The Effects of Lifting With Intent on Hip and Knee Moments During Back Squats

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THE EFFECTS OF LIFTING WITH INTENT ON HIP AND KNEE MOMENTS

DURING BACK SQUATS

by

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B.S. December 2021, Old Dominion University

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Back squatting is a widely used movement in the strength and conditioning community. Within the last few years, velocity-dependent training and its application of tracking intensity have increased in popularity. Biomechanics research has frequently examined force generation, joint loading, and muscle contributions of back squats with different bar placement, stance width, and increasing barbell loads. However, no information exists regarding whether lifting with intent increases velocity and how increased velocity is biomechanically achieved. This study aimed to examine how lifting with intent affects bar velocity and how joint moment alterations could contribute to these potential changes in velocity. Fifteen males with ≥1 year resistance training and ≥1 day of lower body training per week participated. Squat stance, bar placement, and footwear were standardized. Participants completed 3 self-selected velocity squats with a pause at the bottom at 70% and 80% then 1 repetition at 90% and 1RM. Participants then performed back squats with the same 70% and 80% 1RM load, but with the instruction to ascend “as fast as possible” along with visual feedback via a tendo unit. Paired samples t-tests were used to examine differences in average ascent velocity and peak hip and knee moments. Ascent velocity was significantly increased during instructed velocity compared to self-selected for both 70% and 80% (p<.01) 1RM. Peak hip moments were significantly increased with instructed velocity at 70% (p=.024) and 80% (p<0.01) 1RM. However, peak knee moments were not different between self-selected velocity and instructed velocity for neither the 70% nor 80%
conditions. This study illustrates that 1) lifting with intent can increase ascent velocity and 2) increases in velocity are achieved via increased hip moments. Thus, training with the same load but higher velocities can enhance hip loading/strengthening. Considering the hip is the limiting factor in maximal squatting, increasing strength at the hip via velocity squats could be a beneficial alternative to maximal load squats.
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CHAPTER 1
INTRODUCTION

The following sections will outline the biomechanics of squatting. Topics include defining a squat, the concentric regions of the squat and how activation changes across them, squatting depth, and resistance training with intent of maximizing movement velocity (i.e., partial, parallel, and full range of motion). This section will also cover velocity-dependent training and how it used to assess performance variables. Additionally, bar placement and stance will be discussed. These aspects of the squat will be assessed to better control for variables when examining the effects of velocity on joint moments.

SQUAT DEFINITION

The loaded barbell squat exercise can be defined as a two-movement exercise with an initial eccentric phase followed by a concentric phase. The initial eccentric phase is generated by appropriate eccentric hip, knee, and ankle flexion to lower the body and external load to the desired depth while maintaining an upright trunk. The following concentric phase is developed through concentric hip, knee, and ankle extension to return the body and external load to its upright initial starting position. Research conducted by Kristiansen et al. found that muscle activation varies from region to region in traditional squatting (Kristiansen et al., 2021). The authors state that biceps femoris and glute activity increased in each subsequent region (Kristiansen et al., 2021).

PRE-STICKING REGION

The pre-sticking region of the squat happens at the beginning of the concentric portion (Van Den Tillaar et al., 2020). In the pre-sticking region of the squat there are greater contributions from the knee moment (Maddox et al. 2021). Similarly, Larsen et al (2021) found the knee moments in the pre-sticking region of the squat where the greatest (Larsen et al., 2021). In the pre-sticking region of the squat is where greatest quadricep activation is also seen (Larsen et al., 2021). The gluteus maximus showed less muscle activation in the pre-sticking region as compared to the sticking region (Larsen et al., 2021). Similarly hip
moments in the pre-sticking region were less than what was seen in the sticking and post-sticking region (Larsen et al., 2021)

STICKING REGION

The sticking region is characterized by a period of mechanical disadvantage for the musculature relative to the barbell/external resistance (Van Den Tillaar et al., 2021). It is hypothesized that the sticking region occurs because of a weak position in the length-force relationship in the musculoskeletal system (Van Den Tillaar et al., 2021). During back squats, the occurrence of the sticking region could be caused by a transition between the hip and knee (Maddox et al., 2021). As the pre-sticking region transitions to the sticking region knee moment contributions diminish and hip contributions increase (Maddox et al., 2021). Larsen et al. (2021) found that muscle activation of the quadriceps stabilized from the pre-sticking to the sticking region, however knee moments decreased (Larsen et al., 2021). The limiting factor for decreasing failure at the sticking region would be the increasing strength at gluteus maximus (Maddox et al., 2021). Throughout the duration of the sticking region Larsen et al. (2021) found that the hip moment stabilizes (Larsen et al., 2021). Additionally, muscle activation for the gluteus maximus increased from pre-sticking region to post-sticking region (Larsen et al., 2021). Van Den Tillaar et al. found that larger descent speeds in the eccentric phase of the squat have an effect on the sticking region and when it occurs in the concentric phase of the squat (Larsen et al., 2021; Van den Tillaar, 2019).

POST-STICKING REGION

The post-sticking region is the final phase of the concentric portion of the squat (Van Den Tillaar et al., 2020). The quadriceps musculature showed decreasing activation from the sticking to the post-sticking region, knee moments also decrease from the sticking region to the post-sticking region (Larsen et al., 2021). Van den Tillar et al., (2020) found that gluteus medius activation significantly increased from region to region (Van Den Tillaar et al., 2020). These findings are similar to that of Larsen et al., (2021) and Kristensen et al., (2021) which observed increasing gluteus maximus activation from pre-sticking, sticking, to post-sticking region (Larsen et al., 2021, Kristiansen et al., 2021). Larsen aet al., also
found that hip moments increased from the sticking to the post-sticking region, however, knee moments decrease from the sticking region to the post-sticking region (Larsen et al., 2021).

SQUAT DEPTH

Squatting depth in the current literature seems to lack a clear definition of varying ranges of motion (i.e., partial range of motion, parallel range of motion, and full range of motion). Partial squatting has been defined as a range of motion from 19-61° of knee flexion (Bloomquist et al., 2013; Bryanton et al., 2012; Caterisano et al., 2002; Ciccone et al., 2015; Comfort et al., 2018; Escamilla, Fleisig, Zheng, et al., 2001; Esformes & Bampouras, 2013; Gabbett, 2010; Gorsuch et al., 2013). Parallel squatting is often defined as a range of motion of 90-130° of knee flexion (Bishop & Turner, 2017; Bryanton et al., 2012; Caterisano et al., 2002; Chapman et al., 2019; Ciccone et al., 2015; Esformes & Bampouras, 2013; Gabbett, 2010; Gorsuch et al., 2013; Hartmann et al., 2012), while full squatting has been defined as a range of 75-135° degrees of knee flexion (Bloomquist et al., 2013; Bryanton et al., 2012; Caterisano et al., 2002; Ciccone et al., 2015; Comfort et al., 2018; Gorsuch et al., 2013; McAllister, 2018).

As squatting depth increases net joint moment at the knee increases. Hip and knee joint moments increase with load. The largest contributions from the knee extensors are seen at full range of motions in the squat (105°-119°) (Bryanton et. al., 2012, Wretenberg et al., 1993). Similarly, the knee extensors had large contributions in partial range of motion in the squat (30°-44°). Similar findings were seen in hip extensor activation at full range and partial range of motion squats (Bryanton et. al., 2012, Wretenberg et al., 1993).

SQUAT STANCE

Squat stance has been shown to influence muscle activation with exception to the quadriceps. Quadriceps musculature, the musculature responsible for extending the knee, showed no differences in EMG activity in varying squatting stances, this may be due to the lack of muscle length change in varying stances (Anderson et al., 1998). In contrast, increasing stance width has shown an increased muscle activation for the gluteus maximus musculature, but this has only been observed with increasing loads of
75% or greater (Clark et al., 2012; McCaw & Melrose, 1999). Furthermore, the adductor group has also shown an increase in muscle activation as stance width increases (Clark et al., 2012).

Narrow stance squatting has shown significant increased knee and ankle moments as compared to wide-stance conditions which had increased hip moments (Escamilla, Fleisig, Lowry, et al., 2001). Wide-stance squatting resulted in a more vertical shank angle and a more horizontal thigh angle (Escamilla, Fleisig, Lowry, et al., 2001). Furthermore, trunk angle showed significant difference among the different stance positions there is a more upright posture in narrow stance squatting as compared to wide stance squatting which results in greater forward lean of the trunk (Escamilla, Fleisig, Lowry, et al., 2001).

BAR PLACEMENT

High-bar squatting results in higher muscle activation in the lower erector spinae (van den Tillaar et al., 2020). Additionally, the hamstrings group shows a higher muscle activation (Glassbrook et al., 2017). Furthermore, high-bar placement has been found to result in high ranges of motion for the knee (Kristiansen et al., 2021). In contrast, low-bar placement has been shown to result in increased muscle activation of the entire erector spinae musculature (Kristiansen et al., 2021). Gluteal muscle activation increases in low-bar conditions in consistent loads (Glassbrook et al., 2017). Also, adductor musculature increased in low-bar conditions because low-bar squatting is usually associated with wider stance squatting (Glassbrook et al., 2017).

RESISTANCE TRAINING WITH VELOCITY AND INTENT TO MAXIMIZE VELOCITY

Using velocity-based training provides coaches and athletes with immediate data to make determinations on training needs within daily training session. Velocity-based training has been utilized in research to assign certain load percentages with certain velocities (Weakley et al., 2021). Furthermore, the use of velocity loss establishes a threshold in which sets for a given lift (i.e., squats, bench, and deadlifts) should be terminated to prevent maladaptation’s (Weakley et al., 2021). In a study by Young et al. (1993) examining a 7-week training program with the intent to move with instructed velocity in comparison to self-selected velocity it was found that the instructed velocity group increased power.
output (Young et al., 1993). Additionally, the instructed velocity group also increased rate of force production (Young et al., 1993). However, the instructed velocity group did not increase strength (Young et al., 1993). It is possible that these increases in power could be caused by increases in joint moments. In a study by Hutchison at el. (2019) comparing a flexible barbell to a steel barbell squat with equated (30% 1RM) loads it was found that the flexible barbell condition had greater squatting velocity (Hutchison et al. 2019). These increases in velocity in the flexible barbell condition were caused by an increase in hip moments (Hutchison et al., 2019).

PROBLEM

Back squatting is used in strength and conditioning by both elite level athletes and recreationally trained athletes alike. Back squatting results in strength, hypertrophy, and neuromuscular adaptations (Schoenfeld et al., 2010). In the literature, the effects of stance width, bar placement, and depth have been explored regarding muscle activation, joint moments, and joint angles. However, the literature regarding joint moments, and how they are altered with maximal velocity intent is lacking. This will examine how velocity is altered in participants that lift with a self-selected velocity in comparison to being instructed to lift with maximal ascent velocity. Furthermore, this study will examine peak joint moments at the hip and knee and their role as participants squat with self-selected velocity and with maximal intent.

PURPOSE

This study has two purposes. First, this study aims to determine whether moving with intent increases barbell velocity. Second, this study aimed to determine the biomechanics behind squatting at a self-selected velocity or an instructed velocity. Specifically, this study determined whether hip moment, knee moment, or both increases to increase squat velocity.
HYPOTHESIS

Back squat velocity will be higher when participants are instructed to lift with maximal velocity intent compared to lifting without instruction. Furthermore, increases in velocity will be accompanied by increases in joint moments at the hip and knee.

SIGNIFICANCE

This study will compare set loads of 1RM (70% and 80%) examine how joint moments at the hip or knee change as the use of maximal ascent velocity is used by participants. This study hopes to explain where the increases in velocity come from, from a biomechanical perspective.

LIMITATIONS

- Diet- we will not ask participants to partake in certain eating habits.
- Sleep duration – participants will be allowed to sleep in their normal manner.
- Outside training protocol- participants may training however they please, with whatever volume and intensity prescriptions they see fit for themselves.

DELIMITATIONS

- Squat stance/width- standardized to 140% of shoulder width.
- Bar placement- standardized to placement on the spine of the scapula.
- Footwear- all subjects will be barefooted.
- Training experience, subjects must train a minimum of 3 times a week for at least a year.
- Clothes will be provided.
- No lifting aids, no caffeine 24 hours before testing days, weight belts, straps, or wraps.

OPERATIONAL DEFINITIONS

1. Recreationally trained- minimum of 1 year resistance training, participate in resistance training a minimum of three times a week, and does a lower body training at least once a week.
2. Bar placement- on the spine of scapula
3. Squat stance- width of feet relative to the shoulders; in this study 140%
4. Maximal velocity intent - lifting concentrically as fast as one can.

5. Self-selected velocity - lifting as one desires with no instruction.
CHAPTER
LITERATURE REVIEW

INTRODUCTION

The squat consists of two phases, first the eccentric phase followed by the concentric phase. The initiation of the squat starts with flexion of the hip, knee, and ankle while the hips are lowered to the desired depth while maintaining an erect truck. Once the desired depth is achieved, the concentric phase begins with hip, knee, and ankle extension returning the body to its starting position. Squatting is commonly used in strength training protocols, for the reason squatting is a highly variable task. Due, to the highly variable nature of the squatting task it is important to manage a lifter's ability as closely as possible. This can be accomplished by using velocity dependent training.

Joint angles during squatting, joint loads, and muscle activations are not only a function of one’s anthropometry, but also the style of squat they chose to use, such as front squat, back squat, safety bar squat, bar placement, loading styles and stance width. Additionally, the regions of the squat (eccentric, concentric [pre, stick, and post-sticking regions]) are known to be affected by variables such as muscle force production and length tension relationships of agonist and antagonist muscles (Van Den Tillaar et al., 2021). Therefore, it is important to review the current literature to see how these variables and their effects are currently understood, and this understanding will help control for confounding variables in the proposed study. Understanding these variables as it pertains to traditional squatting. However, the effects on the variables are not well understood in literature as it pertains to the application of velocity dependent training.

VELOCITY-DEPENDENT RESISTANCE TRAINING

In study conducted by Sanchez-Medina et al. (2011) velocity loss from prescribed rep max was used to quantify muscle fatigue. Rep maxes were taken at 12RM, 10RM, 8RM, 6RM,
and 4RM. This can be reliable for a rep range 4-6 (Dohoney et al., 2002), but at higher rep ranges (i.e. 7-10) this measure becomes less reliable. Furthermore, this study failure to look at how velocity loss would impact variables such as joint moments, EMG, and muscle coordination (synergy). Therefore, it is unknow how velocity loss from one rep range to a subsequent would affect the mechanics involved in muscular fatigue. However, the article did attempt to quantify muscle fatigue to comparing force generated in countermovement jumps via percentage difference pre and post-test. In a similar study conducted by Loturco et al. (2017), participants performed a prescribed number of repetition at a certain percentage intensities determined, once again by an estimation, 50%, 60%, 70%, 80%, and 90% on both a Smith machine and a free barbell (Loturco et al., 2017). The others then used a linear regression equation to determine how much velocity loss would occur at differing intensities (Weakley et al., 2021). However, a true 1RM was not obtained and the authors did not explicitly tell the participants to lift with maximum velocity. Therefore, this may render the values acquired to not be representative of the percentages of load lifted. Once again, this article failed to examine biomechanical principals (i.e., joint kinetics and kinematics) in conjunction with the loss of velocity from each subsequent load lifted. In a study conducted by Rodríguez-Rosell et al. (2020), it was stated that “the relationship between the percentage of velocity loss in the set and the percentages of performed repetitions depends on the relative load being lifted and the type of exercise used (Rodríguez-Rosell et al., 2020).” If this holds true, then it is of sound mind that the mechanics at different loads will be dependent as well, and therefore need to be examined when a participant is explicitly told to lift a specified load as fast as possible. Additionally, loads should be examined all the way to a 1RM, and researchers should not use a 1RM equation to “properly” examine the velocity load relationship (Sanchez-Medina et al. 2011).
VELOCITY INTENT

While moving with the intent to move explosively is important, is it known that the movement velocity is determined by the impulse that is applied by the musculoskeletal system and the magnitude of the external load (McBride et al., 2002). When comparing training same training loads (70%) Fielding et al. (Fielding et al., 2002) found that in two different training groups, one that trained more explosively (fast training), and one that trained in a more controlled manner (slow training). It was observed that the group that training with explosive intent there was a significant increase in muscular power, more so than the slow training group. Similarly, Young et al. (Young et al. 1993) found that training groups that used explosive intention saw greater increases in rate if force development. In this experiment intensities (8-12RM). This study by Young et al. (Young et al. 1993) also showed that groups that trained with explosive intent had higher movement velocities and power than the slow group. These studies do indicate that training with explosive intent does make a difference. Cronin et al. (Cronin et al., 2001) and Blazevich et al. (Blazevich et al. 2002) found that when training with the intent to move explosively in resistance training coupled with sport specific movements there were significant improvements in adaptations.

VERBAL ENCOURAGEMENT

Weakley et al. found that when providing semiprofessional rugby players with verbal encouragement, either verbal kinematic feedback, visual kinematic feedback, and verbal encouragement all groups saw an increase in mean concentric velocity. Verbal kinematic feedback showed the biggest increase in velocity a 6.6% improvement over the control group (no feedback), visual kinematic feedback and verbal encouragement showed a moderate
improvement of the control (Weakley et al., 2020). McNair et al. (McNair et al., 1996) in a similar study found that positive reinforcing statements (e.g., “Come on, you can do it!”)

SQUAT MECHANICS

Ankle

Starting in an upright position before beginning the squat causes the center of pressure to be placed at midfoot (Schoenfeld, 2010). Ankle torque is directed towards plantar flexion (Schoenfeld, 2010). Once the eccentric phase of the squat begins, the center of pressure is shifted towards the heel and plantar flexion torque is decreased (Schoenfeld, 2010). As depth is achieved, the center of pressure is shifted forward, towards the toes, and consequently there is a large increase in plantar flexion. There is a moderate amount of gastrocnemius activation in the squat with increasing levels of knee flexion and decreasing levels of knee extension (Hemmerich et al., 2006). During high-speed squats, there is a co-activation observed in the gastrocnemius and the tibialis anterior to provide stability (Hemmerich et al., 2006). The gastrocnemius serves as a stabilizer to the knee (Elias et al., 2003). The gastrocnemius aids in preventing knee valgus and prevents posterior translation (Elias et al., 2003). This is achieved by acting as an antagonist, because the gastrocnemius is moving the tibia anteriorly (Elias et al., 2003). In contrast to the gastrocnemius, the soleus is reported as being more active in squats using a high degree of ankle flexion; being that the soleus is strictly a plantar flexor, this is logical (Hemmerich et al., 2006). Hemmerich et al. found that a dorsiflexion angle of $38.5 \pm 5.9^\circ$ was necessary to keep the heels down during a full squat (Hemmerich et al., 2006).

Knee

The knee joint is comprised of the tibiofemoral joint (Schoenfeld, 2010). This joint carries out sagittal plane movement (Schoenfeld, 2010). The tibiofemoral joint is classified as a
modified hinge joint (Schoenfeld, 2010). Supporting the tibiofemoral joint is a myriad of ligaments and cartilage (Schoenfeld, 2010). The anterior cruciate ligament (ACL) helps prevent unwanted anterior translation, external and internal movement, as well as knee varus and valgus. The posterior cruciate ligament (PCL) is the counterpart to the ACL (Schoenfeld, 2010). The PLC’s main function is to prevent any unwanted tibia shift posteriorly (Schoenfeld, 2010). The medial collateral ligament (MCL) and lateral collateral ligament (LCL) aid in preventing any unwanted medial or lateral movement of the knee (Schoenfeld, 2010). Musculature stabilizing the knee in the quadriceps is comprised of the vastus lateralis, vastus medialis, vastus intermedius, and rectus femoris (Schoenfeld, 2010). The quadriceps carry out concentric knee extension, and resist knee flexion (Schoenfeld, 2010). The antagonist muscle to the quadriceps is the hamstrings. The hamstrings are comprised of the biceps femoris, semitendinosus, and semimembranosus (Schoenfeld, 2010). The hamstrings act synergistically with the quadriceps by enhancing stability of the knee joint, exerting an opposite but equal pull on the tibia, and helping neutralize anterior tibiofemoral shear (Schoenfeld, 2010).

**Hip**

The hip joint is a ball and socket joint that moves in all three planes of movement; the sagittal, frontal, and transverse (Schoenfeld, 2010). The primary hip musculature included in squatting is the gluteus maximus and the hamstrings (Schoenfeld, 2010).

**Spine**

The spine has 24 vertebra, each of them displaying 3 degrees of freedom on the sagittal, frontal, and transverse plane, and each of the vertebra increase in size from the cervical to the lumbar region (Schoenfeld, 2010). The spinal column is supported by the trunk musculature. The trunk musculature includes the erector spinae, transverse abdominis, quadratus lumborum, and
deep posterior spinal group (multifidus, rotatores, interspinales, and intertransversarii) (Signorile et al., 1995). The erector spinae group is extremely important in squatting because it helps to resist vertebral shear and maintain anteroposterior spinal stability (Toutoungi et al., 2000). Rigid midsections are paramount to a proper squat, as they will help eliminate any unwanted plantar motion. There is a lumbar-pelvis relationship, in that the spinal angle increases when the hips are flexed (Schoenfeld, 2010). Van Den Tiller et al. (2020) suggests that the activation of the erector spinae muscles is very important in the pre-sticking region to withstand peak hip joint moment. This then enhances a rigid and stable spine through the concentric portion of the squat (van den Tillaar et al., 2020).

SQUATTING DEPTH

Squatting depth is poorly defined throughout literature and is comprised of a wide range of knee flexion angles for partial, parallel, and full range of motion squats. This study will provide a clear definition of what a parallel squat is; however, its justification may not match what is denoted by literature.

Partial range of motion

There is no set consensus on what constitutes partial range of motion in squatting. Booth et al., (2002) Esformes and Bampouras (2013), Gorsuch et al. (2013), and Bloomquist et al. (2013) all define partial range of motion as 45º at the knee joint. Esformes and Bampouras (2013) define it as a tibiofemoral angle of 19-61º depending on foot stance. Comfort et al., and Ciccone et al. define a partial range of motion squat as 60º of knee flexion (Ciccone et al., 2015; Comfort et al., 2018). Gabbett et al. defines a partial range of motion squat as 30-74º of knee flexion (Gabbett et al., 2010).
Parallel range of motion


Full range of motion

Bryanton et al., (2012) defines full squat depth as 75-119° of knee flexion (Bryanton et al., 2012). Bloomquist et al. and Gorsuch et al. defines it as 90° of knee flexion (Bloomquist et al., 2013; Gorsuch et al., 2013). In another study, Comfort et al. defined full squatting as 115-125° of knee flexion (Comfort et al., 2018). Ciccone et al. defined full range of motion squats as 120° of knee flexion (Ciccone et al., 2015). In a different study, McAllister et al. defined full range squatting as a range between 110-120° of knee flexion (McAllister, 2018). Booth et al. defines a full range of motion squat as 135° at the knee joint (Caterisano et al., 2002).

MUSCLE ACTIVATION AT VARYING DEPTHS

Erector spinae

Gorsuch et al. showed that squatting to a deeper knee angle of 90° increased the activation of the rectus femoris and lumbar erector spinae muscles more so than when squatting to a depth of 45° (Gorsuch et al., 2013).

Quadriceps

Muscular forces of the quadriceps tend to peak at 80 to 90° of flexion in the squat (Schoenfeld, 2010). Squatting past 90° may not recruit more quadriceps muscle activation. There has been found to be no statistically significant difference between the activation of the vastus
medialis or the vastus lateralis in squatting mechanics (Schoenfeld, 2010). However, the vasti group have been shown to produce 50% more muscle activation than the rectus femoris (Schoenfeld, 2010). Because the rectus femoris is both a hip flexor and a knee extensor, lengthening at one end and shortening at the other, with little net length change throughout the squat this explains the lack in change of muscle activation (Schoenfeld, 2010). The rectus femoris would have a greater advantage when the trunk is more upright because this would increase the force and length advantage (Schoenfeld, 2010). However, muscle activation in the rectus femoris resulted in the same levels or activation at varying depths supporting Schoenfeld et al. (da Silva et al., 2017). Muscle activation in vastus medialis and vastus lateralis showed very little variability across each studied depth, and there was no statistical difference (Caterisano et al., 2002). The vastus medialis contributes 30.88% to the total electrical activity of the thigh during the partial squat; yet it contributes only 18.85% and 20.23% during the parallel and full squats (Hemmerich et al., 2006).

Gluteal muscles

Activation of the gluteus maximus is affected by squat depth (Caterisano et al., 2002). In a study conducted by da Silva et al. (2017), there was reported to be a higher activation in the gluteus maximus, biceps femoris and erector spinae of partial range of motion group. In contrast, the gluteus maximus were not significantly different in neither the partial squat (16.92 ± 8.78%) or parallel squat (28.00 ± 10.29%). However, it did increase significantly during the full squatting (35.47 ± 1.45%) (Caterisano et al., 2002). In a study conducted by Caterisano et al. (2002), the gluteus maximus showed the biggest variability in the 3 different studied depths (i.e., full range of motion to partial range of motion). In this study it was found that the gluteus maximus had the least amount of muscle activation in partial range of motion squatting
In contrast, the gluteus maximus was found to have the most amount of activation in the full range of motion group (Caterisano et al., 2002).

*Hamstrings*

The hamstrings group shows a consistent force output during squatting, because the hamstrings both extend at the hip and flex at the knee. The greatest hamstring activity was shown between 10 and 70° of flexion, with the lateral hamstring having more activation than the medial hamstring (Escamilla et al., 1998). In contrast to the gluteus maximus, the hamstring group does not show any difference in activation with squat depth (Schoenfeld, 2010). A study conducted by Wretenberg et al. found that as depth increased from 45 to 90 degrees of knee flexion, the muscle activity of the biceps femoris also increased (Wretenberg et al., 1993). Increasing depth in the squat limits hamstrings activity, rendering them unable to produce force (Glassbrook et al., 2017). This is because of their shortened length with respect to the length-tension relationship (Ninos et al., 1997). To compensate for the hamstrings’ decrease in force application, the gluteal muscles’ activity increases (Glassbrook et al., 2017). The lowest velocity of the squat is when the hamstring and glute groups increase the muscle activity (Kristiansen et al., 2021).

**SQUATTING STANCE**

Narrow stance squatting shows a larger EMG amplitude in the gastrocnemius as compared to wide stance squatting as seen by Escamilla et al. (Escamilla, Fleisig, Zheng, et al., 2001). When examining low-bar back squatting and varying stances, McCaw and Melrose found no differences in quadriceps muscle activity at varying stance widths. However, they did observe a greater muscle activation of the adductors and gluteus maximus in wider stance squatting (McCaw & Melrose, 1999). Additionally, Anderson et al. (1998) also found no significant difference in quadricep activation at varying stances. Paoli et al. also showed a greater muscle
activation of the gluteus maximus muscles with larger stance width, which corroborates McCaw and Melrose (McCaw & Melrose, 1999; Paoli et al., 2009). Clark et al. (2012) theorize that the lack of change in quadriceps muscle activity during different stance widths, results from no differences in muscle lengths (Clark et al., 2012). Longer muscle lengths and anthropometric influences may explain the increase in adductor and gluteus maximus activity in wider stances (Clark et al., 2012). However, the higher EMG in the gluteus maximus with increased stance width was only observed with high loads (Clark et al., 2012).

Escamilla et al. (2001) examined the kinematic and kinetic differences of narrow stand, medium stance, and wide stance squatting at varying depth positions. The depth positions were defined as a) acceleration phase to maximum knee flexion to first peak bar velocity; b) sticking region to first peak bar velocity to minimum bar velocity; c) maximum strength region 3 minimum bar velocity to second peak bar velocity; and d) deceleration phase to second peak bar velocity to lift completion Escamilla et al., (2001). There was no difference observed between medium and wide-stance squatting. However, the most significant differences were between narrow and wide-stance squatting (Escamilla et al., 2001). Observed both in the medium and wide-stance squatting groups at 45°, 90°, and maximum knee flexion, the hips were flexed approximately 10° as compared to the narrow stance group (Escamilla, Fleisig, Lowry, et al., 2001). Furthermore, compared with the narrow-stance group, the shanks were approximately 8° more vertical and the thighs were roughly 10° more horizontal (Escamilla, Fleisig, Lowry, et al., 2001). Additionally, the feet were turned out approximately 6° more in the wide stance squatting group (Escamilla, Fleisig, Lowry, et al., 2001). There were no significant differences in trunk positions among the three difference stance groups (Escamilla, Fleisig, Lowry, et al., 2001). A significantly greater hip flexion (12–14°) was seen as well as forward trunk tilt (7–10°) at
minimum bar velocity during the concentric phase as compared with hip and trunk angles at corresponding knee flexion angles during the eccentric phase. The hips flexed 67 ± 7°, 68 ± 10°, and 69 ± 12°, respectively, and trunk angles were 65 ± 5°, 64 ± 4°, and 66 ± 5°, respectively, during the narrow stance, medium stance, and wide stance groups (Escamilla, Fleisig, Lowry, et al., 2001).

Bar velocities did not differ between the three different stance groups (Escamilla, Fleisig, Lowry, et al., 2001). The major significant difference was a greater hip angle in the medium and wide-stance squatting groups compared with the narrow-stance group at peak hip, knee, and ankle angular velocities (Escamilla, Fleisig, Lowry, et al., 2001). There was significantly greater forward knee movement over the feet during the narrow-stance squatting compared with the medium-stance and wide-stance squatting (Escamilla, Fleisig, Lowry, et al., 2001). The most significant differences seen in moments and moment arms were at the ankle (Escamilla, Fleisig, Lowry, et al., 2001). Resultant plantar flexor muscle moments were generated exclusively in the narrow-stance squatting group (Escamilla, Fleisig, Lowry, et al., 2001). Whereas ankle dorsiflexor resultant muscle were generated exclusively during the medium-stance and wide-stance squatting groups (Escamilla, Fleisig, Lowry, et al., 2001). In the narrow-stance group at maximum knee flexion is when peak ankle moments and moment arms occurred (Escamilla, Fleisig, Lowry, et al., 2001). In the medium and wide-stance groups, peak ankle moments and moment arms occurred at 45° knee flexion (Escamilla, Fleisig, Lowry, et al., 2001). Peak knee moments and moment arms occurred at maximum knee flexion, and peak hip moments and moment arms occurred at minimum bar velocity (Escamilla, Fleisig, Lowry, et al., 2001). The only significant differences between the squat eccentric and concentric phase occurred at 45° knee flexion (Escamilla, Fleisig, Lowry, et al., 2001). At 45° knee flexion the hip moments and
moment arms were significantly greater during the concentric phase compared with the eccentric phase (Escamilla, Fleisig, Lowry, et al., 2001).

Squatting stances show variation in both muscle activation, namely in the gluteal and adductor musculature. Additionally squat stance has been shown to have a significant difference in joint angles. Therefore, providing a clear definition to how squat stance was chosen in this study will be important, as to not allow for confounding variables in muscle activation, joint moments, and joint angles. This will provide more sound evidence for the application of velocity dependent training.

EFFECTS OF BAR PLACEMENT

*High-bar squatting*

*Erector spinae*

Van Den Tillaar et al. found that there was a higher muscle activation on the lower erector spinae in a higher bar position (van den Tillaar et al., 2020). The authors theorize this happens because the higher placement of the barbell on the upper back causes a larger moment arm on the hip joint; thus, the lower part of the erector spinae must be more active to resist flexion in the spine and maintain an upright torso (van den Tillaar et al., 2020). Hip-bar squatting results in lesser hip flexion as compared to that of low-bar squatting. Erector spinae iliocostalis showed the second lowest EMG activity in high-bar squatting (Kristiansen et al., 2021). However, there were no significant differences in EMG data in any squatting conditions when comparing the squat in its entirety (Kristiansen et al., 2021). High-bar squatting showed the second highest amount lifted by participants in a study conducted by Kristiansen et al (Kristiansen et al., 2021). High-bar squatting showed the second most upright torso (Kristiansen et al., 2021). Van Den Tillaar et al. theorizes that the higher muscle activation seen in high-bar
squatting is a result of the higher barbell placement on the shoulders, which causes a larger moment arm about the hip joint. Therefore, the lower erector spinae muscles must be more resistant to spinal flexion to maintain an upright trunk posture. However, this is not the case in low-bar squatting (van den Tillaar et al., 2020). Due to the higher bar placement, the subjects have to resist the anterior load by leaning backwards which would change the center of pressure on the subject’s foot (van den Tillaar et al., 2020). In a study conducted by Kristiansen et al. examining different intensities per barbell, and it was found that high-bar squatting resulted in the second least amount of load lifted (Kristiansen et al., 2021).

**Hamstrings**

Glassbrook et al. theorize that there is a greater gluteal muscle activity in high-bar back squatting as compared to low-bar back squatting because the impact of the hamstring’s activity is insufficient (Glassbrook et al., 2017). In high-bar back squatting, the hamstrings’ role is to extend the hip and maintain an upright torso (Glassbrook et al., 2017).

Under high-bar squatting conditions, there was seen to be a difference in muscle activation of the rectus femoris, vastus medialis and lower part of the erector spinae (Van Den Tillaar et al., 2020). Van Den Tillar et al. hypothesize that placing the barbell higher on the shoulders will most likely result in small joint angle adjustments to the ankle, knee, and hips, which may cause the participant to lean backwards to balance the external load above the center of pressure (Van Den Tillaar et al., 2020).

High-bar back squatting resulted in a larger knee range of motion and peak hip flexion. The only exception was in low bar squatting at 100% of 1RM (Van Den Tillaar et al., 2020).
**Low-bar squatting**

**Erector spinae**

Studies have shown that there is a smaller absolute trunk angle in low-bar squatting, which results in a greater lean forward (Glassbrook et al., 2017). This greater forward lean of the trunk results in a greater posterior hip displacement. Furthermore, placing the bar lower on one’s back may lead to a decreased moment arm. As forward lean increases, the muscle activation of the erector spinae increases (Glassbrook et al., 2017). Low-bar squatting results in greater hip flexion. Erector spinae iliocostalis showed the highest amount of EMG activity in low-bar squatting, with exception to the post sticking region where high-bar squatting showed the most EMG activity (Kristiansen et al., 2021). However, there were no significant differences in EMG data in any squatting conditions when comparing the movement in its entirety (Kristiansen et al., 2021). Low-bar squatting showed the highest amount lifted by participants in a study conducted by Kristiansen et al. (2021). Low-bar squatting showed a lesser upright torso posture and resulted in a greater torso angle (Kristiansen et al., 2021). Since low-bar squatting reduces the hip moment, it results in a greater torso inclination to produce the same moment around the hip (Kristiansen et al., 2021). In a study conducted on different intensities per barbell, low-bar squatting resulted in the highest amount of load lifted (Kristiansen et al., 2021). Low-bar squatting led to the greatest hip flexion (Kristiansen et al., 2021). Low-bar squatting causes a more anterior displacement of the center of pressure, which is visible in the increased moment arm of the ankle (Kristiansen et al., 2021).

**Gluteal Muscles**

There is an increase in muscle activation of the gluteal musculature in low-bar squatting, namely due to the wider stance that is associated with low bar squatting (Glassbrook et al., 2017).
Adductors

The adductor musculature has an increase in muscle activation in low-bar squatting because of the wider stance that is associated with low-bar back squats (Glassbrook et al., 2017).

Experience

No significant differences were observed between the experienced Olympic lifting and power lifting groups for any joint angles. It was expected that the Olympic group would display a greater angle at peak hip flexion because of the more upright torso position and a smaller knee flexion angle. Previous research by Fry et al. (1993) and Wretenberg et al. (Wretenberg et al., 1996) demonstrated a larger hip angle in the high-bar back squats and a greater forward lean in the low-bar back squats. However, the squats were performed only at 50% and 65% 1RM, respectively, in these studies, and the results showed no statistical significance (Glassbrook et al., 2019). This study by Glassbrook et al. (2019) observed significant differences in the hip and knee joints, between the high-bar back squats performed by the high-bar comparison group, and the low-bar back squats performed by the low-bar comparison group (Glassbrook et al., 2019). Potentially, this could indicate that there may have been an influence of experience on the significant results in this study (Glassbrook et al., 2019).

A change in one body segment will typically result in a change in the other segments in the body (Glassbrook et al., 2019). The distance from the bar to the center of pressure can help indicate the level of change in these segments, particularly when paired with kinematic joint angle data (Glassbrook et al., 2019). The results of the study conducted by Glassbrook et al. (2019) indicate that the mechanisms the body uses to maintain the balance of the system are concentrated at the hip joint and not at the knee or ankle joint. A wider stance is also often employed when performing the low-bar back squat (Escamilla, Fleisig, Lowry, et al., 2001), and
anecdotally it is performed to suit the hip structure of the lifter to allow them to obtain the required depth. An increased stance width also acts to effectively increase the base of support (Glassbrook et al., 2019).

CONCENTRIC REGIONS OF THE SQUAT

*Pre-sticking region (acceleration)*

Van Den Tillaar et al. found across low and high-bar groups there was no significant difference in muscle activity in the lower and upper erector spinae. However, high-bar squatters did exhibit higher amounts of lower and upper erector spinae activation as compared to that of low-bar squatters when standardizing squatting loads, stance width, and depth (Van Den Tillaar et al., 2020). Varying the intensities on the squat, instead of maintaining a standardized load, could change these observations. The pre-sticking region is comprised of the coupling between the rising of the thigh and falling of the trunk (Maddox et al., 2020). The gluteus maximus muscle shows the greatest activation at the start of the squat. Hip musculature cannot be too active early on in the squat because it may cause a disadvantageous position moving into subsequent regions of the squat (van den Tillaar et al., 2021). Too early increased activation of the hip musculature in the squat may cause an extra stretch in the gluteus maximus and erector spinae (Van Den Tillaar et al., 2021) However, there was limited horizontal movement in this study due to the use of a smith machine, which was a limitation discussed by the authors (Van Den Tillaar et al., 2021).

Muscle activity varies from region to region of the squat. The muscle activity of the semitendinosus increased their muscle activity from the pre-sticking region to the post-sticking region (Kristiansen et al., 2021). The biceps femoris and glute activity increased across each region (Kristiansen et al., 2021). The increase of biceps femoris activity from pre-sticking region to post-
sticking region could contribute to the sticking region due to the co-contraction of the knee extensors and flexors (Kristiansen et al., 2021).

**Sticking region**

Van Den Tillaar et al. (2020) found that there was no significant difference in EMG data when comparing high-bar squatting with low-bar squatting. High-bar squat did result in greater muscle activation when compared to low-bar squatting when standardizing squatting loads, stance width, and depth. Varying the intensities on the squat instead of maintaining a standardized load could change these observations. Activation of all erector muscles increased in the sticking region when intensities were standardized from group to group (Kristiansen et al., 2021). When squatting with supra-maximal loads, the prolonged coupling of the rising on the thigh and falling of the trunk continues into the sticking region (Maddox et al., 2020). This results in a large moment arm about the hip extensors that causes failure (Maddox et al., 2020). The posterior chain’s involvement of the squat may be decreased due to the lumbar spines ability to tolerate excessive loads (Maddox et al., 2020). The largest hip moments were found at V0 for all three squat conditions (Kristiansen et al., 2021). Large hip moments in correspondence with a poor position for the gluteus maximus to produce force contribute to the sticking region (Kristiansen et al., 2021).

The sticking region is due to a mechanical disadvantage in positions (Van Den Tillaar et al., 2021). The sticking region occurs due to the weak position in length-force relationships in the musculoskeletal system (Van Den Tillaar et al., 2021). There is not significant increase in muscle activation of the erector spinae iliocostalis and longissimus when in the sticking region of the squat (Larsen et al., 2021; Van den Tillaar, 2019). In a study conducted by Van Den Tillaar comparing different descent speeds and its effects on the sticking region, it was found that in repetitions 2 and 3 there was a significant drop in muscle activation in the erector spinae muscles in the fast descent
group (Larsen et al., 2021; Van den Tillaar, 2019). However, in the slow and regular-descent groups, there was an increased muscle activation in each subsequent rep (Larsen et al., 2021; Van den Tillaar, 2019). Additionally, it was found that descent speed influences when the sticking reaching occurs (i.e., earlier, or later) (Larsen et al., 2021; Van den Tillaar, 2019). When reaching the sticking region, the erector spinae muscles reached their peak muscle activation (Larsen et al., 2021; Van den Tillaar, 2019). Peak knee and ankle moments were the highest at the bottom position. However, they then decreased through the subsequent regions in all three squat conditions (Kristiansen et al., 2021). Since the peak hip, knee, and ankle moments are all at the bottom position, it could be ascertained that this would be the most difficult position since it is the least advantageous point to exert force (Kristiansen et al., 2021). However, peak knee moments occur at \( v_0 \) and \( v_{\text{max1}} \) during the ascent phase, which may not impact squat performance to a considerable degree. This is because the transition from eccentric to concentric at the bottom position of the squat is aided by elastic/stretch reflex contributions to force production (Kristiansen et al., 2021). The gluteus maximus could be thought of as an agonist to the sticking region, because of the musculature’s increased EMG activity from the pre-sticking to the sticking region (Kristiansen et al., 2021).

Post-sticking region (deceleration)

Van Den Tillaar et al. (2020) found a significant difference in EMG data of the upper and lower erector spinae in the post-sticking region when comparing high-bar and low-bar squatting. However, high-bar squatting resulted in a much greater muscle activation in the lower erector spinae when standardizing squatting loads stance width and depth. Erector spinae muscle activation decreases in the concentric phase of the squat (Van Den Tillaar et al., 2020). Varying the intensities on the squat instead of maintaining a standardized load could change these
observations. Hip moment decreased in the post-sticking region (Kristiansen et al., 2021). The gluteus maximus muscle shows the least activation at the end of the squat (Van Den Tillaar et al., 2021). However, there was limited horizontal movement in this study due to the use of a smith machine, which was a limitation discussed by the authors (Van Den Tillaar et al., 2021). However, in a different study conducted by Larsen et al. (2010), peak gluteus maximus activation was seen in the post-sticking region.

**Muscle activation of the regions**

The erector muscle increased activity in the sticking region for all conditions (high bar, low bar, and safety squat bar at equal intensities [3RM]) (Kristiansen et al., 2021). Additionally, no differences were found in the gluteus medius or adductor longus in any condition (Kristiansen et al., 2021). The gluteus maximus and biceps femoris muscles showed an increase in EMG activity in each region of the squat (Kristiansen et al., 2021). Furthermore, the semitendinosus increased EMG activity from the pre-sticking region to the post-sticking region in all three conditions examined (Kristiansen et al., 2021). While the quadriceps EMG data showed a decrease in activity from the pre-sticking and sticking region to the post-sticking region. Additionally, the gastrocnemius and soleus showed a decrease in EMG activity from the pre-sticking to the post-sticking region (Kristiansen et al., 2021). The ascent phase of the lift starts with the quadriceps muscles and soleus performing knee extension and plantar flexion, which decreases around the lowest velocity time point (vmin). Whereas the gluteus muscles and hamstrings increase their EMG activity (Kristiansen et al., 2021). The authors theorized that the reason the gluteal muscles low activity begins at the ascent phase is because of the large muscle length and the moment arms this could cause a disadvantageous mechanical position that does not allow for optimal force output (Kristiansen et al., 2021). Furthermore, Kristiansen et al.’s findings showed that the gluteus
maximus EMG initially peaked in the post-sticking region (Kristiansen et al., 2021). This may indicate that the muscle’s ability to produce the force required to help the hip extensor moment may not be optimal during the sticking region (Kristiansen et al., 2021). These finding support Van Den Tillar et al. (2020) who also observed that the gluteus maximus peaked in EMG activity firstly at 0.25 m of displacement. This coincided with the beginning of the sticking region in other studies (Kristiansen et al., 2021). Regardless of bar position, the sticking region occurs because of the combination of the large hip moment and disadvantageous position for the gluteus maximus to produce force (Kristiansen et al., 2021). Muscle activation of the erector spinae, soleus, vastus lateralis and rectus femoris decreases from the pre- to post-sticking region (van den Tillaar et al., 2020). Whereas as the gluteal musculature increases from the pre- to post-sticking region (Van Den Tillaar et al., 2020).

Effects of velocity on concentric regions

It is accepted that the muscles maintaining trunks upright posture (i.e., erector spinae) must function isometrically to stabilize the truck (Van Den Tillaar et al., 2020). The decrease seen in the erector spinae muscles is theorized to be due to the large moment arms in the pre-sticking region, which decrease when moving through the ascent phase of the squat (van den Tillaar et al., 2020). Varying the intensities on the squat instead of maintaining a standardized load could change these observations. A hip extension that is too early is undesirable because it could cause an anticlockwise rotation moment of the barbell and thereby increase the danger of slipping. In summary, it can be concluded that slow descent velocity caused lower peak force and velocities at vmax1 and vmin, and it takes longer in the sticking and post-sticking regions (Larsen et al., 2021; Van den Tillaar et al., 2019). It thereby increases the chance of failure since the sticking region is the weakest region of the lift. Based on the present findings, it is advised to athletes and coaches that
the descent velocity in back squats would be as high as possible in velocity, without losing control (Van den Tillar et al., 2019). This helps in the ascending part, to overcome the sticking region quicker and thereby decrease the chance of failure of the lifting the barbell backward.

SUMMARY

The current body of literature suggest that multiple factors such as, joint angles, joint moments, the regions of the squat, and muscle activation are affected by variations of squatting with the use of traditional loading. However, the literature has not set out to clearly understand the effects on these same variables with the addition of velocity-dependent resistance training. Therefore, this study hopes to illuminate how the additional use of velocity-dependent resistance training effects such things as muscle activations, joint angles, the regions of the squat, and joint moments. Due to the increase in concentric velocity, it is likely that there will be an increased muscle activation throughout the range of motion of the squat. Potentially there will be a difference of when the regions of the squat occur (i.e., the pre-stick, and post-sticking region) due to the faster eccentric portion of the squat. Finally, because velocity is now being manipulated (i.e., increased concentric velocity) there may be a difference in joint angles and joint moments.
CHAPTER 3
METHODOLOGY

GENERAL DESIGN

This study is quasi-experimental with a repeated measures design that takes place on one day. Squat stance, bar placement and footwear will be standardized across conditions.

PARTICIPANTS

This study was approved by the Institutional Review Board at Old Dominion University. Participants were informed of all study procedures and required to sign (i.e., agree to) consent forms prior to beginning the study. The study included 15 males between the ages of 18-30 years old. Inclusion criteria for this study was defined as participants having proper squatting knowledge, a minimum of 1 year resistance training in any capacity, resistance training a minimum of three times a week, and lower body training at least once a week. Exclusion criteria for participation in this study includes being free from lower extremity injuries such as bone breaks, ligament, and musculature tears, using orthotics, allergies to silver, and taking medication that cause dizziness. Additionally, participants were asked to refrain from strenuous exercise 24 hours prior to testing day. The participants in this study had an average training age of 7 years. The average load lifted for the 70% condition was 230 pounds, and the average load lifted in the 80% condition was 265 pounds.

PROTOCOL

This study took place over one day. Each participant’s stance width was 140 percent of shoulder width (Escamilla et al, 2001). Their bar placement was held constant on the top of the spine of the scapula. All participants squatted barefoot to eliminate any variation in footwear. The time of day for which testing took place was not regulated.


Experimental protocol

The risks and benefits of partaking in this study were explained to the participants; after consenting to participate, participants filled out a medical history form. Once the medical history was obtained, reflective markers were placed for motion capture. Next, but prior to beginning the testing protocol, participants were given 10 minutes for self-selected warm up.

Next, participants completed a 1-repetition maximum (1RM) protocol. The participants performed lifts from 70% to 100% of their self-reported 1RM in 10% increments. Participants performed 3 repetitions at loads of 70%-80%. From 90%-100%, the repetitions decreased to 1 until their last successful lift with the highest weight.

After completing the 1RM protocol, the participants were given a 3-5-minute break. Following this break, participants performed back squats with the same 70% and 80% loads as performed during the 1RM test, but with verbal and visual instruction to lift as fast as possible. Throughout the duration of the protocol, a Tendo unit was attached to the barbell. The participant was informed the Tendo unit measured their velocity during the upward phase of the squat. The participants were provided visual feedback during intentional maximal velocity squats via an iPad with the output from the Tendo unit (Figure 1). The participants were informed that a yellow line on the bar graph is the fastest rep they have achieved, a blue line means they were within 80% of their best rep, and red line means they were beginning to become fatigued refer to figure below.

INSTRUMENTATION

Force data was recorded using two Bertec force plates (FP4060-10, Bertec Inc., Columbus, OH). Three-dimensional motion capture data was collected using a 10 Vicon camera (Vicon Motion Systems, Los Angeles, Ca.). Vicon motion capture has an ICC value of 0.99 and 0.94 (Barker et al., 2006; Macleod et al., 2014). A Tendo unit was used to measure average
barbell velocity during the ascent phase. The Tendo unit was placed in line with the foot of the participant and the side of the barbell sleeve. This placement ensured that the most accurate displacement would be obtained, and therefore the most accurate velocity.

**Reflective marker placement**

Retroreflective markers were placed to track the trunk, pelvis, both thighs, shanks, and feet. Markers were placed on the first and fifth metatarsals, lateral and medial malleoli, lateral and medial epicondyles of the femur, the greater trochanters, anterior superior iliac spines, posterior superior iliac spines, and the acromion processes. Velcro straps were then placed around each shank and thigh, four rigid tracking clusters will be placed on each of the Velcro straps. There were an additional two markers placed on the posterior pelvis and four markers on the upper back for tracking. All tracking clusters were secured with athletic tape (Collins Sports Medicine, Raynham, MA). Prior to beginning the protocol, participants were instructed to stand in anatomical position to record a static trial.

**DATA ANALYSIS**

Visual3d was used for all data processing (v6, C-Motion Inc., Rockville, MD). An inverse dynamic model was created for each participant, consisting of the trunk, pelvis, right and left thigh, shank, and feet, which was created from a static calibration trial at the beginning of each data collection. Ground reaction force data and marker data was filtered using a 4th order Butterworth low-pass filter 5Hz. The three-dimensional ankle, knee, and hip angles were calculated using joint coordinate system approach. Variables of interest were average barbell velocity and peak hip and knee extensor moments during the ascent phase at self-selected and fast speed squats at 70% and 80% 1RM.
STATISTICAL ANALYSIS

Distribution of variables were assessed using the Sharpio-Wilk test. Peak hip and knee moments were the variables of interest and were normalized to participants body weight. Hip and knee moments were normally distributed for the 70% 1RM squats and for the 80% 1RM squats. 70% 1RM joint moments and 80% 1Rm joint moments were assessed using dependent t-tests in SPSS software (version 27, Armonk, NY). A two-sided alpha level of <.05 will be used as the threshold for statistical significance. Cohen’s D effect sizes were calculated for each variable.
CHAPTER 4

RESULTS

VELOCITY MOMENT INTERACTION

Descriptive statistics for average ascent velocity, hip moments, and knee moments at 70% 1RM and 80% 1RM are provided in Tables 1 and 2, respectively. Graphical representation of each subject’s data is provided in Figures 3-8.

There was a significant difference in ascent velocity between self-selected and instructed velocity at 70% 1RM (p<0.01, t=-5.73 and a Cohen’s d=-1.48). There was also a difference in hip moments when comparing self-selected and instructed velocity at 70% 1RM (p=0.024, t=2.53, and Cohen’s d=0.08). However, there was no difference between knee moments at self-selected and instructed velocity at 70% 1RM (p=0.92, t=0.11 and Cohen’s d=-0.48).

There was a significant difference in ascent velocity between self-selected and instructed velocity at 80% 1RM (p<0.01, t=-4.65 and a Cohen’s d=-1.21). There was also a difference in hip moments when comparing self-selected and instructed velocity at 80% 1RM (p<0.01, t=4.85, and Cohen’s d=1.25). However, there was no difference between knee moments at self-selected and instructed velocity at 80% 1RM (p=0.5, t=0.69 and Cohen’s d=0.55)
CHAPTER 5

DISCUSSION

The aims of this study were to 1) determine whether back squat velocity can be increased when instructed to squat faster at a set load and 2) how, biomechanically, increased velocity is generated. The first hypothesis was supported: participants displayed a significantly lower self-selected ascent velocity compared to their ascent velocity when instructed to squat as fast as possible. However, our second hypothesis was only partially supported as peak hip moments, but not peak knee moments, were significantly greater when instructed to squat with maximal velocity. The findings of this study illustrate that typical squats are not performed with maximal velocity; however, moving with intent can result in increased velocity predominately due to increased contributions from the hip musculature.

Previous studies have shown that velocity can act as a performance variable, in lieu of load, in back squatting (Weakley et al. 2021). However, there is a paucity of literature regarding the influence of velocity on lower extremity kinetics. This study found quite large differences in velocity between intentional and self-selected velocities (average increase of 25% across loads). Thus, this study has shown that intent to lift concentrically with maximum velocity is an important factor. The findings of this study raise questions about the effectiveness of velocity-based training: velocity-based training assumes that participants are always lifting with maximal velocity intent. Because it is subjective to the participants ability to lift intentionally, application of average (i.e., velocity throughout the range of motion of one singular rep) velocities for each rep may be incorrect. Additionally, these findings support the need to create a velocity profile for the athlete. In fact, it is possible multiple profiles are required: one for lifting at self-selected velocities and one for maximal velocities. Also, the application of the predication equations
based upon a lifter velocity may be moot due to the fluctuations in a lifter’s intent to lift with maximal velocity.

This study found significant difference between self-selected and instructed velocities in participants. These findings may indicate that participants are not lifting as their true maximal velocities. Previous literature examining velocity degradation with increasing intensity has found similar findings to the self-selected velocities of this study (Jovanović et. al., 2012). Jovanović et. al., (2012) found that squatting at 70% intensity for 3 repetitions resulted in an average velocity of .50 m/s. Additionally squatting at 75% intensity for 3 repetitions resulted in an average velocity of .47 m/s (Jovanović et. al., 2012). Similarly, Weakley et. al., (2021) found that squatting at 80% 1RM resulted in a velocity of .55 m/s (Weakley et. al., 2021). In this current study squatting at 70% intensity for 3 repetitions at a self-selected velocity resulted in an average velocity of .54 m/s. Squatting at 80% intensity for 3 repetitions at a self-selected velocity resulted in an average velocity of .49 m/s. This indicates the previous literature may be accurate in creating self-selected velocity profiles for lifters. However, may be flawed due to a lifter’s wavering intent to lift maximally from day to day or training session to training session. Findings in this study show that squatting with instruction/intent results in 25% average increase in velocity. While it is known that individual participants velocity profiles may vary drastically as shown by Jovanović et. al., (2012) and Weakley et. al., (2021) (Jovanović et. al., 2012, Weakley et. al., 2021). They may not be exhibiting their maximum potential as a self-selected velocity could be significantly lower than that of an instructed one, maybe by 25%. Therefore, previous literature regarding performance adaptations may be showing only a fraction of the adaptations lifters could be accruing.
No previous literature has examined the effects of velocity on squat biomechanics, applying the beliefs of dynamics that a greater internal load must be generated to move a resistance further and/or faster. As such, previous literature reports that as external loads increase, which would be required with increased velocity, there is an increase in joint moments in squatting (Maddox et al., 2021. Moir et al., 2012). Maddox et al. (2021) compared lower extremity kinematics and kinetics across maximal and submaximal back squats, finding that hip moments were decreased by 0.41Nm/kg in submaximal vs. 1RM loads, but that knee moments were similar across submaximal and successful (1RM) lifts. It is unlikely the 0.16Nm/kg increase in hip moments when squatting with intentional velocity found herein would match those of 1RM loads. However, squatting with intentional maximal velocity increases emphasis on the hip musculature, which could have positive effects on maximal squat strength.

Despite limited research existing that has examined biomechanics of velocity differences in resistance training, much research has been performed in other tasks. For instance, when running with higher velocity, a similar increase in joint moments at the knee occur (Petersen et al., 2014). Furthermore, research has also shown in order in to increase take off velocity in countermovement jumps, joint moments increase (Vanrenterghem, et al. 2004). Moving from submaximal to maximal take off velocity, knee joint moments maximize at 75% take of velocity, and decrease at each subsequent increased take off velocity (Vanrenterghem, et al. 2004). As participants move from submaximal to maximal take off velocities the hip joint moments increase with each condition and are the largest contributor for increasing take off velocity (Vanrenterghem, et al. 2004). In a study conducted examining the effects of a flexible barbell and a steel barbell at a set load of 30% estimated 1RM significant differences were found in maximum movement velocity (Hutchison et al. 2019). This study by Hutchison et al. (2019)
found that the hip moment was the only lower extremity joint moment to increase from the steel barbell condition to the flexible barbell condition as the movement velocity increased (Hutchison et al. 2019). Similar results to Hutchison et al. (2019) were found in this study; however, a steel bar was used throughout the duration of this research. Combined with the results of this thesis, it appears that increased velocities are generated via increased contributions from the hip (i.e., hip moments) and not from the knee (Hutchison et al. (2019); Vanrenterghem, et al. (2004). Hip and knee joint moments found within this study were with in range of previous literature (Swinton et. al, 2012, and Chloe et. al., 2021).

While the results of this thesis suggest that training at higher velocities could emphasize hip strengthening, it is important to note the impact of modifiable postures during a squat. For example, widening stance width has been shown to increase hip joint moments (Escamilla et al. 2001, Kristiansen et al., 2021, Bloomquist et al., 2013). Our joint moments were like those of a back squat with medium stance width (i.e., 140% of shoulder width) (Escamilla et al. 2001). In a study conducted by Escamilla et al. have shown that varying stance width influences joint moments. Hip extensor moments were smaller for narrow stance squatting, while for wide stance squatting hip extensor moments were larger. It is possible squatting with maximal velocity intent would augment these findings. For example, increased hip moments seen at higher squat velocities could be further heightened by performing these with a wider stance width. Studies by Kristiansen et al. have shown that varying bar placement has an effect of joint moments (Kristiansen et al., 2021). Larger hip moments are found in low bar back squatting as compared to high back bar squatting (Kristiansen et al., 2021). Future studies should aim to examine the effects of bar placement and intent of maximal velocity lifting on joint moments.
Squatting with a low-bar placement results in a more vertical shank angle as compared to its high bar counterpart. Similarly, when squatting with a restricted squat stance (i.e., positioning a wooden board at the distal aspect of the foot) there is a more vertical shank angle than that of unrestricted squats (Fry et al., 2003). This more vertical shank causes an increase in trunk flexion, this increase in flexion results in greater increases in hip moments (Fry et al., 2003, List et. al., 2013). When examining alterations in maximal back squatting Maddox et al., (2021) found a decrease in knee flexion as compared to submaximal squatting (Maddox et al., 2021). During testing participants were instructed to have the back of the thigh touch the back of their calf. This decrease could be a result of greater increased trunk flexion to accommodate the heavier load being lifted (Maddox et al., 2021). This increased trunk deviation in 1RM squats as compared to submaximal back squatting could result in larger hip moments (Maddox et al., 2021). In this research it was also found the there are larger hip moments seen in 1RM squatting as compared to submaximal back squatting (Maddox et al., 2021). In this research larger hip moments were seen in the instructed condition. It is likely that these increased hip moments may have been a product of increased trunk flexion in an attempt to move the barbell with greater velocity.

**Future Research**

This study has shown joint moments increase with greater velocities during a weighted back squat; however, the effect this has on muscle activation was not examined. Future research should examine how muscle activations are affected by changes in velocity at equated loads. This study focused on male participants. Considering the anatomical (segment lengths, circumferences, etc.), strength, and joint-level biomechanical (e.g., females land with knee dominant loading) differences between sexes, the results of this thesis may not be generalizable.
to females. Studies implementing a sex comparison along with velocity-based training are warranted for individualized training prescriptions. Furthermore, future research should focus on how application of velocity-based training could be implemented to aid in greater muscle hypertrophy gains at the hip. Lastly, a comparison of joint moments across bar placements accompanied by velocity differences would be pertinent. This study standardized bar placement to the spine of the scapula, therefore reducing the impact of this confounding variable. It is likely changing the barbell position on the back would influence results.

This study has given insight to changes in hip and knee kinetics when maximal velocity intent is used by experienced lifters. The information generated via this thesis gives insight to coaches and athletes who hope increase force generated by the hip. Velocity may play a major role in promoting advantageous adaptions while not having the need to increase load on lifters. Increasing strength by using maximal velocity may be an optimal way to not only reduce the need for increasingly heavy loads, but aid and achieving increases in load lifting more quickly when it is needed.
**Table 1.** Mean and STD. Normalized Joint Moments and Average Velocity during 70% 1RM Condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Vertical Velocity m/s</th>
<th>Hip Moment Nm/kg</th>
<th>Knee Moment Nm/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-Selected</td>
<td>0.54 ±0.06</td>
<td>-2.96 ±0.54</td>
<td>1.84 ±0.48</td>
</tr>
<tr>
<td>Instructed</td>
<td>0.69 ±0.10</td>
<td>-3.12 ±0.43</td>
<td>1.83 ±0.44</td>
</tr>
</tbody>
</table>

**Note:** m/s: meters per second, Nm/kg: moment normalized to body mass

**Table 2.** Mean and STD. Normalized Joint Moments and Average Velocity during 80% 1RM Condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Vertical Velocity m/s</th>
<th>Hip Moment Nm/kg</th>
<th>Knee Moment Nm/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-Selected</td>
<td>0.49 ±0.07</td>
<td>-3.21 ±0.50</td>
<td>1.94 ±0.57</td>
</tr>
<tr>
<td>Instructed</td>
<td>0.60 ±0.10</td>
<td>-3.35 ±0.50</td>
<td>1.84 ±0.43</td>
</tr>
</tbody>
</table>

**Note:** m/s: meters per second, Nm/kg: moment normalized to body mass
Figure 1. Visual feedback from the Tendo unit that was provided to participants.
Figure 2. Experimental protocol.

- Participant fills out consent and medical history.
- Participant does a self-selected warm-up.
- Reflective markers are placed.
- Participant squats 70%, 80%, of estimated 1RM for 3 reps.
- Participant squats 90%, 100% of estimated 1RM for 1 rep.
- Participant squats the same 70%, 80% of estimated 1RM for 3 reps with max concentric velocity.

Figure 3. Self-Selected and Instructed Velocity during 70% Condition.

Note: m/s: meters per second
Figure 4. Self-Selected and Instructed Velocity during 80% Condition.

Note: m/s: meters per second

Figure 5. Peak Hip Moment during 70% Condition for Self-Selected and Instructed Velocities.

Note: Nm/kg: moment normalized to body mass
**Figure 6.** Peak Hip Moment during 80% Condition for Self-Selected and Instructed Velocities.

**Figure 7.** Peak Knee Moment during 70% Condition for Self-Selected and Instructed Velocities.

**Note:** Nm/kg: moment normalized to body mass
Figure 8. Peak Knee Moment during 80% Condition for Self-Selected and Instructed Velocities.

Note: Nm/kg: moment normalized to body mass
REFERENCES


Petersen, Jesper, et al. "Comparisons of increases in knee and ankle joint moments following an increase in running speed from 8 to 12 to 16 km· h− 1." *Clinical Biomechanics 29* 9 (2014): 959-964.

Rodríguez-Rosell, D., Yáñez-García, J. M., Sánchez-Medina, L., Mora-Custodio, R., & González-Badillo, J. J. (2020). Relationship between velocity loss and repetitions in


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Master’s Thesis – Effects of Intent on Hip and Knee Moments in Back Squats
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Graduate Teaching Assistant – Old Dominion University - 2022-2023
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- Barrett KB, Parrish K, Bennett HJ. Rotation Sequences for the Calculation of Shoulder Kinematics of the Volleyball Attack. Journal of Biomechanics
- Barrett KB, Parrish K, Laverdure, P. Interventions to Improve Shoulder Health in Volleyball Players: A Systematic Review. Under review in Injury Prevention

ABSTRACT CO-AUTHORSHIP
- Barrett KB, Parrish K, Luginsland LA, Bennett HJ. Does direction matter? An analysis of the volleyball attack. American Society of Biomechanics, Knoxville, TN, August 2023
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