p < 0.037$). Initially, there appeared to be a main effect increase in activity across weights for peak lateral gastrocnemius ($F(_{3.27)}$ = 12.561, $p < 0.001$), however, post-hoc testing did not indicate any statistically difference.

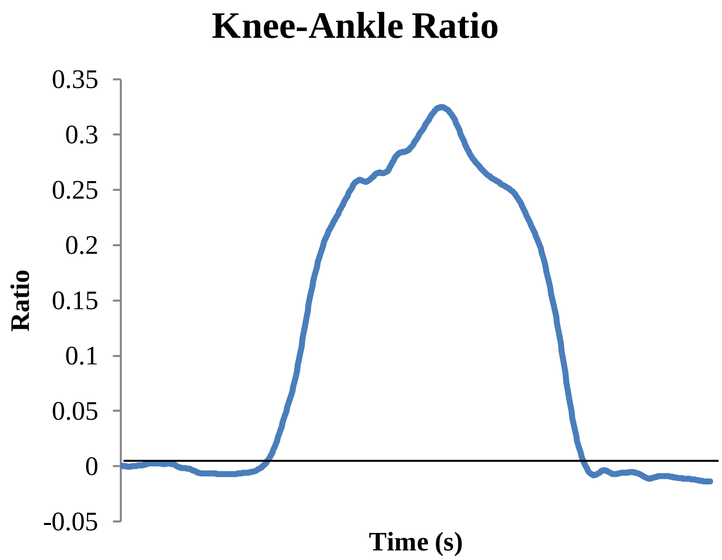

Figure 1. Example of the path of the knee in relation to the ankle.

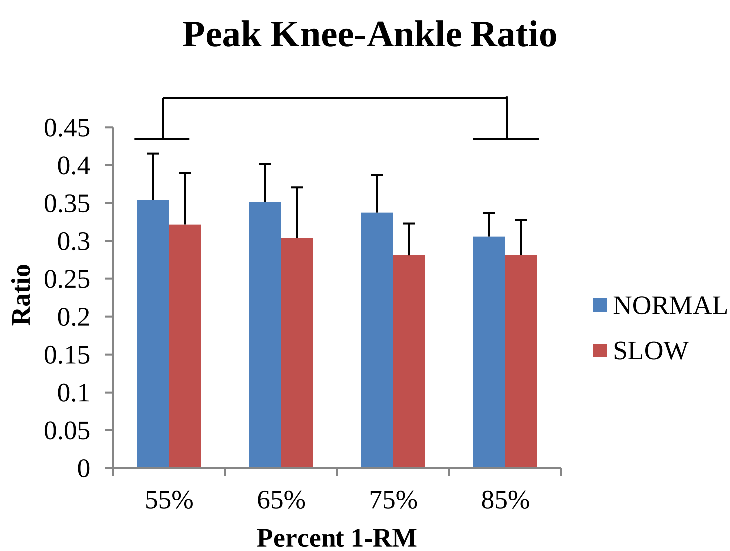

Figure 2. Knee displacement in relation to ankle position.

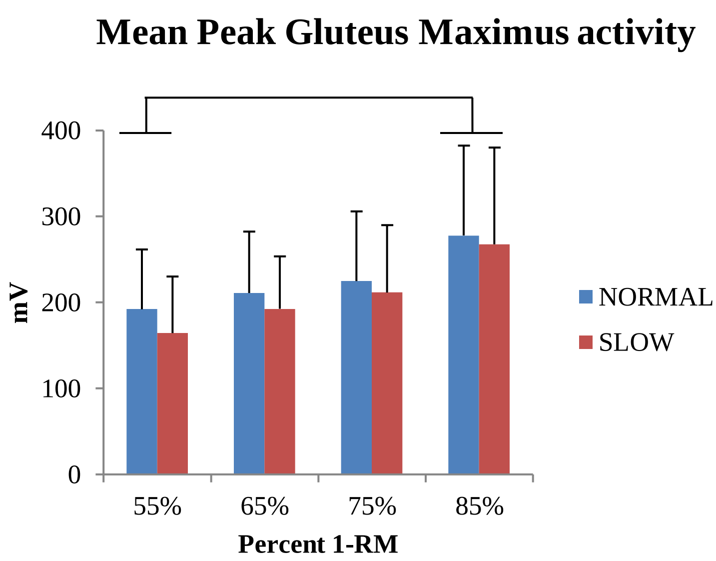

Figure 3a. Mean muscle activity of the gluteus maximus across all trials.

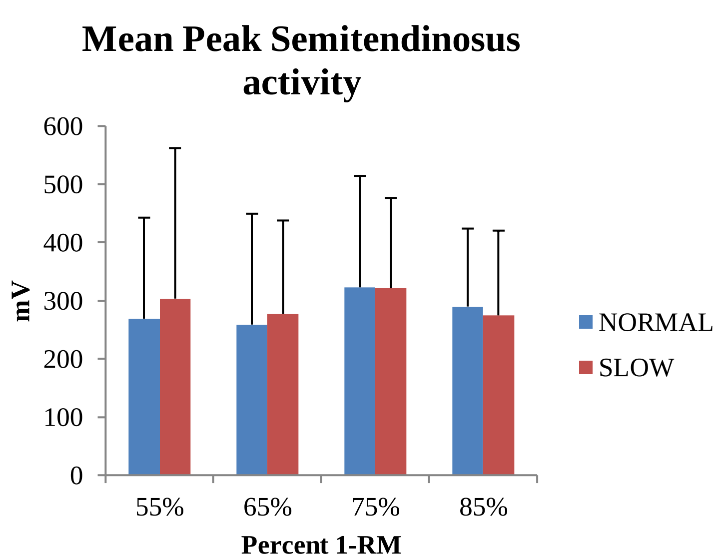

Figure 3b. Mean muscle activity of the semitendinosus across all trials.

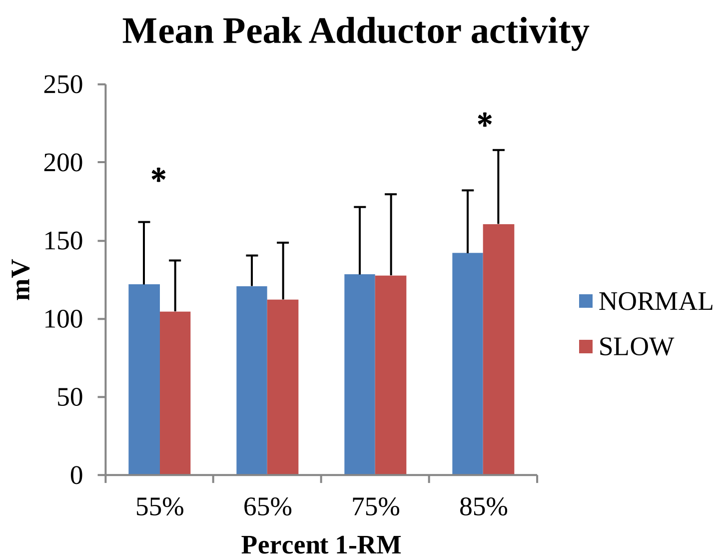

Figure 4a. Mean muscle activity of the adductor longus across all trials.

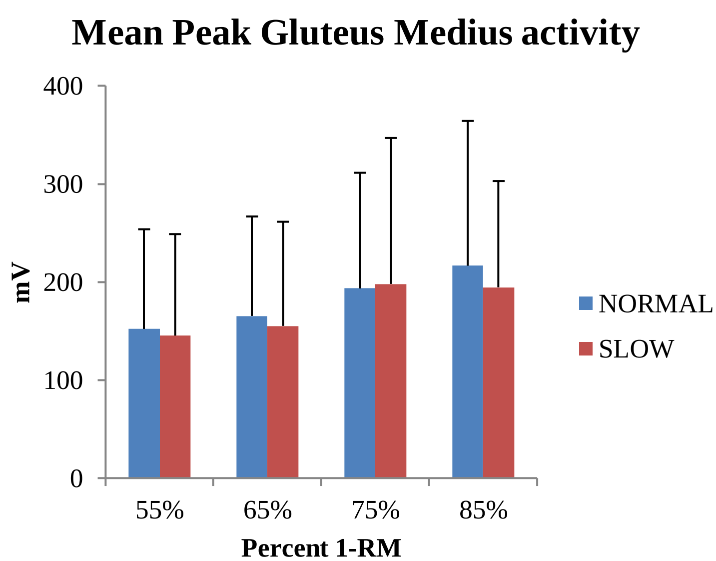

Figure 4b. Mean muscle activity of the gluteus medius across all trials.

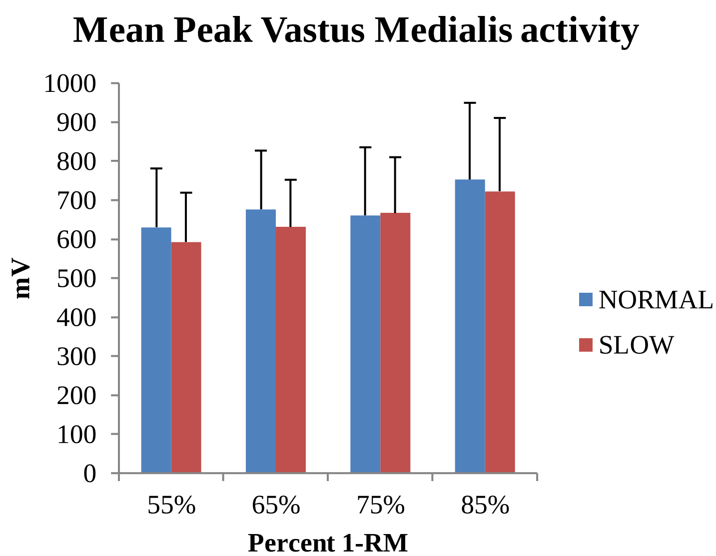

Figure 5. Mean muscle activity of the vastus medialis across all trials.

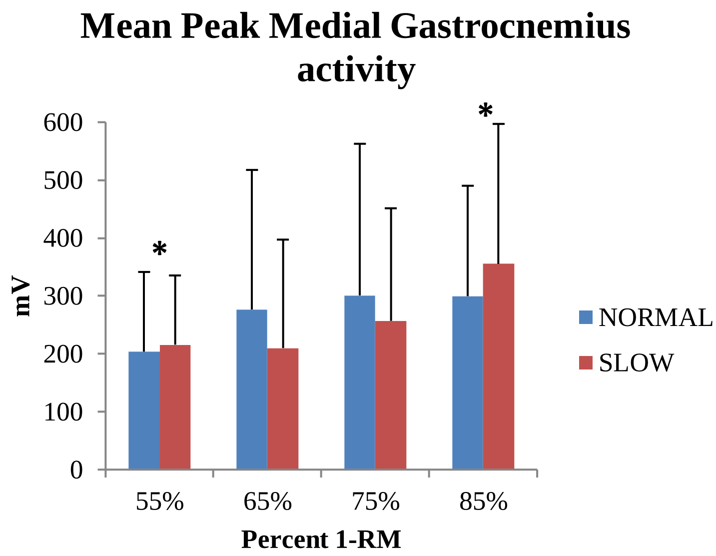

Figure 6a. Mean muscle activity of the medial gastrocnemius across all trials.

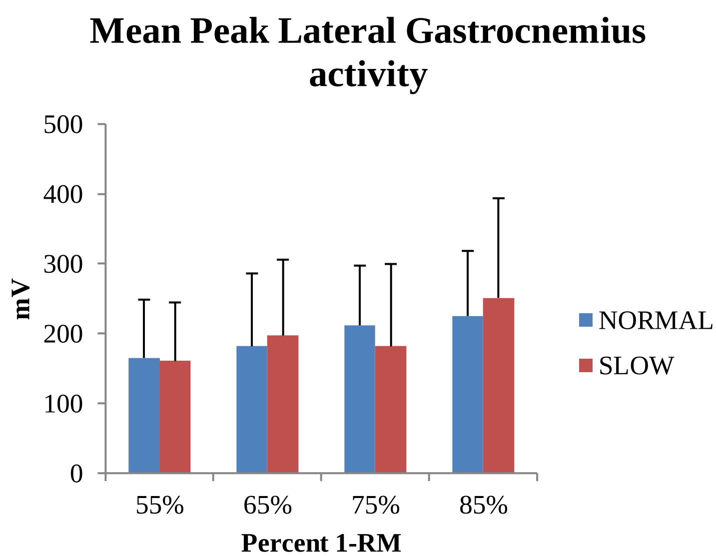

Figure 6b. Mean muscle activity of the lateral gastrocnemius across all trials.

DISCUSSION

Knee Displacement

The purpose of this study was to determine if velocity had an effect on MKD when squatting. It was hypothesized that performing slower squats would result in less MKD. The results demonstrated in figure 1 indicate that the knee-ankle relationship was smaller with increased weight and slower speed. Therefore, the knees were closer together, however, at no point did the knees travel inside of the ankle. Therefore, the results did not support the original hypothesis. When MKD, it was important to relate the knees to the ankles, as simply determining the distance between the knees does not suffice. The term “medial” simply determines a path and simply moving the knees toward the midline of the body is not necessarily dangerous. However, when the knees travel excessively towards to the midline into a valgus position, it is at this point it can cause injury. By allowing the participants to place their feet as wide as they wanted and only measuring the distance between the knees it would be impossible to determine if the knee were in a dangerous position or not.

There is little research to support whether a slower squat speed is beneficial for MKD. Myer et al. (2014) suggested that individuals should perform the back squat at a constant velocity but make no mention if a faster or slower velocity may be more beneficial. However, they do mention that squatting too quickly can have a detrimental effect on the muscles if they are stretched too quickly. Though the results show the knees being closer together during all trials, they were only statistically significant when comparing between the 55- and 85-percent trials. Therefore, the results can be interpreted to say that slower squats may only be dangerous when lifting upwards of 85 percent of 1-RM.

Electromyographic Data

The second purpose of this study was to examine if differences in lower limbs muscle activation were associated with changes in MKD. It was hypothesized that performing slower squats would result in lower activation of the gastrocnemius and adductor longus. This study showed increased muscle activity of the AL and MG at higher weights and slower velocities, as seen in figures 4a and 6a, respectively. Therefore, these results also do not support this hypothesis. GM and VM also showed greater activity, however, only when comparing weights. As the weights increased the need for increased muscle activity of the hip and knee extensors was required, however, there was no increased activity of the semitendinosus, which is also a hip extensor.

When a muscle performs a contraction, it pulls its two attachment points closer together. Since both the MG and AL attach on the medial aspect of the knee, the muscles would pull the knee in the medial direction thus supporting the results obtained from this study. Again, it is difficult to compare the results of velocity from this study with results from past literature as the only mention of velocity states that it should remain constant. However, when looking at the force-velocity relationship of a concentric muscle action, maximum force is produced at zero velocity, therefore, it’s possible that slowing down the squat, produced more force of the MG and AL.

However, when looking at the muscle activity, the results of this study were similar to what was found in other studies. Bell et al. (2011) tested muscle activity and ankle flexibility with MKD. They determined that with limited ankle dorsiflexion, there was an increase in adductor longus muscle activity, which they stated may have caused the MKD. Padua et al. (2012), tested the effects of limited dorsiflexion on MKD. It was concluded that tibialis anterior, hip adductors, and the gastrocnemius all had increased muscle activity. Therefore, it is suggested that limited ankle dorsiflexion was related to increased MKD. When there is limited ankle dorsiflexion and a requirement of having a parallel squat depth, individuals would be required to lift their heel from the ground. Though center of pressure was not examined, lifting the heels would shift the center of pressure anteriorly, to the forefoot. This would result in increased activation of the plantar flexors, such as the gastrocnemius and soleus muscles. Foley et al. (2017) tested the effects of using a band-loop around the distal aspect of the thigh to prevent MKD. Interestingly, their results indicated an increase in lower extremity muscle activation, which in their case was the vastus lateralis, biceps femoris, gluteus medius, and gluteus maximus muscles. Therefore, though there was increased activity of the upper leg and hip musculature, MKD was still present, which could suggest that other muscles may cause of MKD. However, it is mentioned that if individuals train with the band-loop for an extended period of time, it may result in less MKD.

Limitations

There are some limitations to this study. Firstly, only one trial was performed at each percentage and speed by each participant. All the participants were experienced in the back squat and one could assume that the knee movement and muscle activation would be similar. However, it would be beneficial to have the participants perform multiple trials of the same percentage and speed to ensure accuracy of the data collected. That being said, the benefit of having the participants perform only one trial was to avoid fatigue.

Secondly, since all participants performed their preferred technique, although they may be similar to others, it is difficult to compare results to another participant that had a completely different technique. As we know, different foot placements create different forces on the hip or knee joints. In a narrow stance squat, there is more activation of the gastrocnemius and quadriceps. Since the gastrocnemius is suspected at being related to MKD, it can be assumed that a participant with a narrow stance back squat to have different MKD results than a participant with a wide stance back squat.

Conclusion

The results from this study indicate that there is an increase in MKD accompanied with an increase in back squat weight and a decrease in squat speed. It should be noted that the slower speed is relative to the individual participant's normal back squat speed. The speed was determined based on control trials at each percentage for the participants and not all participants performed their reduced velocity squat at the same speed. Therefore, an exact value of what a slow back squat is cannot be determined, but rather a reduction in an individual's normal back squat speed. This can be an important factor as performing slow back squats is a common technique while exercising. Being able to determine if there is a certain percent 1-RM that can increase the risk of injury is beneficial. Since the back squat is a common exercise movement in both fitness and rehabilitation, it’s important to be able to provide accurate information to health professionals.

Excessive MKD is related to knee injuries such as ACL, MCL, and meniscus damage, and the cause of MKD needs to be further investigated to mitigate the risk of injury. In saying this, there is a possibility that MKD may not be avoidable. As mentioned, MKD is the direction of travel of the knees to the midline. And the only mention of dangerous MKD is when the knee travels medially to the medial malleolus. Nowhere in past research does it mention the possibility of avoiding MKD but only minimizing it. What the research does suggest is that increased activity of medial leg muscles appear to cause excessive MKD. Since the gastrocnemius is a plantar flexor it could be suggested to individuals that while performing the back squat to shift the center of pressure towards the heels. Thus, potentially causing less activity of the gastrocnemius and preventing excessive MKD.

Future research could shed light on these risks as they could direct computer simulations estimating the stresses on these knee structures. As mentioned, better study methods could be adopted to provide for better and more comparable results.

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