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EFFECTS OF KNEE SLEEVES ON KNEE MECHANICS DURING SQUATS AT
VARIABLE DEPTHS

by

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B.S. May 2009, United States Coast Guard Academy

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE IN EXERCISE SCIENCE

HUMAN MOVEMENT SCIENCES

OLD DOMINION UNIVERSITY
December 2018

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ABSTRACT

EFFECTS OF KNEE SLEEVES ON KNEE MECHANICS DURING SQUATS AT VARIABLE DEPTHS

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The squat is a functional, compound and multi-joint exercise that targets several muscles of the lower body and is widely used in both athletics and many exercise programs. This exercise has been the subject of many studies, comparing different squat variations and examining how external gear, such as squat suits and knee wraps impact the exercise. The aim of this study was to assess the effects of wearing neoprene knee sleeves on lower extremity kinematics, kinetics, and muscle activations during weighted back squats. Fifteen resistance trained men and women, aged 28 ± 5 years, from the local fitness community and university campus performed a one-repetition maximum (1-RM) of a deep squat during two separate sessions (5-7 days apart), one session while wearing knee sleeves and one session without; this was counterbalanced. A deep squat was classified as calf-hamstring contact in the bottom of the squat. Post 1-RM testing, two sets of three repetitions at a submaximal weight (80% 1-RM) were performed, one with deep squats (D) and one with parallel squats (P). A ten-camera motion capture system was used to collect three-dimensional (3D) kinematics and electromyography (EMG) was used to record muscle activity of the vastus medialis, rectus femoris, gluteus maximus, gluteus medius, and biceps femoris. Between sleeve and no-sleeve conditions, no significant differences were found in subject's 1-RMs or in ratings of perceived exertion (RPE) during 1RMs or submaximal lifts. No significant differences were found in knee joint angles at maximum depth or in knee moments or powers during descent, maximum depth, or ascent. Only

integrated gluteus maximus (GM) activation during ascent (full depth to standing) was significantly greater during no-sleeve (1.35 ± 0.52 %MVIC*seconds) compared to the sleeve (0.98 ± 0.48 %MVIC*seconds) condition ($p=0.05$; Cohen's $d = 0.74$) during 1-RM testing. For submaximal sets, a significant main effect was found for external rotation moments during descent, where moments were larger for the sleeve compared to no-sleeve condition ($p=0.05$; $d = 0.67$). No other kinematic or kinetic differences were found between conditions. Similar to maximal sets, greater integrated GM activation was found without sleeves (0.53 ± 0.19 %MVIC*seconds) compared to sleeves (0.44 ± 0.13 %MVIC*seconds) ($p=0.04$; $d = 0.55$). No other differences were found in muscle activations during maximum or sub-maximum squats. Comparing the sub-maximal squat depths, peak knee flexion angles were significantly greater ($p < 0.01$; $d = 1.09$), knee extension moments increased at depth ($p=0.03$; $d = 0.57$), and negative knee powers increased during the descent ($p=0.03$; $d = 0.58$) in deep compared to parallel squats. Overall, wearing knee sleeves during maximal and sub-maximal back squats has little to no effect on muscle activity or joint mechanics. With no significant differences in 1-RM or RPE, it appears that wearing knee sleeves doesn't provide a mechanical advantage over squats without knee sleeves among resistance-trained adults.

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DEDICATION

This paper is dedicated first and foremost to my parents who have always encouraged me to charge at my goals head-on, academic, athletic or otherwise. This is also dedicated to all my fitness enthusiast friends and clients I've trained, both past and present. Keep lifting and stay strong!

ACKNOWLEDGEMENTS

Over the last two years, countless hours were dedicated to the completion of this thesis. First and foremost, thank you to my committee, Dr. David Swain, Dr. Hunter Bennett and Dr. Patrick Wilson. Dr. Bennett took the time to teach me the ins and outs of the biomechanics lab and guide me through the thesis process. Thank you to Old Dominion University for being an extremely military friendly college, enabling me to finish my degree while serving as an active duty Coast Guard member. Thank you to the graduate lab assistants, Abby and Ryo for their dedication to helping me with each and every data collection, to include early morning and late evening sessions. The multiple sets of complimentary knee sleeves and support from Rehband was greatly appreciated. Thank you to my friends and parents for all the support they have given me over this period. Lastly, a tremendous thank you to my 15 subjects who committed to not only one, but two 1.5-hour sessions with me in the biomechanics lab, without any cancellations, despite them all having careers and hectic schedules of their own. This wouldn't have been possible without your willingness to help me and enthusiasm for strength training, I am extremely grateful.

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I. INTRODUCTION

The squat is a widely used exercise both in athletics and other exercise regimens. The squat is a functional, compound and multi-joint exercise that targets several muscles of the lower body and the lumbo-pelvic-hip complex (Flanagan et al., 2003). This exercise has been the subject of countless biomechanical evaluations in the areas of kinetics, kinematics, and muscle recruitment during different squat stance and load variations (Flanagan et al., 2003). The back squat is also a multi-planar movement, involving all available motions at the lower extremity joints (Schoenfeld, 2010). The squat exercise involves two distinct phases: lowering and lifting, both of which are facilitated by movements of the lower extremities and trunk (McKean et al., 2010). The importance of squat depth (lowest point) is debatable, but depth should be limited to movement that can be properly and safely executed without unfavorable compensations such as collapsing knees, the lower back rounding or the chest falling. The ascent of the squat reverses the descent phase, with the hips being the primary mover and the weight kept in the heels and lateral parts of the foot. To rise up from the bottom of the squat, the gluteal muscles are contracted and the athlete must drive through the heels as the knees and hips extend (Haff & Triplett, 2016).

The three main joints involved during the squat are the ankle, knee and hip. The ankle provides support and power generation during the squat (Schoenfeld, 2010). Based upon peak joint moments during squat descent at maximum knee flexion (full squat depth) and during ascent, passing through the point of 45° of knee flexion (Escamilla et al., 2001), the ankle provides ~7% of the total joint moment, whereas the knee and hip each produce ~46-47% to perform a full depth squat.

Biomechanics of the Ankle Joint

Although the ankle joint provides a reduced contribution to the squat movement, the ankle is integral in providing support and mobility for the foot/floor interaction during squatting. The talocrural joint, where the tibia, fibula and talus meet, allows the movement of dorsiflexion and plantarflexion during the squat, where great mobility is required. The gastrocnemius and soleus, the muscles found at the shank, or lower leg, are the primary muscles responsible for ankle movement and are utilized in all contraction types (concentric, isometric, and eccentric). The gastrocnemius assists in offsetting knee valgus moments and limits posterior tibial translation, as the medial head of the gastrocnemius acts as a dynamic knee stabilizer during squats (Bell et al., 2008; Hay et al., 1983). Moderate levels of activation are found in the gastrocnemius during squats, with the greatest activity found as knee flexion increases and less activity as the knees extend (Donnelly et al., 2006). The soleus has been noted to be more active than the gastrocnemius when squatting to great depths (Toutoungi et al., 2000). Squat form may be compromised if weakness exists in the musculature of the ankle (Bell et al., 2008).

Biomechanics of the Knee Joint

The knee joint complex is comprised of the tibiofemoral (classically referred to as knee joint) and patellofemoral joints (Schoenfeld, 2010). The squat exercise can involve as much as 140° knee flexion or as little as 20° knee flexion (Marchetti, 2016), depending on the target depth. An exerciser can choose to utilize any range of motion as a specific or optimal squat depth does not exist and is assessed per individual. For well-trained and coached athletes utilizing a progressive loading program, deep squats offer effective training to strengthen and protect against injury (Hartmann et al., 2013). Typically, squats should not cause injury to the healthy anterior cruciate ligament (ACL) since the ACL's failure load range is much greater than peak

knee anterior shear forces between 0-60° of knee flexion (Noyes et al., 1984; Steiner et al., 1986). Moments at the knee can vary during the back squat with lower moments recorded in low bar back squats compared to high bar back squats (Wretenberg et al., 1996). The quadriceps, hamstrings and gastrocnemius comprise about 98% of the total cross-sectional area of the knee musculature (Wickiewicz et al., 1983). During a squat, the quadriceps muscles (vastus lateralis, vastus medialis, vastus intermedius and rectus femoris) are utilized both eccentrically (lowering phase) and concentrically (lifting phase). The hamstring muscles (biceps femoris, semitendinosus, and semimembranosus) act as eccentric and concentric hip flexors during the lowering and lifting phases, respectively (Ebben et al., 2000). Both the hamstring and quadriceps muscles co-contract to enhance the integrity/stability of the knee joint during the squat, thus requiring both muscles to be of adequate strength (Schoenfeld, 2010). Moving from the ankle to knee joint, the hip is the last joint to be assessed in examination of the back squat.

Biomechanics of the Hip Joint

Previous research claims the average hip range of motion while squatting is $95 \pm 27^\circ$ of flexion (Hemmerich et al., 2006). Range of motion also affects torque at the hip joint, as hip flexion increases, torque increases, with maximal torque seen at the bottom of the squat (Nissell et al., 1986). Greater hip extensor moments have also been found with increasing squat depth from 90° to parallel but squatting from parallel to deep does not result in further increases in hip torques (Wretenberg et al., 1993). Hence, avoiding squat depths greater than 90° will limit hip moments. The main hip muscles used while squatting are the gluteus maximus (GM) and the hamstrings (biceps femoris (BF) and semitendinosus). The GM act eccentrically during the descent of the squat to maintain control and overcome resistance while working concentrically during the ascent (Schoenfeld, 2010). GM activation is significantly greater during deep squats

than partial and parallel squats (Schoenfeld, 2010). The hamstrings are only moderately active while squatting, producing about half the amount of activation compared to a leg curl and stiff-legged deadlift (Schoenfeld, 2010). With the hip, knee and ankle working together, combined with proper mobility, an athlete can safely complete a squat. However, the back squat is one of many variations of the squat exercise, all of which impact lower extremity biomechanics and provide the ability to focus on certain joints, musculature, and movements.

Squat Variations

There is an abundance of research comparing different variations of the squat, such as modifying stance width and displacing to different depths. Not one specific squat prescription exists for everyone, as there are multiple factors to consider such as mobility, training goals, kinesthetic awareness and individual physical abilities. Several studies have compared aspects of the front and back squat, with results showing no significant difference between shear forces on the knee and no significant variance between muscle activity in most of the involved muscles (Contreras et al., 2016; Diggin et al., 2011; Gullett et al., 2009). Regardless of squat depth (parallel or deep), positioning the barbell high on the back emphasizes knee loading, while low bar positions emphasize hip loading (Wretenberg et al., 1996). Concerning squat depth, the consensus within many studies is that if proper technique and progressive loading is used, deep squats are effective and safe and can help with protection against injuries, while also strengthening the lower body without increasing the risk of injury to passive tissues (Calhoun et al., 1999; Chandler et al., 1989; Hamill et al., 1994; Kulund et al., 1978; Panariello et al., 1994). However, squat depth does affect lower extremity loading, as deep squats increase hip joint loading compared to parallel squats (Wretenberg et al., 1996). Varying stance widths can also change the biomechanics of the back squat (Escamilla et al., 2001). Utilizing a wide compared to

narrow stance during back squats results in: greater ankle angles, reduced knee angles, decreased joint moments in the ankle, knee and hip, and greater muscle activity in the hamstrings, gluteus maximus and ischial fibers of the adductor magnus (Escamilla et al., 2001). The many variations in squat style, bar positioning, foot positions, and depths utilized all influence lower extremity loading, which can be tailored to an athlete's needs. Similar to modifying technique, external equipment (training accessories) is also commonly utilized to assist in lifting greater loads and emphasizing different muscular adaptations.

Squat Suits

Squat suits are worn as supportive equipment to lift maximal weight during competition. They are cut and fit much like a weightlifting singlet but are made of a more constricting material. The majority of competitive powerlifters are able to increase their 1-RM while wearing a squat suit (Blatnik et al., 2012). Elastic energy is thought to be stored during the eccentric phase of the squat and then released during the concentric phase, allowing the lifter to lift increased weights through greater force, velocity and power (Doan et al., 2003). During a study involving elite and professional male powerlifters, kinetic and kinematic characteristics were found to be significantly different between squats performed with squat suits and without squat suits (Blatnik et al., 2012). Eccentric force was significantly higher with a squat suit during 100% 1-RM, concentric velocity was significantly higher during all squat percentages (80% 1-RM, 90% 1-RM and 100% 1-RM) and peak concentric power was significantly higher at 80% 1-RM and 90% 1-RM while wearing a squat suit. The increased power and velocity values found suggest the potential to lift heavier weight while using a squat suit (Blatnik et al., 2012). If a squat suit, made of similar material to the knee sleeves in question, causes kinetic and kinematic changes to the squat and potentially increases maximal weight lifted, speculation arises as to how

knee sleeves affect the squat. Another accessory common to powerlifters is the knee wrap, thought to help lifters safely lift more weight.

Knee Wraps

There are several strength training accessories that athletes and recreational exercisers use for a multitude of different reasons, mostly for enhancing training or preventing injury. Examples include weightlifting shoes, wrist straps, wrist wraps, weightlifting belts and bench press shirts. Primarily used in heavy back squats, knee wraps (an elastic material) have previously been found to increase peak power output during back squats through the usage of elastic energy (Lake et al., 2012). Storage of elastic energy during a fast lowering phase can then be released during ascent, resulting in increased vertical impulses (force * time), improving squat performance (Lake et al., 2012).

External loads lifted have been noticed to increase with the use of a knee wrap. With the knee wrap being made of elastomeric material and polyester, it springs back to its original shape after it is deformed or stretched. When mechanically deformed, the elastic energy stored in the knee wrap is transferred into kinetic energy and added to the lifter (Gomes et al., 2014). Knee wraps are applied in a specific way, the “spiral technique” and the “X technique” being the two commonly used applications (Marchetti et al., 2015). It was determined that both techniques increase the carry-over effect and peak forces were significantly greater with the wraps on but were not different between methods (Marchetti et al., 2015). Considering maximum weight lifted, the knee wraps appear to be a helpful accessory but there are disadvantages to be considered. Some drawbacks of using knee wraps are 1) wrapping technique likely changes the muscles recruited and possibly compromises knee joint integrity (Lake et al., 2012), 2) knee wraps may involve significant occlusion, which can be painful and can alter barbell patterns in

Olympic lifting (Harman & Frykman, 1990) and 3) they may increase patellofemoral compression (Marchetti et al., 2015). Athletes utilizing wraps may not be able to wear them for an extended duration due to high levels of occlusion from the intense wrapping required and often remove the wraps after each lift due to pain and tourniquet-like effect they create (Gomes et al., 2015; Harman & Frykman, 1990). Although yet to be determined, reduced amounts of occlusion are predicted while using knee sleeves due their thinner, more pliable composition and they are generally not worn as tightly. Since knee wraps can be too tight to the point of movement and agility restriction, they are less popular amongst Olympic lifters although widely used by powerlifters (Harman & Frykman, 1990). Knee wraps also demonstrated motion restriction around the hip joint, resulting in a more upright position, and forcing greater flexion of the knee (Lake et al., 2012). The knee sleeve, an alternative to the knee wrap, may not cause the same squat mechanics alterations found with knee wrap usage.

Although knee wraps and knee sleeves likely share similarities in their applications of stored elastic energy, the mechanics of the knee sleeve during weight lifting are unknown. To highlight some general differences for the user, there is no complex technique or assistance required to put on the knee sleeves, just proper sizing. The sleeves can stretch and degrade over time, in which case, a new pair can be purchased. Although knee sleeves for weight lifting haven't been previously investigated, softer and less dense rehabilitative knee sleeves have been investigated. Similar to knee wraps, knee sleeves surround the knee joint with elastic material, possibly providing increase stability/support for rehabilitation and prevention of injuries.

Knee Sleeves and Rehabilitation

Currently there is no research done on the popular neoprene knee sleeve that can be frequently seen being worn amongst many different lifting communities. A fair amount of research on similar support pieces exist, such as thinner knee sleeves or braces and taping of the knee, focusing on knee injuries, typically in a rehabilitation setting and not under heavy loads (Bryk et al., 2011; Park & Lee, 2016; Schween et al., 2015). Improvements have been noted amongst knee osteoarthritis (KOA) patients while using knee sleeves, in the areas of joint position sense, pain, stiffness and function, enabling them to continue exercise and complete physical therapy (Mazzuca et al., 2004; Tiggelen et al., 2008). Walking with an elastic knee sleeve reduced knee adduction angles, moments and impulse in persons with KOA, resembling a normal gait. A potential mechanism behind the improvements provided by these knee sleeves is increased proprioception (Schween et al., 2015). Increased proprioception using knee sleeves may be similar to that of kinesio tape, which induces continuous contraction of muscles under the taped skin through gamma reflexes (Park & Lee, 2016). The tape on the skin is thought to increase cutaneous sensation, producing a strong proprioceptive cue (Park & Lee, 2016).

Knee Sleeves and Injury Prevention

In addition to applications for KOA, elastic knee sleeves may positively impact ACL injury prevention. A previous investigation found that knee sleeves reduced tibial translation a small but significant amount (Csapo et al., 2016). The knee sleeves appear to have a load dependent response, as the greater the elongation of the sleeve, the greater resistive force provided by the sleeves (Csapo et al., 2016). Thus, it appears knee sleeves may provide similar enhancements as knee wraps during back squats. However, knee sleeves may provide a more

convenient and less painful form of assistance due to their thinner and more flexible composition. They also possess more versatility as they are commonly used in not only the back squat, but Olympic weightlifting, walking lunges, and box step-ups, to name a few exercises, whereas knee wraps are primarily used by powerlifters during the back squat. Nevertheless, the true impact of knee sleeves on back squat mechanics remains unknown. Given the popularity of knee sleeves in weight lifting, an investigation is warranted.

Hypothesis

We hypothesized that while using knee sleeves for maximal and sub-maximal back squats: 1) the support provided by the knee sleeve will reduce muscle activations compared to not wearing the knee sleeve, 2) loads on the knee joint will be reduced while wearing knee sleeves and 3) knee joint angles will decrease while wearing knee sleeves due to the fabric causing a physical barrier between calf and thigh contact. Additionally, we hypothesize that wearing knee sleeves will 1) increase a lifter's 1-RM and 2) decrease rating of perceived exertion (RPE) during submaximal lifts.

Statement of Purpose

The purpose of this study is to assess the effects of wearing neoprene knee sleeves on lower extremity kinematics, kinetics, and muscle activations during weighted back squats.

Significance

Determining what knee sleeves, an external piece of equipment, actually do to the lower limb muscles and joints, and how they alter the back squat, will help athletes, coaches and recreational fitness enthusiasts determine if they should be wearing knee sleeves. Given the scarcity of information regarding knee sleeves, yet vast popularity of utilizing this training

accessory, this study will provide the first empirical evidence of alterations, if any, in lower extremity biomechanics due to knee sleeves.

Delimitations

1. All subjects were healthy, with no history of knee injuries.
2. Subjects were adults between the ages of 18-55 years old.
3. Subjects resistance trained at least 3 times a week, at least 2 of the days including lower body exercises but only 1 day needed to include some form of weighted squats.
4. Subjects had at least one-year experience back squatting at or near maximal loads.
5. Subjects all currently use knee sleeves to back squat and have done so for at least 6 months.

Limitations

1. We could not blind subjects to the fact they were wearing knee sleeves. Although subjects were blinded to the weight they were lifting, the placebo effect will always remain, possibly promoting more confidence in a lifter, if they believe their knees are being protected. We believe that blinding subjects to the weight they were lifting was the best way to diminish the possibility of the placebo effect, although it is impossible to completely remove this factor. Randomizing the order of sessions (i.e., first session with sleeves/second session without sleeves and vice versa) was also performed to minimize placebo and/or training effects.
2. There are many outside factors that may affect human subjects in between sessions and contribute to fatigue. Although directed to continue their normal routine in regards to exercise (other than squats), nutrition and sleep patterns, this is impossible to completely enforce without constant monitoring of subjects. Subjects were directed to avoid any

heavy squatting in between sessions or high-volume bodyweight or light squatting, of any variant (body weight squats, front squats, overhead squats etc.). Again, randomizing the order should have helped to minimize the effect of outside stressors on the testing conditions.

3. Subjects might have lifted lighter maximal loads in the laboratory compared to the “gymnasium” due to the changes in environment/setting. Subjects lifted in only knee sleeve and exercise clothing; therefore, any other gear they are accustomed to wearing such as lifting shoes, belts, etc. was not utilized and may have detracted from their “normal” lifting environment.
4. Due to the experimental setup including knee sleeves covering the knee joints, it was impossible to measure occlusion. In addition, joint compression forces, patellofemoral kinematics/kinetics, cartilage forces, and the like were not included in this study; however, these measures could provide further insight into the efficacy of knee sleeves.
5. This study only included a shoulder-width squat stance, therefore results will only be applicable to that specific stance. Since previous work has shown differences in muscle activation between different stance widths, future work could assess how knee sleeves affect squats of varying stances (Escamilla et al., 2001).

II. LITERATURE REVIEW

The purpose of this thesis research is to assess if and to what extent wearing a neoprene knee sleeve during the back squat alters squat biomechanics, including muscle activation and joint mechanics. This review of literature will cover: 1) Biomechanics of the squat, 2) Squat variations, 3) Other strength training accessories, 4) Knee sleeves and injury prevention, and 5) Summary.

Overview of the Squat Exercise

The squat is a complex multi-joint exercise that targets several muscles of the lower body and the lumbo-pelvic-hip complex (Flanagan et al., 2003). The squat has been the subject of many biomechanical evaluations in the areas of kinetics, kinematics, and muscle recruitment during different squat stance and load variations (Dionisio et al., 2006; Flanagan et al., 2003; Schoenfeld, 2010). Increasing weight lifted increases tibio- and patellofemoral compressive forces (Hartmann et al., 2013). The back squat is also a multi-planar movement, involving all available motions at the lower extremity joints. The ankle, hip and spine all must move through all planes of motion, while the knee moves primarily in the sagittal plane (Schoenfeld, 2010). Flexion and extension of the knee and ankle occur in the sagittal plane but only if the feet are facing straight forward, as the knee and ankle are both hinge joints and move in the direction the foot is pointing. As the toes rotate outward or the squat stance widens, the legs will move out of the sagittal plane (Escamilla et al., 2001).

The squat exercise involves two distinct phases: lowering and lifting. Both lowering and lifting phases are predominately motivated by movements of the lower extremities and trunk. To initiate the lowering phase of the squat, an athlete hinges at the hips and begins knee flexion while allowing the pelvis to translate posteriorly, behind the body, as if reaching for a chair (Haff

& Triplett, 2016). For a typical/neutral squat posture, feet should be approximately shoulder width apart with as much as 7° of external foot rotation (Schoenfield, 2010). The descent is achieved through flexing the hip, knees and ankles (dorsiflexion) in a simultaneous and coordinated manner, while under controlled eccentric contractions. The initial breaking of the hips decreases the load placed on the posterior chain, making the movement safer for the knees and lumbar spine (Myer et al., 2014). The chest should remain upright and the cervical spine in a neutral position, avoiding excessive flexion or extension of the spine. Squat depth (lowest point) is a debatable topic, but depth should be limited to movement that can be properly and safely executed without unfavorable compensations such as collapsing knees, the lower back rounding or the chest falling. If an individual exhibits mobility with joint stability, the individual will likely be able to squat through a full range of motion, which includes at least 15-20° of ankle dorsiflexion and 120° of hip flexion (Greene, 1994). The ascent of the squat reverses the descent phase, with the hips being the primary mover and the weight kept in the heels and lateral parts of the foot. The athlete's torso should maintain a static position with the shoulders and hips rising at the same rate, while the knees, hips and ankles extend to their original positions, completing the movement (Myer et al., 2014). To rise up from the bottom of the squat, the gluteal muscles are contracted and the athlete must drive through the heels as the knees and hips extend (Haff & Triplett, 2016).

Although many variations of the squat exercise exist, the primary movements of the ankles, knees, and hips remain similar, allowing for distinctions to be made about the joint mechanics. However, the roles of each lower extremity joint differs during squatting. The ankles are the first interaction between the lower extremity and the ground/squat surface. The ankles must provide a solid foundation for bearing the load of the person and the external weights,

while also providing a pivot for the body to ascend and descend the squat. Sufficient ankle dorsiflexion in the descent of the squat is required to reach full squat depth, while plantarflexion in the ascent of the squat is necessary to reverse the squat descent motions. Both the knees and hips provide large muscle forces required to control flexion during the descent of the squat and extension during the ascent of the squat (Haff & Triplett, 2016). Therefore, an in-depth analysis of each joint is required to fully describe squat mechanics and implications of external weightlifting accessories.

Biomechanics of the Ankle Joint

The ankle joint complex contains the talocrural and subtalar joints, which allow dorsiflexion, plantarflexion, eversion, inversion, and slight abduction and adduction. While squatting, the talocrural joint, where the tibia, fibula and talus meet, allows the movement of dorsiflexion and plantarflexion. Typical sagittal plane range for motion for the talocrural joint is 20° of dorsiflexion and 50° of plantarflexion (Clarkson & Gilewich, 1999). The subtalar joint maintains postural stability and stops excess eversion/inversion of the foot, allowing for ~15° and ~35° of eversion and inversion, respectively (Clarkson & Gilewich, 1999). During the squat exercise, the ankle joint complex allows for continual and stable foot-ground contact, while also providing necessary flexibility for reaching squat depth. The muscles primarily responsible for ankle joint movement during the squat exercise are the gastrocnemius and soleus and are utilized in all contraction types (concentric, isometric, and eccentric) (Signorile et al., 1995).

A large amount of mobility is needed in the ankle to demonstrate control in both eccentric and concentric phases of the squat (Schoenfeld, 2010). When the proper range is not available in the ankle, this may cause the heels to rise during greater knee flexion during the squat (Schoenfeld, 2010). Excessive heel rise can result in compensatory joint moments at the

ankle, knees, hips and spine that can potentially lead to injury (Schoenfeld, 2010). Hemmerich et al. determined that an ideal amount of dorsiflexion of $38.5^\circ \pm 5.9^\circ$ was needed to keep the heels down (foot flat) during a full squat (Hemmerich et al., 2006). Assessing the downward phase of a squat, researchers have found increased foot pronation results in varied compensations at the hip and ankle joints. Participants squatting with a pronated foot exhibited increased ankle dorsiflexion by $>5^\circ$ during the terminal portion (reaching squat depth) of the downward phase and decreased hip flexion during middle and terminal phases by 13° & 18° , respectively (Lee et al., 2015). The group with excessive foot pronation likely increased ankle movement to compensate for the reduced hip movement, which illustrates that increased foot pronation during squatting results in a different squat strategy compared to those utilizing neutral foot positions. The excessive ankle movement found in subjects with pronation may cause injury to their feet, making control of the ankle and hip joint movements crucial in those with pronated feet during the squat (Lee et al., 2015).

The ankle provides support and power generation during the squat (Schoenfeld, 2010). Within the current literature, ankle moments have been found to be anywhere from 50-300 Nm during the squat (Lander et al., 1986; Lander et al., 1990; Wretenberg et al., 1993; Wretenberg et al., 1996) and making up nearly 18% of the total lower extremity moments during a variety of squat styles (Escamilla et al., 2001). Specifically during a medium/neutral squat depth, the ankle produces a maximum of 47 Nm during descent and a maximum of -112 Nm during squat ascent, which make up ~7% of the total lower extremity moment required to perform a squat to full depth (Escamilla et al., 2001). Peak ankle moments and moment arms occur at maximum knee flexion during the narrow stance and at 45° during the medium and wide stances (Escamilla et al., 2001). Ankle moments during maximum knee flexion for narrow, medium and wide stances

also vary greatly, with wide stance producing the greatest moments (Escamilla et al., 2001). Additionally, narrow stance reportedly generates a plantar flexor muscle moment while the medium and wide stances generates net ankle dorsiflexor moments (Escamilla et al., 2001). Therefore, modifying squat stance appears to have a dramatic effect on the primary musculature involved at the ankle joint. As such, it is important to investigate the primary musculature surrounding the ankle joint involved in squatting.

The gastrocnemius is the most studied muscle of the ankle joint in relation to squatting. It is believed that the gastrocnemius assists in offsetting knee valgus moments and limits posterior tibial translation since the medial head of the gastrocnemius acts as a dynamic knee stabilizer during squats (Bell et al., 2008; Hay et al., 1983). Moderate levels of activation are found in the gastrocnemius during squats, with the greatest activity found as knee flexion increases and less activity as the knees extend (Donnelly et al., 2006). This correlates with the gastrocnemius' moment arm peaking at or near maximal knee flexion (Escamilla et al., 2001). The soleus has been noted to be more active than the gastrocnemius when squatting to great depths (Toutoungi et al., 2000). Due to its biarticular nature, the gastrocnemius acts mostly isometrically throughout the squat, with little to no muscle fiber length change (Toutoungi et al., 2000). Squat form may be compromised if weakness exists in the musculature of the ankle. Knee valgus and foot pronation may be less controllable in subjects who lack strength in their medial gastrocnemius, tibialis anterior and tibialis posterior (Bell et al., 2008). This weakness can also cause excessive medial knee displacement and dynamic valgus (Bell et al., 2008). Since previous research has identified an ideal range of motion of the ankle and the necessary ankle joint moments during different squat depths and widths, the ankle joint requires attention to ensure squat safety and effectiveness. It is evident that issues originating at the ankle affect ranges of

motion at the proximal/superior joints involved with the squat, potentially causing inefficiencies or even injury.

Biomechanics of the Knee Joint

The knee joint complex is comprised of the tibiofemoral (classically referred to as knee joint) and patellofemoral joints. The knee joint provides movement in the sagittal and transverse planes, with ranges of motion of $\sim 160^\circ$ and $\sim 75^\circ$, respectively (Li et al., 2004; Signorile et al., 1994; Van Eijden et al., 1987). The patellofemoral joint is a gliding joint where the patella slides over the trochlear surfaces of the femur during knee flexion and extension. The patellofemoral joint is an important factor of the knee joint complex because it provides additional mechanical leverage for the quadriceps during extension by increasing the quadriceps moment arm and reduces wear on the quadriceps and patellar tendons from friction against the intercondylar groove (Schoenfeld, 2010). There are 4 primary ligaments within the knee complex and cartilage, all of which support the knee in both static and dynamic situations. As such, the primary ligaments and joint cartilage have been the focus of many previous studies investigating knee stability during squatting exercises (Henning et al., 1985; Klein et al., 1961; Meyers et al., 1971; Steiner et al., 1986). Of all the knee ligaments, the anterior cruciate ligament (ACL) is considered the most important stabilizer as it plays a major role to prevent anterior tibial translation, as well as limiting internal and external knee rotation. The ACL is reported to provide 86% of the restraining force to anterior drawer, while the PCL provides 95% of the restraining force to posterior drawer (Butler et al., 1980). The PCL possesses greater strength than the ACL, mostly because it has a 20-50% larger cross-sectional area (Harner et al., 1995). Forces within the PCL gradually increase as the knees flex and decrease as the knees extend, with forces slightly greater during the ascent compared to the descent (Escamilla, 2001). Several

studies have reported no ACL tensile forces during the squat, which may be attributed to hamstring activity as the hamstring assists in unloading the ACL by creating a posteriorly directed force during knee movement (Dahlkvist et al., 1982; Escamilla et al., 1997; Stuart et al., 1996; Wilk et al., 1996). Forces produced from the quadriceps by the patella tendon produce an anterior force on the leg with knee flexion less than 50-60° and a posterior force with knee flexion greater than 50-60° (Castle et al., 1992; Herzog et al., 1993; Singerman et al., 1999).

The squat exercise can involve as much as 140° knee flexion or as little as 20° knee flexion (Marchetti, 2016), depending on the target depth. During a back squat, an exerciser can choose to utilize the full range of motion (120°+), partial range of motion (squat to parallel, 70-100°), or quarter squat (40°) (Schoenfeld, 2010). A specific or optimal squat depth does not exist. Depth needs to be individually assessed on a case by case basis, taking into consideration multiple factors such as the purpose of training, previous injuries and other pathologic conditions. For elite athletes and others trained with progressive loading programs under professional supervision, deep squats offer effective training to strengthen and protect against injury. Since much less weight is able to be used during deep squats, half and quarter squats may be preferred for those desiring to use more weight, but with a shorter range of motion (Hartmann et al., 2013).

Typically, squats should not cause injury to the healthy ACL. The ACL's failure load can range from 1725 to 2160 N, while peak knee anterior shear forces range from 28 to 500 N, occurring between 0-60° of knee flexion (Noyes et al., 1984; Steiner et al., 1986). If needed, one way to reduce stress placed on the ACL during squatting is to increase hamstring muscle activity, which can be elicited by increasing forward trunk tilt and hip flexion (Ohkoshi et al., 1991; Yasuda et al., 1987). The PCL is stronger than the ACL due to its size and has an estimated

strength of 4000 N (Race et al., 1994). Posterior shear forces during maximum knee flexion have been recorded between 294-2704 N and increase with knee flexion (Race et al., 1994).

Therefore, participants with injured or reconstructed PCLs should avoid knee flexion angles greater than 50-60° (Race et al., 1994).

Muscle activity surrounding the knee has been at the forefront of a large portion of the research on squatting, specifically focusing on the quadriceps, hamstrings and gastrocnemius. The quadriceps, hamstrings and gastrocnemius comprise about 98% of the total cross-sectional area of the knee musculature (Wickiewicz et al., 1983). During a squat, the quadriceps muscles (vastus lateralis, vastus medialis, vastus intermedius and rectus femoris) are utilized both eccentrically (lowering phase) and concentrically (lifting phase). The hamstring muscles (biceps femoris, semitendinosus, and semimembranosus) act as eccentric and concentric hip flexors during the lowering and lifting phases, respectively (Ebben et al., 2000). Training the agonist muscle (quadriceps) without training the antagonist muscle (hamstrings) may result in injury due to a muscle imbalance. Although an agonist/antagonist strength ratio doesn't exist for dynamic exercises such as the squat, a desirable isokinetic strength ratio of 3:2 has been recommended for the quadriceps and hamstrings (Ebben et al., 2000). The further away the muscle balance is from 1:1, the larger muscle imbalance, and thus a larger potential injury (Ebben et al., 2000).

Previous squat studies have researched three main areas of focus: tibiofemoral shear force, tibiofemoral compressive force, and patellofemoral compressive force. During closed-chain exercises such as the squat, both the hamstring and quadriceps muscles co-contract to enhance the integrity/stability of the knee joint. This co-contraction occurs from the hamstrings exerting a counter-regulatory force on the tibia by pulling it posteriorly, reducing anterior tibial translation imposed from the quadriceps and decreasing stress on the ACL (Schoenfeld, 2010).

This reduction in force was specifically noticed between 15-60° of knee flexion (Li et al., 1999). During a maximum contraction of the quadriceps, shear knee forces generated can reach 2000 to 8000 N, depending on the angle of knee flexion (Van Eijden et al., 1987). Therefore, adequate strength of both the quadriceps (as agonists) and hamstrings (antagonists/stabilizers) are required to maintain healthy knee mechanics. Due to the external loads applied (weights lifted) and co-activation of surrounding knee musculature, tibiofemoral compression and patellar tendon forces can reach 8,000 N and 6,000 N, respectively, at 130° of knee flexion (Schoenfeld, 2010), with forces slowly declining as the angle decreases to 30°. When the knees move forward in the squat, it is believed to increase patellofemoral and tibiofemoral shear forces due to the tibia sliding anteriorly on the femur during flexion (Schoenfeld, 2010). However, forces are reduced at maximal amounts of knee flexion (155°) due to calf-thigh contact, with an average compressive knee force reduction from 4.89 to 2.29 times bodyweight (BW) (Zelle et al., 2009). Larger circumferences of thighs and calves result in even further decreased forces due to more surface area contact (Zelle et al., 2009).

It is critical to closely investigate both the hip and knee joint because as squat methods vary, the load distribution can vary from lifter to lifter between the two joints. It is often evident that the angle of one joint affects the other. For example, powerlifters using the low-bar back squat method tend to have greater hip flexion than weightlifters who use the high-bar back squat method and show a more even distribution between knee and hip flexion (Wretenberg et al., 1996). Therefore, analysis of the knee is important, but as we move up the lower extremity, the hip joint warrants examination as well.

Biomechanics of the Hip Joint

The hip is a ball-and-socket joint made up of the articulation between the head of the femur and the acetabulum of the os coxae. This joint can move in all 3 planes of motion, allowing for flexion, extension, abduction, adduction, internal and external rotation and horizontal abduction and adduction (Byrne et al., 2010). The main hip muscles used while squatting are the gluteus maximus (GM) and the hamstrings (biceps femoris (BF) and semitendinosus). The GM acts eccentrically during the descent of the squat to maintain control and overcome resistance while working concentrically during the ascent (Schoenfeld, 2010). The GM is the largest and most powerful extensor of the hip and it contributes to external rotation, abduction and adduction (Byrne et al., 2010). The iliopsoas, made up of the psoas major and minor and the iliacus, is the major flexor of the hip. The iliopsoas is aided by the sartorius, rectus femoris, and tensor fascia latae (TFL) to flex the hip. The gluteus medius and minimus are the main hip abductors (Byrne et al., 2010). The hip adductors include the obturator externus, pectineus, gracilis, adductor longus, adductor brevis, adductor magnus and adductor minimus (Byrne et al., 2010). The muscles of the hip contribute to movement in varying planes dependent upon hip position. The gluteus medius and minimus behave as abductors for hip extension and as internal rotators with hip flexion. The adductor longus is a flexor at 50° hip flexion and as an extensor at 70° (Byrne et al., 2010). After identifying the primary muscles involved at the hip, their activation throughout the squat can be examined.

Activation of the GM is significantly greater during deep squats than partial and parallel squats (Schoenfeld, 2010). The hamstrings are only moderately active while squatting, producing about half the amount of activation compared to a leg curl and stiff legged deadlift (Schoenfeld, 2010). Previous research claims the average hip range of motion while squatting is

95 ± 27 degrees of flexion (Hemmerich et al., 2006). Electromyography (EMG) of the GM showed the greatest peak, mean and integrated EMG (iEMG) during the concentric phase of the squat to be at a parallel depth (65.9% maximum voluntary isometric contraction (MVIC)), greater than full depth (56.8%), which was also greater than partial depth (46.9%). Activity of the GM also slightly increases after rising from the bottom of the squat to a parallel depth (Hammond et al., 2016). The hamstrings reach peak activation anywhere from 10-70° of flexion. However, activation does not seem to be affected by squat depth like the GM, with only small variations in hamstring torque between squat depths (Hammond et al., 2016). Hamstring EMG was the lowest compared to the GM and muscles of the quadriceps, but showed its greatest activity at parallel depth during the concentric phase, with negligible differences found between parallel and full squats (Hammond et al., 2016). Range of motion affects muscle activation but it also affects torque at the hip joint.

As hip flexion increases, torque increases, with maximal torque seen at the bottom of the squat (Nissell et al., 1986). Hip torque also increases as subjects are restricted from allowing their knees to come forward past the toes during the squat (Fry et al., 2003). This causes an increased compensatory forward lean, subsequently increasing the moment arm as well as torque in the hip (Fry et al., 2003). Hip torque during unrestricted squatting was found to be 28.2 ± 65.0 Nm and 302.7 ± 71.2 Nm for restricted squatting (Fry et al., 2003). Although knee torque decreased with the restriction of the knees, hip torque increased with restriction. Therefore, allowing the knees to come slightly forward in front of the toes and the torso to remain upright may be advantageous for certain populations to limit hip and low back torques. Greater hip extensor moments have also been found with increasing squat depth past 90° (parallel) (Wretenberg et al., 1993). However, increasing depth from parallel to deep does not result in

further increases in hip torques (Wretenberg et al., 1993). Hence, avoiding squat depths greater than 90° will limit hip moments. Additionally, bar location (high versus low) may impact hip joint moments during squatting. Previous research investigating bar placements and squat depth found increased hip moments were found in deep compared to parallel squats with low bar placements (Wretenberg et al., 1993). No differences were found between squat depths with high bar placements. Therefore, the location of the external load also plays a significant role in hip joint mechanics during squatting.

The hip is greatly involved during the squat and given that it is one of the major joints involved, detailed investigation is needed to include the joint itself, musculature, angles and forces associated with it. The GM and hamstrings, being the major muscles involved in the squat, are active throughout the movement with the GM being more active and for longer. Torque generated at the hip can vary with depth and restriction of the knees, creating options for a squatter desiring to limit torque of the hips. Lastly, bar placement alters the squat in such a way that alters hip flexion, torque and moments at the joint.

Squat Variations

There is certainly no lack of research comparing different variations of the squat, such as modifying stance width and displacing to different depths. Not one specific squat prescription exists for everyone, as there are multiple factors to consider such as mobility, training goals, kinesthetic awareness and individual physical abilities. Since there is a variety of populations that use the squat for exercise, from professional athletes to recreational gym goers, there is a need for different types of squats and squat variations.

Squat Depth

A 2014 meta-analysis, including over 164 articles published from 2011-2013 (Hartmann et al., 2013), was written to determine if squatting with less knee flexion is safer for the musculoskeletal system than deep squats. After extensive review of all relevant articles, the researchers concluded that the deep squat, assuming proper technique and progressive loading is used, is an effective exercise that can help protect against injuries while strengthening the lower body (Calhoun et al., 1999; Hamill et al., 1994; Kulund et al., 1978). Previous researchers also oppose some commonly stated ideas by commenting that deep squats do not increase the risk of injury to passive tissues (Chandler et al., 1989; Kulund et al., 1978; Panariello et al.; 1994). Prior research has found that as an athlete increases squat depth, there is increasing difficulty to lift similar loads to partial squats, as well as increasing time under tension (Escamilla, 2001). The inherent increased time under tension leads to an undesirable length-tension relationship with increased muscle lengths of the vasti and GM (Escamilla, 2001). In both powerlifters and weightlifters, knee joint loads increase significantly with increased squat depth (Wretenberg et al., 1996). Squat depth is an important topic as it affects joint moments, muscle activity, relative contribution of the lower limb joints, and load lifted (Hammond et al., 2016). After squat depth, two of the most debated squat forms are stance width and bar placement.

Stance Width & Bar Placement

Stance width during squatting is commonly increased or decreased depending upon multiple factors, including: mobility issues, kinesthetic awareness, training goals, and targeting of specific muscles. There has been debate discussing if muscle activation is altered with differing stance widths (McCaw et al., 1999). A study investigating stance width (SW) in national powerlifters using narrow, medium and wide stances found a significant relationship

between stance width and lower extremity movement patterns and load, significant angle differences between NS and WS during maximum knee flexion for both the thigh, 7° difference, and the shank, 9° difference (Escamilla et al., 2001). There was a significant difference between NS and WS in ankle moments at maximum knee flexion, the difference being 191 Nm greater during WS. At maximum knee flexion, joint angle analyses showed greater ankle, but reduced knee, angles with a wider stance (ankle angles: $58 \pm 5^\circ$, $64 \pm 4^\circ$, to $67 \pm 7^\circ$ and knee angles: $106 \pm 8^\circ$, $102 \pm 7^\circ$ to $99 \pm 10^\circ$, for NS, MS and WS, respectively). However, hip angles were not different between stance widths: $107 \pm 10^\circ$, $109 \pm 8^\circ$ and $110 \pm 7^\circ$ for NS, MS and WS, respectively. Joint moments at maximum knee flexion decreased in the ankle, the knee and the hip as stance widened. Net ankle plantar flexor moments were generated during the NS (10-51 Nm), whereas net ankle dorsiflexor moments (34-284 Nm) were produced during the MS and WS. Conversely, during the ascent phase, hip and knee moments increased with stance width (Escamilla et al., 2001). Muscle activation altered from NS to WS with greater muscle activity found in the hamstrings, gluteus maximums and ischial fibers of the adductor magnus (Escamilla et al., 2001). Therefore, it appears stance width has a complex relationship with lower extremity loading patterns, affects the various phases of the squat exercise differently.

Comparisons of low bar and high bar back squats depict a significant influence of bar placement on lower extremity joint load distributions (Wretenberg et al., 1996). A study found greater peak moments of force at the hip in the powerlifters (low-bar) and at the knee in weightlifters (high-bar) at both parallel and deep depths (Wretenberg et al., 1996). Both low-bar and high-bar positions produced greater peak hip moments during deep compared to parallel squats: low 324 Nm (deep) and 309 Nm (parallel), high 230 Nm (deep) and 216 Nm (parallel). Knee moments were also influenced by bar placement, with increased loads for high-bar

compared to low-bar positions during both deep (191 Nm vs. 139 Nm) and parallel (131 Nm vs. 92 Nm) squats (Wretenberg et al., 1996). The low-bar position also resulted in nearly 2x hip moments than knee moments (Wretenberg et al., 1996), possibly due to technique utilized during these squats. The high bar back squat is executed in an upright position, creating a more equally distributed joint moment force between the hip and the knee. Utilizing the low bar back squat reduces the moment arm at the knee as the technique brings the load closer to the knee but the moment arm between the ground reaction force and the hip becomes greater, increasing the moment of force at the hip. Therefore, similar to stance width, modification of bar placement influences lower extremity movement and loading during the back squat exercise.

Front vs. Back Squats

Both back squats and front squats can strengthen the lower back, hip and leg muscles. However, technique and biomechanical variations exist between the two exercises. Several athletes commonly utilize both methods, with the front squat being performed much less and the back squat allowing individuals to typically lift more weight (Gullett et al., 2009). Performance of the back squat requires the barbell be placed across the shoulders on the trapezius while the front squat requires the barbell to be placed across the anterior deltoids and clavicles with a grip allowing the elbows to be high and the upper arms parallel with the floor (Gullett et al., 2009). The descent and ascent of both movements are the same. The back squat produces higher compressive forces on the knee than front squats, 11 ± 2.3 N/kg and 9.3 ± 1.5 N/kg, respectively (Gullett et al., 2009). Additionally, knee extensor moments are greater for back squats (1.0 Nm/kg) than front squats (0.7 Nm/kg) (Gullett et al., 2009). Shear forces on the knee and muscle activity do not differ significantly between front and back squats (Gullett et al., 2009). The front squat was found to be as effective in muscle recruitment, but with less compressive forces and

extensor moments, suggesting that front squats may be a preferred exercise over back squats for anyone with knee problems and possibly long-term joint health (Gullett et al., 2009). A more recent study found no differences in muscle activation of the upper gluteus maximus, lower gluteus maximus, biceps femoris and vastus lateralis when comparing full depth back squats, parallel depth back squats and full depth front squats (Contreras et al., 2016). Subjects were able to lift the most during parallel back squats, then full depth back squats, and lastly full depth front squats (Contreras et al., 2016). Thus, front squats, like the variations of back squat technique, significantly alters lower extremity loading, especially at the knee joint. In addition to different squat forms and variations, athletes and exercisers can further alter the squat through use of accessories to improve performance and safety.

Strength Training Accessories

There are several strength training accessories that athletes and recreational exercisers use for a multitude of different reasons. Frequently, the main uses fall into the two categories of either enhanced training or injury prevention/rehabilitation. Squat suits, knee wraps and bench press shirts are worn, most commonly by competitive powerlifters, as they enable the lifter to lift more weight in the back squat and bench press, respectively. For example, bench press shirts were found to increase shoulder stabilization, decrease tension and shear forces acting on the shoulder and subsequently decreasing injury risk (Silver et al., 2009). Following this idea, elastic accessories worn around the knee joint, such as knee wraps and sleeves, may also increase stability of movement during squats. Knee sleeves are worn frequently by knee rehabilitation patients either for activities of daily living or during exercise. Knee wraps worn for lifting and thinner rehabilitative knee sleeves can be compared to the knee sleeve because of their similar placement and functions at the knee joint. Looking closer at the most similar pieces of equipment

and equipment location, squat suits and knee wraps appear to be the most closely linked to and comparable to knee sleeve usage.

Squat Suits

Squat suits are worn as supportive equipment to lift maximal weight during competition. They are cut and fit much like a weightlifting singlet but are made of a more constricting material. The majority of competitive powerlifters are able to increase their 1-RM while wearing a squat suit (Blatnik et al., 2012). Elastic energy is thought to be stored during the eccentric phase of the squat and then released during the concentric phase, allowing the lifter to lift increased weights through greater force, velocity and power (Doan et al., 2003). During a study involving elite and professional male powerlifters, kinetic and kinematic characteristics were found to be significantly different between squats performed with squat suits and without squat suits (Blatnik et al., 2012). Eccentric force was significantly higher with a squat suit on during 1-RM weights; $31962.2 + 470.6$ N without a suit and $3369.7 + 589.9$ N with a squat suit. Concentric velocity was significantly higher during all squat percentages (80% 1-RM, 90% 1-RM and 100% 1-RM) while wearing a squat suit (Blatnik et al., 2012). Peak concentric power was significantly higher at 80% 1-RM and 90% 1-RM but not 100% 1-RM with the squat suit on. The increased power and velocity values found suggest the potential to lift heavier weight while using a squat suit (Blatnik et al., 2012). Compressive gear (squat suit and knee wraps) while worn during a 10-week progressive powerlifting style program (squat, bench, deadlift) resulted in greater improvements for those wearing the gear. Both groups improved in all three lifts, the group wearing gear made greater improvements in the squat, although the difference did not reach a significant value. The noted trend suggests a potential ergogenic increase of maximal weight lifted while using compressive gear during a strength program (Doan et al., 2003). If a

squat suit, made of similar material to the knee sleeves in question, causes kinetic and kinematic changes to the squat and potentially increases maximal weight lifted, speculation arises as to how knee sleeves affect the squat. Another accessory common to powerlifters is the knee wrap, thought to help lifters safely lift more weight.

Knee Wraps

Knee wraps are often worn to support the knee joint, gain a mechanical advantage during the back squat or to potentially lift greater loads or perform more repetitions (Gomes et al., 2015). It is thought that elastic energy is generated as the knee wraps stretch during the descent of the squat and return the energy to the movement on the ascent (Gomes et al., 2015). A previous investigation has found mechanical output was increased by the elastic properties of the knee wrap, but back squat technique was changed in a way that likely changes the muscles recruited, and possibly compromised integrity of the knee joint (Lake et al., 2012). Using knee wraps, the lowering phase was performed faster, storing elastic energy in the wraps during descent. Then, the elastic energy was released in ascent and increased vertical force applied to the center of mass and a 10% increase in peak power from 1,841 W to 2,121 W (Lake et al., 2012). Vertical impulse increased from 169 Ns to 192 Ns, due to an increase of elastic energy generated and stored in the knee wraps (Lake et al., 2012). In addition to peak power and vertical impulse increases, results showed that knee wraps do provide a mechanical advantage (Lake et al., 2012).

External loads lifted have been noticed to increase with the use of a knee wrap. With the knee wrap being made of elastomeric material and polyester, it springs back to its original shape after it is deformed or stretched. When mechanically deformed, the elastic energy stored in the knee wrap is transferred into kinetic energy and added to the lifter (Gomes et al., 2014). The

additional weight lifted is known as “carry-over.” Various studies have found carry-over with knee wraps to be anywhere from 10-13% to 20-25% while squatting to 90 degrees, resulting in increased external loads lifted with knee wraps (Gomes et al., 2014; Harman & Frykman, 1990, Marchetti et al., 2015). Marchetti et al. verified an increase in external load for subjects while wearing knee wraps and contributed it to the elastic energy stored in the knee wrap. Wearing knee wraps alone significantly increases the vertical force at the feet by an average of 25.1 ± 5.9 lbs, showing direct mechanical assistance by the knee wraps that can affect a powerlifter’s maximal weight lifted (Harman & Frykman, 1990). Knee wraps are applied in different specific ways, the “spiral technique” and the “X technique” being the two commonly used applications (Marchetti et al., 2015). The spiral technique consists of wrapping the material around the knee in a spiral pattern while the X-technique applies the wrap in a crossover pattern. It was determined that both techniques increase the carry-over effect and peak forces were significantly greater with the wraps on, but peak forces were not different between methods (Marchetti et al., 2015). RPE did not differ between wearing them or not, nor did it differ between wrapping methods (Marchetti et al., 2015). Considering maximum weight lifted, the knee wraps appear to be a helpful accessory but there are disadvantages to be considered.

Some drawbacks of using knee wraps are 1) wrapping technique likely changes the muscles recruited and possibly compromises knee joint integrity (Lake et al., 2012), 2) knee wraps may involve significant occlusion, which can be painful and can alter barbell patterns in Olympic lifting (Harman & Frykman, 1990) and 3) they may increase patellofemoral compression (Marchetti et al., 2015). Athletes utilizing wraps may not be able to wear them for an extended duration due to high levels of occlusion from the intense wrapping required (Gomes et al., 2015). Knee wraps need to be removed after each lift due to the pain they cause and the

tourniquet-like effect they create (Harman & Frykman, 1990). It has yet to be determined if the knee sleeve, a thinner piece of equipment, creates less occlusion, which may make it more advantageous than the knee wrap. Reduced amounts of occlusion are predicted as the knee sleeve is composed of a thinner, more pliable material and generally not worn as tightly. Additionally, knee wraps can be too tight to the point of movement and agility restriction, hence making them less popular amongst Olympic lifters although widely used by powerlifters (Harman & Frykman, 1990). Olympic lifters use a lighter, looser wrap or no wraps at all. During Olympic weightlifting, the bar passes quickly and extremely close to the body so the thicker knee wrap could hinder the clearance of the bar (Harman & Frykman, 1990). A reduced horizontal barbell displacement was found while wearing knee wraps, resulting in the knee wraps restricting motion around the hip joint, leading to a more upright position, and forcing greater flexion of the knee (Lake et al., 2012). Two concerns arise from restriction of the hip flexors and extensors: 1) use of knee wraps may blunt the development of hip extensors and flexors and 2) flexion around the physical barrier formed by the knee wrap may put the integrity of the knee joint at risk. Therefore, usage of knee wraps should be closely monitored for all athletes and any muscular insufficiencies/joint instability should be remedied before usage in strength training (Lake et al., 2012). The knee sleeve, an alternative to the knee wrap, being made of a thinner material and likely causing less patellofemoral compression and alteration of squat mechanics may not need such close monitoring to ensure safety.

Although knee wraps and knee sleeves likely share similarities in their applications of stored elastic energy, the mechanics of the knee sleeve during weight lifting are unknown. To highlight some general differences for the user, there is no complex technique required to put on the knee sleeves but the proper size needs to be acquired, typically based on an upper calve

measurement. Also, the sleeves can stretch and degrade over time, in which case, a new pair can be purchased. They are more convenient in the sense that they can be put on without the assistance of another person. Although knee sleeves for weight lifting haven't been previously investigated, softer and less dense rehabilitative knee sleeves have been investigated. Similar to knee wraps, knee sleeves surround the knee joint with elastic material, possibly providing increase stability/support for rehabilitation and prevention of injuries.

Knee Sleeves and Injury Rehabilitation/Prevention

A somewhat newer accessory for weight lifting is the knee sleeve. There are over 10 different manufacturers of knee sleeves, which also come in a range of thicknesses (e.g., 3 mm to 7 mm), some of the major brands being Rehband, RockTape and ExoSleeve. Knee sleeves are frequently seen being worn during the televised, “CrossFit Games,” in fitness facilities, and even during the Olympics. Despite the popularity of knee sleeves for weight lifting and their possible implications for injury rehabilitation/prevention (further information found in subsequent sections), little to no empirical evidence can be found on the efficacy of knee sleeves for improving weight training.

No research exists that has analyzed the efficacy of knee sleeves for the squat exercise. In contrast, there is a fair amount of research on similar support pieces, such as thinner knee sleeves or braces and taping of the knee; however, even with similar support pieces, the primary research focus has been knee injuries, typically in a rehabilitation setting and not under heavy loads.

Knee Sleeves and Knee Rehabilitation

Knee sleeves can provide an easy self-use method to ease pain during exercise, enabling knee osteoarthritis (KOA) patients to continue to exercise and complete physical therapy. Improvements have been noted amongst KOA patients in the areas of joint position sense, pain, stiffness and function (Mazzuca et al., 2004; Tiggelen et al., 2008). A previous investigation has assessed effectiveness of an elastic knee sleeve in KOA patients (132 knees) during functional exams, including the stair climb power test, timed up and go and 8-meter walk tests (Bryk et al., 2011). The specific sleeve used was an elastic sleeve without a patellar opening by Tensor® - ANVISA/MS. The elastic knee sleeve improved functional capacity and pain felt by the subjects, shown through improved test performance (Bryk et al., 2011). Using the visual analog scale, it was discovered that subjects felt less pain while wearing the knee sleeves. Two of the assessments, 6-meter walk and timed up and go, were performed significantly faster while wearing knee sleeves. However, this increased performance was not found in the stair climb power test. Although not tested, these improvements can be attributed to the biomechanical balance from an improvement in joint contact area and lower pressure in knee extension (Bryk et al., 2011). In addition to researching knee sleeve use on exercising KOA patients, the efficacy of knee sleeves concerning frontal plane gait biomechanics has also been investigated.

Elastic knee sleeves (Genustrain 7 by Bauerfeind) may also be beneficial for osteoarthritis of the medial tibiofemoral joint (Schween et al., 2015). Walking with elastic knee sleeves reduces knee adduction angles, moments and impulse in persons with medial osteoarthritis (Schween et al., 2015). With knee sleeves, mean knee adduction angle at ground contact decreased from 11.5° to 9.6°, peak knee adduction angle decreased from 14.1° to 12.6°, first peak knee adduction moment decreased from 0.85 to 0.78 Nm/kg and positive knee adduction impulse

decreased from 0.24 to 0.22 Nm•s/kg (Schween et al., 2015). The improvements in frontal plane knee mechanics are thought to be from increased proprioception with wearing the knee sleeves, which is an ability that can be diminished in those with KOA, causing gait pattern alterations. With increased proprioception, knee sleeve wearers were found to have gait patterns more similar to what is considered a normal gait pattern (Schween et al., 2015). Having a high knee adduction moment is a risk factor for medial knee osteoarthritis progression. Given the previous research using elastic knee sleeves for post-injury activity and prevention, it is inferred that the knee sleeve may have some helpful qualities in movement of the knee. However, it is uncertain if this supportive piece of equipment can provide any performance enhancement for athletes performing heavy back squats, hence why knee sleeves need to be assessed on subjects while squatting. Not only are knee sleeves used to reduce pain or improve performance in those already injured, but they are also used and thought to be beneficial in injury prevention.

Knee Sleeves and ACL Injury Prevention

Knee sleeves may also be beneficial in providing stability to the knee in activities of daily living, such as walking. The elasticity of the sleeve materials appears to limit the amount of anterior tibial translation in healthy female athletes during passive tibial translation tests (Csapo et al., 2016). In this study, participants' anterior cruciate ligaments were stretched to a maximum of 6.5 mm using 250 N of force. When using a knee sleeve, the knee sleeve countered the pushing force by provided a resistive force of approximately 13 N. This resistance force provided by the knee sleeve had a linear relationship with tibial translation, and reduced tibial translation by average of 0.7 mm (Csapo et al., 2016). Although the results of this study illustrate some increased stability provided by knee sleeves in a passive condition, it is unclear if knee sleeves would provide significant and clinically relevant protection of the ACL if used under

large loads. Similar to the previous investigation of knee wraps during squatting, knee sleeves produce increased stability and force with increased stretch. Therefore, during a squat maneuver, it is likely knee sleeves would produce greater force as squat depth increases. However, the efficacy of knee sleeves during squats or any similar activity remains unknown. With clear advantages evident while using a thinner knee sleeve for prevention of knee injuries, there are serious possibilities of discovering the advantages induced by wearing a slightly thicker knee sleeve during weightlifting exercises.

Summary

The squat is a fundamental exercise that can benefit people of all ages and fitness levels as it improves sport performance, reduces injury risk and can enhance activities of daily living (Myer et al., 2014). The squat is a multi-joint movement that recruits multiple muscle groups in a single movement (Escamilla, 2001; Wretenberg et al., 1996). Many activities of daily living involve coordinated muscle contractions, making the squat one of the most functional and effective strength exercises for all individuals from athletes to those simply looking for an improved quality of life (Gullet et al., 2009). The back squat in particular is known to show great improvements in sport performance such as increasing sprint and vertical jump results (Vanderka et al., 2016). When squatting itself is the sport, specifically the back squat, accessories can be worn that may improve performance, but may also alter the movement (Lake et al., 2012). The closest accessory to the knee sleeve that has been studied is the knee wrap, which was found to increase mechanical output due to the elastic property of the wrap, but also changed the back squat in a way that altered muscle recruitment and possibly compromised the integrity of the knee joint (Lake et al. 2012; Gomez et al. 2014). Currently there is no research resistance-training based published on the popular neoprene knee sleeve frequently worn in

different lifting communities to including powerlifters, Olympic weightlifters, CrossFitters, and average fitness enthusiasts. Speculation exists in regards to what the knee sleeve does and individual users have their own rationale for wearing them, but without actually analyzing this accessory it cannot concretely be stated what effect it has on the back squat. The purpose of this study is to assess how wearing knee sleeves during the back squat changes the movement to include muscle activation, joint angles and maximum weight lifted. This study tests the hypothesis that wearing knee sleeves while back squatting will alter muscle activation, forces at the knee and squat depth as well as increase a lifter's 1-RM and decrease RPE.

III. METHODS

Participants

Fifteen healthy, resistance trained individuals were recruited from the local Hampton Roads fitness community, including the university campus. Inclusion criteria included: healthy with no history of knee injuries. age 18-55 years, must resistance train at least 3 times a week, at least 2 of the days including lower body exercises but only 1 day needs to include some form of weighted squats. Subjects must have at least one-year experience back squatting at or near maximal loads. Exclusion criteria included: any major lower extremity musculoskeletal injuries in the past 3 months, knee pain in the past 6 months during activities of daily living, a diagnosis of lower extremity joint arthritis, a body mass index (BMI) greater than $35 \text{ kg}\cdot\text{m}^{-2}$. All participants were screened with a standard Physical Activity Readiness Questionnaire (PAR-Q) to ensure there were no health or safety concerns. The study was approved by the university Institutional Review Board and all participants provided signed informed consent.

A ten-camera motion capture system (200Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to collect three-dimensional (3D) kinematics during both testing sessions (further information below). Retroreflective anatomical markers were placed bilaterally on the acromion processes, iliac crests, anterior superior iliac spines (ASISs), posterior superior iliac spines (PSISs), greater trochanters, femoral epicondyles, fibula heads, medial condyles, malleoli, 1st and 5th metatarsal heads, and 2nd toes. Clusters of four tracking markers were attached to the posterior trunk, pelvis, thighs, shanks and shoe heels. The anatomical and tracking markers were used to create a biomechanical model consisting of 8-segments (trunk, pelvis, thighs, shanks and feet) with six degrees of freedom each.

Electromyography (EMG) (Delsys Trigno, Delsys, Inc., 2000Hz) was used to collect muscle activity data. Electrodes were placed on five muscles: vastus medialis, rectus femoris, gluteus maximus, gluteus medius, and biceps femoris. Electrode placements were performed following Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines, including shaving, abrading, and cleaning of the skin above the palpated muscle bellies prior to electrode placement. All participants wore a pair of standardized laboratory shoes (NIKE Airmax Glide). A traditional style barbell rack, barbell (20.5 kg) and weighted plates were placed around the center of the motion capture collection area and two force platforms (2000Hz, Bertec FP-4060, Bertec Inc. OH, USA). Force platforms collected ground reaction forces (GRFs) applied to the foot segments (both feet) during the entirety of each squat repetition.

Experimental Procedures

Session 1- ½ subjects with sleeves, ½ without sleeves

After EMG placement, maximum voluntary isometric contractions were performed to determine the peak activation for each individual muscle. Then, after retroreflective anatomical marker placement, a static trial was collected and all anatomical markers were removed. Participants were allowed five minutes for warming up and stretching of their choice. Next, participants completed the National Strength and Conditioning Association's one-repetition maximum (1-RM) testing protocol (Haff & Triplett, 2016). Participants were given approximately 20 minutes to warm up to their 1-RM, beginning with a light resistance that allowed the subject to perform 5-10 repetitions with ease, followed by a 1-minute rest period. Then, a warm-up load was estimated that allows a subject to perform 3-5 repetitions by adding 30-40 lb (14-18 kg) or 10-20%, followed by a 2-minute rest. Next, a conservative, near-maximal

load was used, in which a subject could perform 2-3 repetitions after adding 30-40 lb (14-18 kg) or 10-20%, followed by a 2-4 minute rest. Then a 1-RM was attempted after another load increase of the same amount. If successful, the subject rested 2-4 minutes and another 30-40 lb or 10-20% increase was made for another attempt. If the subject failed, 2-4 minutes of rest was given and the weight was reduced by 15-20 lb (7-9kg) or 5-10% and a 1-RM was attempted again, until an official laboratory 1-RM was found. RPE was recorded for each lift on a scale from 0-10. Subjects were unaware of the load they were lifting in an attempt to avoid a placebo effect from wearing the knee sleeves. To do this, subjects faced away from the barbell and weights during the entire session except for their approach to the barbell and final lift. They immediately turned back around and away from the weights. Spotters were utilized on each side of the subject during near maximal and maximal lifts.

Half the subjects wore knee sleeves during this first session. For those designated as wearing sleeves for the first session, 7mm Rehband knee sleeves were provided in the lab and fitted based off of upper calf circumference, a recommendation from the manufacturer (XS: 31-33 cm, S: 33-35 cm, M: 35-37 cm, L: 37-40 cm, XL: 40-43 cm, XXL 43-46 cm). Participants were instructed to squat with a stance that was shoulder-width. “Bouncing” out of the bottom of the squat was not permitted and was regulated by a command of, “one, up,” upon thigh-calf contact. Participants were required to break parallel with their hip crease descending lower than the top of the knee and reaching a full-depth squat. A successful trial was denoted as a trial where the participant descended to full depth (contact between posterior thigh and shank) and stood all the way up, extending the knees and hips fully. Each participant performed two sets of three repetitions at 80% of their lab-tested 1-RM found earlier in the session. The sets were completed under two squat depth conditions: deep (D) and then parallel (P). A five-minute rest

was enforced between these sets. Subjects were not permitted to wear any of their normal preferred gear (weightlifting shoes, belts, etc.).

Session 2 - Opposite Condition from First Session (5-14 days after first session)

Between 5-14 days later, all procedures were repeated from session one with the exception that subjects who lifted with sleeves at the first session tested their 1-RM without sleeves and those that tested without sleeves on, tested with them on. Counterbalancing performed using a random number generator and was pre-assigned to all participants. Counterbalancing was implemented to eliminate confounding variables/effects and limit the effects of any fatigue. Subjects were directed to avoid any heavy squatting in between sessions or high-volume bodyweight or light squatting, of any variant (body weight squats, front squats, overhead squats etc.).

Data Analyses

All kinematic and GRF data were imported into and processed in commercial biomechanics software, Visual 3D Biomechanical Suite (v6.0, C-Motion, Germantown, MD). Three-dimensional marker trajectories and GRFs were filtered at a cutoff frequency of 8 Hz for joint kinetic calculations using a zero-lag fourth-order Butterworth low-pass filter. The Davis method was utilized to determine hip joint centers (Davis et al., 1991). Knee and ankle joint centers were defined as the midpoint of the femoral epicondyles and malleoli, respectively. Joint angles were computed using direct kinematics. An X-Y-Z (extension-adduction-rotation) Cardan rotational sequence was used for 3D angular kinematics computations. The conventions of 3D kinematic and kinetic variables were determined with the right-hand rule. The GRFs were normalized to body weight (BW). The joint moments were calculated using bottom-up inverse dynamics, normalized to the sum of body mass and weight lifted (Nm/kg) and calculated as

internal moments expressed in the distal segment. Variables of interest included: triplanar knee angles, moments, powers, muscle activity (%MVIC), and integrated EMG (iEMG; %MVIC*seconds) at 45° during the descent and ascent phases and at squat depth.

Statistical Analyses

Paired samples t-tests were utilized to compare weight lifted (kg), RPE, knee biomechanics, and muscle activations between sleeve and no sleeve conditions and between visits (1 vs. 2nd) for 1-RM tests. A two-way ANOVA with repeated measures on both factors was used to determine the effects of knee sleeves and squat depth on lower extremity biomechanics during submaximal squats. In the presence of a significant interaction, post hoc Tukey's Honestly Significant Difference tests were used to determine mean separations. The significance level was set at $p < 0.05$ *a priori*. Effect sizes were reported for significant comparisons (Cohen's *d*). Shapiro-Wilk tests were used to assess normality of the selected variables (test statistic: *W*).

IV. RESULTS

Subject Demographics

No significant differences were found in participants' mass between testing days (occurring 5-14 days apart). No significant no sleeve/sleeve differences were found in 1-RM, RPE during maximum lifts, or RPE during submaximal lifts (Table 1). No significant differences were found between testing days for 1-RM ($p=0.76$) or RPE ($p=0.70$) during maximum lifts.

Maximum Squats

No significant differences were found in knee joint angles at maximum depth (Table 2). There were no significant differences in knee moments or powers during descent, maximum depth, or ascent (Tables 3 & 4).

Integrated gluteus maximus activation during ascent (full depth to standing) was significantly greater during no-sleeve (1.35 ± 0.52 %MVIC*seconds) compared to the sleeve (0.98 ± 0.48 %MVIC*seconds) condition ($p = 0.05$; Cohen's $d = 0.74$). No other differences were found in muscle activations during maximum squats. Waveforms of kinematics, kinetics, and muscle activations during maximal squats for one subject with an 11.4 kg increase in 1-RM using knee sleeves and one subject with a 4.5 kg decrease in 1-RM using knee sleeves are presented in Figures 1a-2b.

Table 1. Subject demographic comparisons between conditions: mean \pm SD.

| | No Sleeve | Sleeve | P-Value | Effect Size |
|-------------------|------------------|------------------|---------|-------------|
| Mass (kg) | 82.4 \pm 14.4 | 83.2 \pm 14.1 | 0.95 | 0.07 |
| 1-RM (kg) | 119.1 \pm 28.2 | 121.4 \pm 29.5 | 0.81 | 0.08 |
| Max RPE | 8.9 \pm 1.1 | 8.8 \pm 0.8 | 0.85 | 0.10 |
| Submax RPE | 6.1 \pm 1.3 | 6.5 \pm 1.0 | 0.36 | 0.34 |

Notes: 1-RM: 1-repetition maximum weight lifted. RPE: rating of perceived exertion measured on 0 to 10 scale. Effect size is based on Cohen's d.

Table 2. Knee angles at full-depth during 1-RM squats: mean \pm SD.

| | No Sleeve | Sleeve | P-Value | Effect Size |
|----------|-------------------|-------------------|---------|-------------|
| X | -117.4 \pm 13.2 | -116.2 \pm 13.7 | 0.53 | 0.09 |
| Y | 12.5 \pm 6.1 | 11.8 \pm 6.4 | 0.73 | 0.11 |
| Z | 15.9 \pm 12.4 | 17.6 \pm 12.8 | 0.32 | 0.14 |

Notes: X, Y, and Z angles denote extension/flexion, add/ab-duction, and internal/external rotations, respectively. Angle polarity follows right hand rule.

Table 3. Knee moment comparisons during 1-RM squats: mean \pm SD.

| | | No Sleeve | Sleeve | P-Value | Effect Size |
|-------------------|----------|------------------|------------------|---------|-------------|
| ASCENT_45 | X | 0.53 \pm 0.12 | 0.54 \pm 0.14 | 0.84 | 0.05 |
| | Y | -0.15 \pm 0.09 | -0.17 \pm 0.12 | 0.62 | 0.12 |
| | Z | -0.07 \pm 0.04 | -0.07 \pm 0.05 | 0.71 | 0.09 |
| DESCENT_45 | X | 0.51 \pm 0.10 | 0.51 \pm 0.14 | 0.85 | 0.05 |
| | Y | -0.17 \pm 0.09 | -0.20 \pm 0.09 | 0.12 | 0.29 |
| | Z | -0.07 \pm 0.03 | -0.07 \pm 0.03 | 0.60 | 0.16 |
| DEPTH | X | 1.07 \pm 0.27 | 1.12 \pm 0.35 | 0.35 | 0.14 |
| | Y | 0.07 \pm 0.18 | 0.01 \pm 0.18 | 0.08 | 0.32 |
| | Z | -0.01 \pm 0.05 | -0.02 \pm 0.04 | 0.19 | 0.25 |

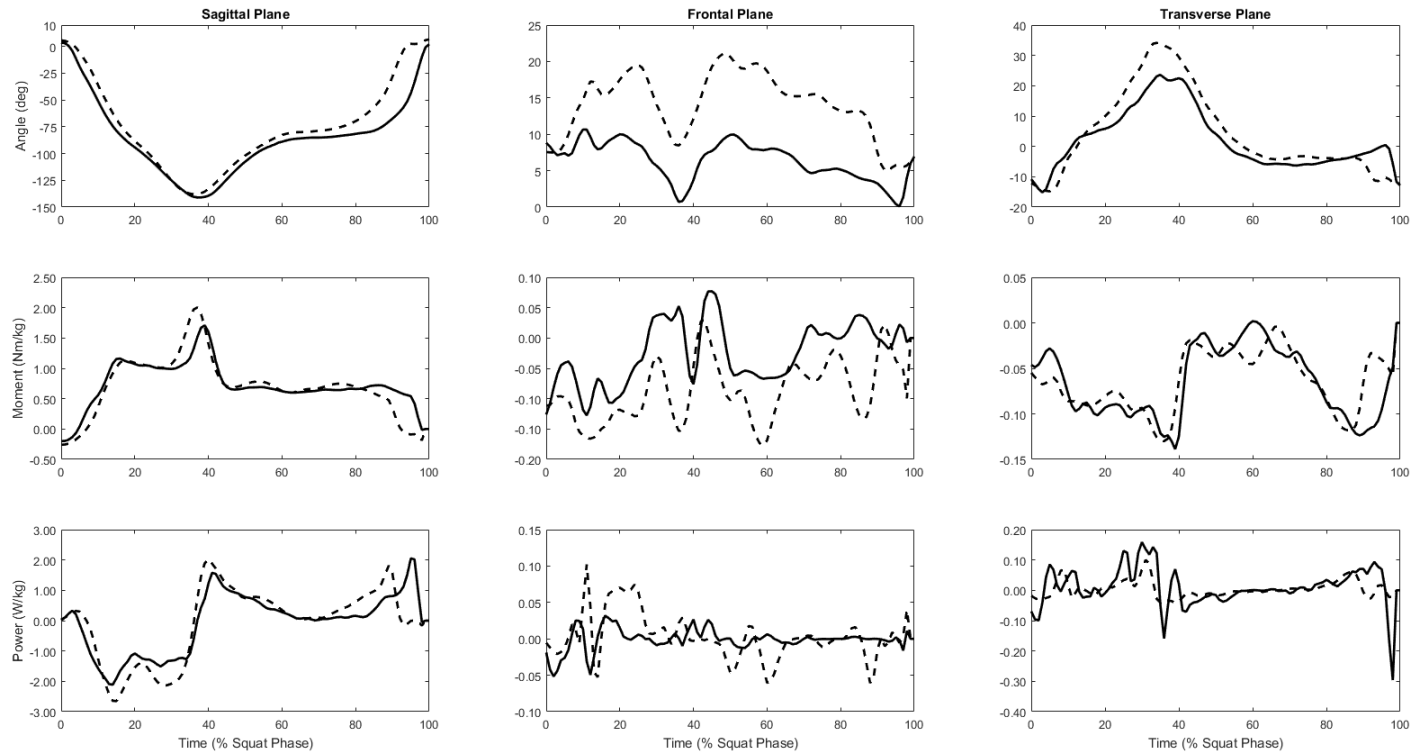
Notes: Moments normalized to mass + weight lifted. Ascent_45 and Descent_45 denote variables measured at 45-degree knee joint angles during ascent and descent phases of squat. X, Y, and Z denote extension/flexion, add/ab-duction, and internal/external moments, respectively. Moment polarity follows right hand rule.

Table 4. Knee power comparisons during 1-RM squats: mean \pm SD.

| | | No Sleeve | Sleeve | P-Value | Effect Size |
|-------------------|----------|------------------|------------------|---------|-------------|
| ASCENT_45 | X | 1.53 \pm 0.62 | 1.49 \pm 0.79 | 0.71 | 0.06 |
| | Y | -0.04 \pm 0.06 | -0.08 \pm 0.10 | 0.12 | 0.52 |
| | Z | 0.01 \pm 0.02 | 0.01 \pm 0.02 | 0.55 | 0.17 |
| DESCENT_45 | X | -1.16 \pm 0.35 | -1.21 \pm 0.45 | 0.53 | 0.12 |
| | Y | 0.01 \pm 0.04 | 0.04 \pm 0.08 | 0.31 | 0.38 |
| | Z | 0.01 \pm 0.02 | 0.00 \pm 0.02 | 0.38 | 0.22 |
| DEPTH | X | 0.02 \pm 0.05 | 0.02 \pm 0.08 | 0.75 | 0.08 |
| | Y | 0.00 \pm 0.02 | 0.00 \pm 0.02 | 0.98 | 0.01 |
| | Z | 0.00 \pm 0.01 | 0.00 \pm 0.01 | 0.19 | 0.38 |

Notes: Power normalized to mass + weight lifted. Ascent_45 and Descent_45 denote variables measured at 45-degree knee joint angles during ascent and descent phases of squat. X, Y, and Z denote sagittal, frontal, and transverse plane powers, respectively.

Figure 1. Knee biomechanics during 1-RM squats with and without knee sleeves for two participants.



1a.

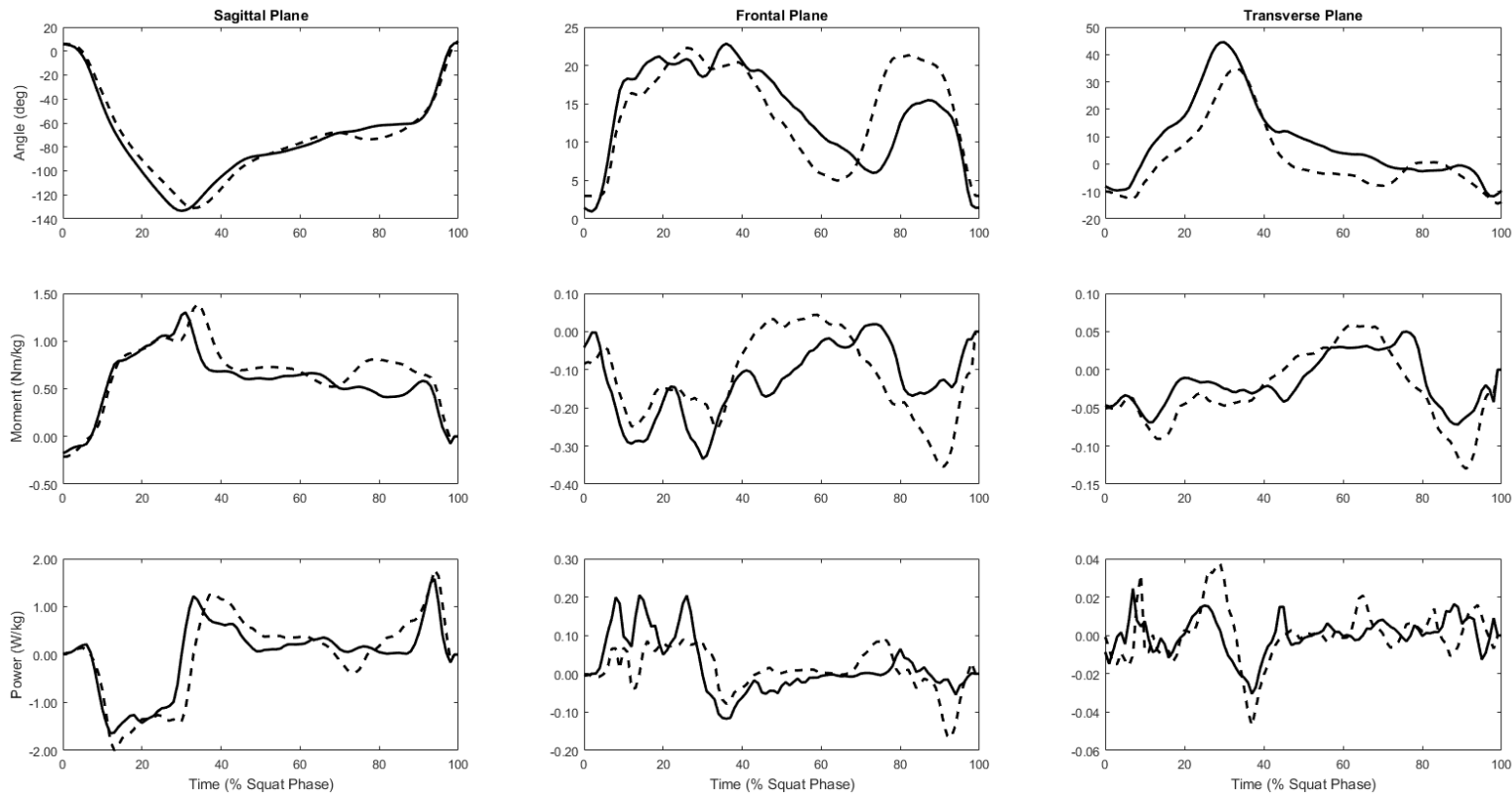
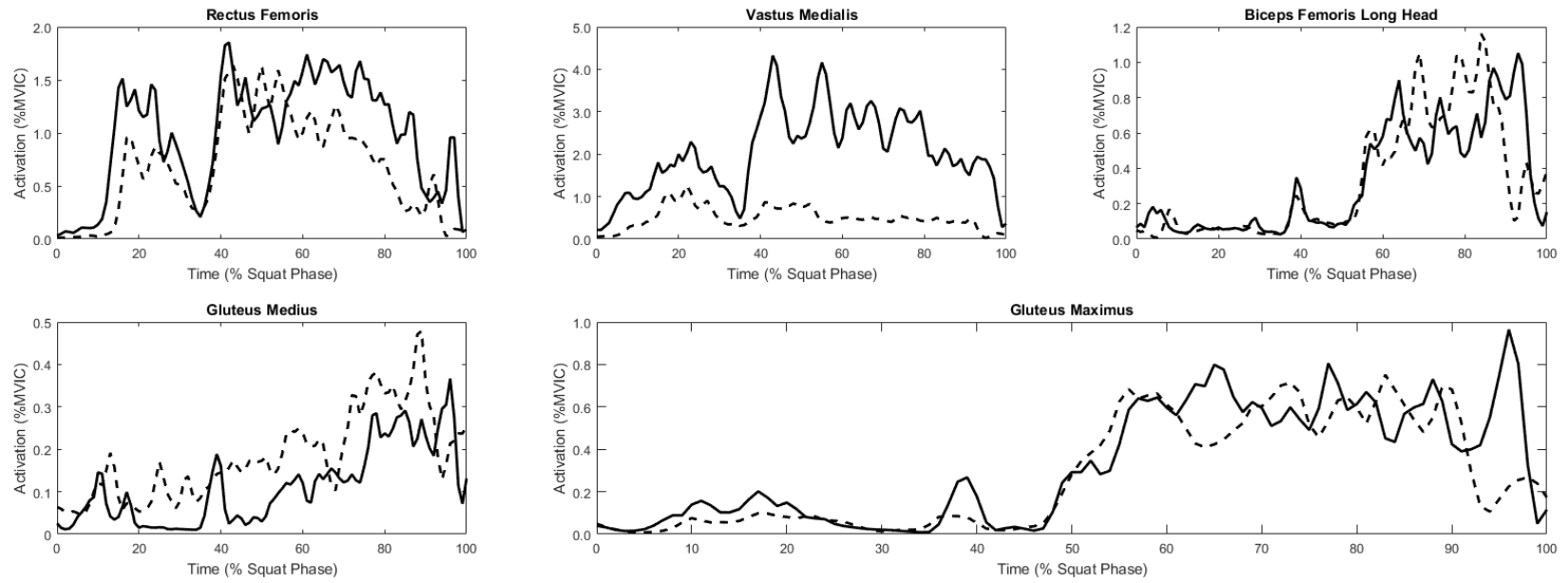
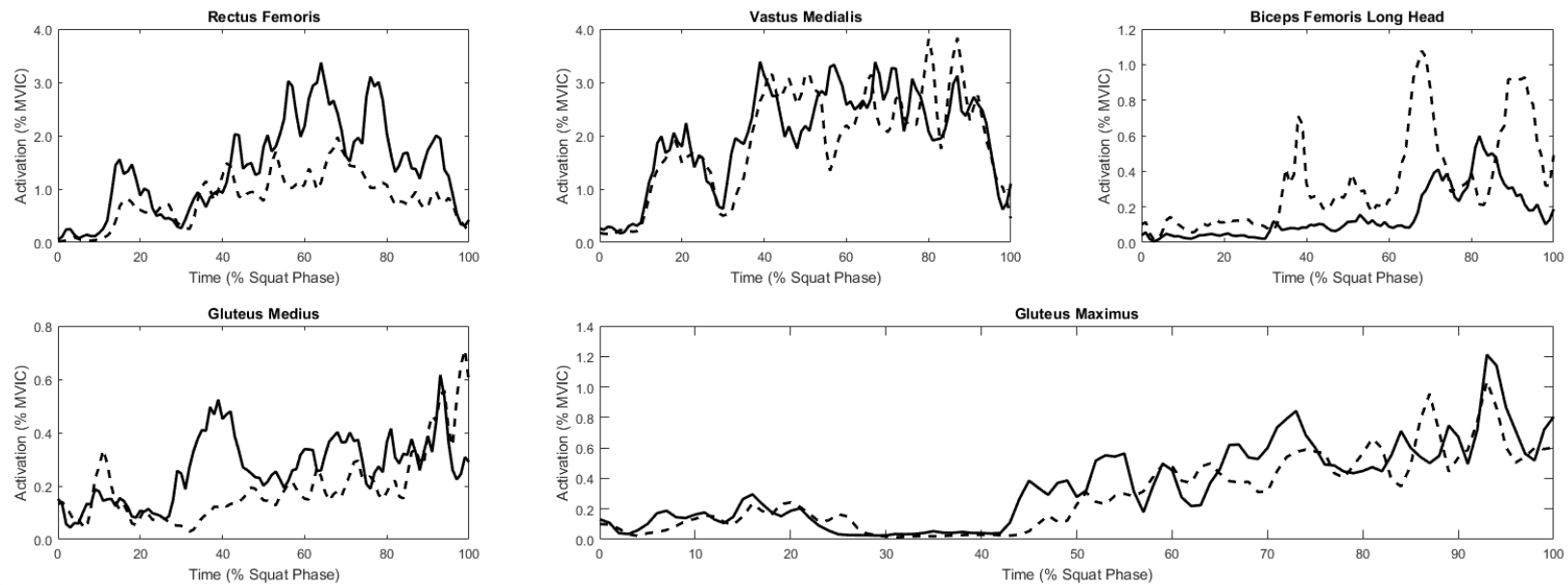


Figure 1 caption: Knee joint angles (top row), moments (middle row), and powers (bottom) are presented for one participant that had an 11.4 kg increase using knee sleeves (1a) and one participant that had a 4.5 kg decrease using knee sleeves (1b). Sleeve and no sleeve conditions are solid and dashed lines, respectively. Moments and powers were normalized to body mass and weight lifted (kg). No angle, moment, or power differences were found between conditions for 1-RM trials.

Figure 2. Muscle activation patterns during 1-RM squats with and without knee sleeves for two participants.



2a.



2b.

Figure 2 caption: Quadriceps (top left and middle), hamstring (top right), hip abductor (bottom right), and hip extensor (bottom right) muscle activation patterns are presented for one participant that had an 11.4 kg increase using knee sleeves (2a) and one participant that had a 4.5 kg decrease using knee sleeves (2b). Sleeve and no sleeve conditions are solid and dashed lines, respectively. Activations were normalized to the maximum voluntary isometric contraction (MVIC). Only integrated gluteus maximus activations were significantly different between conditions.

Sub-maximum Squats

Knee flexion angle at depth was significantly greater during full depth compared to parallel squats (Table 5; $p < 0.01$; $d = 1.09$). Only 3 main effects were found in knee kinetics. Knee external rotation moments during descent were larger with sleeves compared to no sleeves (Table 6; $p = 0.05$; $d = 0.67$). Full depth squats produced increased knee extension moments at depth (Table 6; $p = 0.03$; $d = 0.57$) and negative knee powers during descent compared to parallel squats (Table 7; $p = 0.03$; $d = 0.58$). Integrated gluteus maximus activation during ascent was larger in the no-sleeve (0.53 ± 0.19 %MVIC*seconds) compared to the sleeve (0.44 ± 0.13 %MVIC*seconds) condition ($p = 0.04$; $d = 0.55$). No other differences were found in muscle activations during sub-maximum squats.

Table 5. Knee angle comparisons at full-depth during sub-maximal squats: mean \pm SD.

| | No Sleeves | | Sleeves | | Condition | Depth | Interaction |
|----------|-------------------|------------------|-------------------|-------------------|-----------|-----------------|-------------|
| | Full | Parallel | Full | Parallel | | | |
| X | -120.0 \pm 11.7 | -106.3 \pm 9.9 | -118.3 \pm 13.3 | -107.0 \pm 11.3 | 0.87 | <0.01 | 0.69 |
| Y | 13.1 \pm 5.5 | 15.6 \pm 4.8 | 12.1 \pm 6.8 | 14.6 \pm 4.9 | 0.47 | 0.09 | 0.98 |
| Z | 18.4 \pm 11.4 | 12.4 \pm 10.0 | 19.3 \pm 12.1 | 14.7 \pm 9.6 | 0.57 | 0.06 | 0.81 |

Notes: X, Y, and Z angles denote extension/flexion, add/ab-duction, and internal/external rotations, respectively. Angle polarity follows right hand rule.

Table 6. Knee moment comparisons during sub-maximal squats: mean \pm SD.

| | | No Sleeves | | Sleeves | | Condition | Depth | Interaction |
|------------|---|------------------|------------------|------------------|------------------|-------------|-------------|-------------|
| | | Full | Parallel | Full | Parallel | | | |
| ASCENT_45 | X | 0.96 \pm 0.29 | 0.93 \pm 0.28 | 1.00 \pm 0.31 | 1.02 \pm 0.27 | 0.40 | 0.89 | 0.76 |
| | Y | -0.31 \pm 0.19 | -0.38 \pm 0.17 | -0.35 \pm 0.25 | -0.34 \pm 0.24 | 0.98 | 0.55 | 0.46 |
| | Z | -0.11 \pm 0.06 | -0.13 \pm 0.08 | -0.15 \pm 0.07 | -0.15 \pm 0.05 | 0.11 | 0.62 | 0.40 |
| DESCENT_45 | X | 0.93 \pm 0.22 | 0.98 \pm 0.17 | 0.90 \pm 0.21 | 0.96 \pm 0.26 | 0.61 | 0.36 | 0.97 |
| | Y | -0.33 \pm 0.22 | -0.37 \pm 0.21 | -0.37 \pm 0.21 | -0.37 \pm 0.21 | 0.66 | 0.75 | 0.74 |
| | Z | -0.10 \pm 0.06 | -0.10 \pm 0.06 | -0.13 \pm 0.07 | -0.14 \pm 0.06 | 0.05 | 0.83 | 0.92 |
| DEPTH | X | 2.30 \pm 0.84 | 1.91 \pm 0.42 | 2.45 \pm 0.86 | 2.07 \pm 0.51 | 0.40 | 0.03 | 0.99 |
| | Y | 0.12 \pm 0.34 | 0.06 \pm 0.28 | 0.05 \pm 0.37 | 0.02 \pm 0.29 | 0.56 | 0.60 | 0.88 |
| | Z | -0.04 \pm 0.10 | -0.04 \pm 0.08 | -0.05 \pm 0.10 | -0.06 \pm 0.07 | 0.42 | 0.89 | 0.92 |

Notes: Moment normalized to mass + weight lifted. Ascent_45 and Descent_45 denote variables measured at 45-degree knee joint angles during ascent and descent phases of squat. X, Y, and Z denote extension/flexion, add/ab-duction, and internal/external moments, respectively. Moment polarity follows right hand rule.

Table 7. Knee power comparisons during sub-maximal squats: mean \pm SD.

| | | No Sleeves | | Sleeves | | Condition | Depth | Interaction |
|-------------------|----------|------------------|------------------|------------------|------------------|-----------|-------------|-------------|
| | | Full | Parallel | Full | Parallel | | | |
| ASCENT 45 | X | 2.87 \pm 1.73 | 2.45 \pm 1.45 | 2.73 \pm 1.53 | 2.69 \pm 1.53 | 0.65 | 0.58 | 0.91 |
| | Y | -0.14 \pm 0.18 | -0.12 \pm 0.15 | -0.10 \pm 0.17 | -0.15 \pm 0.15 | 0.47 | 0.79 | 0.82 |
| | Z | 0.02 \pm 0.06 | 0.02 \pm 0.04 | 0.02 \pm 0.03 | 0.02 \pm 0.05 | 0.97 | 0.85 | 0.94 |
| DESCENT 45 | X | -2.40 \pm 0.73 | -2.07 \pm 0.56 | -2.55 \pm 0.78 | -2.04 \pm 0.77 | 0.63 | 0.03 | 0.72 |
| | Y | 0.09 \pm 0.14 | 0.08 \pm 0.06 | 0.06 \pm 0.11 | 0.07 \pm 0.09 | 0.71 | 0.96 | 0.45 |
| | Z | 0.01 \pm 0.04 | 0.00 \pm 0.02 | 0.00 \pm 0.03 | 0.00 \pm 0.03 | 0.53 | 0.36 | 0.72 |
| DEPTH | X | 0.01 \pm 0.10 | 0.00 \pm 0.02 | 0.01 \pm 0.07 | 0.01 \pm 0.06 | 0.99 | 0.65 | 0.86 |
| | Y | 0.01 \pm 0.02 | 0.00 \pm 0.02 | 0.02 \pm 0.04 | 0.00 \pm 0.02 | 0.43 | 0.12 | 0.62 |
| | Z | -0.01 \pm 0.04 | 0.00 \pm 0.01 | -0.01 \pm 0.04 | 0.00 \pm 0.01 | 0.88 | 0.32 | 0.95 |

Notes: Power normalized to mass + weight lifted. Ascent_45 and Descent_45 denote variables measured at 45-degree knee joint angles during ascent and descent phases of squat. X, Y, and Z denote sagittal, frontal, and transverse plane powers, respectively.

V. DISCUSSION

The purpose of this study was to assess the effects of wearing neoprene knee sleeves on lower extremity kinematics, kinetics, and muscle activations during weighted back squats. We hypothesized that while using knee sleeves for maximal and sub-maximal back squats: 1) the support provided by the knee sleeve will reduce muscle activations compared to not wearing the knee sleeve, 2) loads on the knee joint will be reduced while wearing knee sleeves and 3) knee joint angles will decrease while wearing knee sleeves due to the fabric causing a physical barrier between calf and thigh contact. Additionally, we hypothesized that wearing knee sleeves will 1) increase a lifter's 1-RM and 2) decrease rating of perceived exertion (RPE). Our hypotheses are mostly rejected, as donning knee sleeves only affected 1) knee external rotation moment during the descent phase of sub-maximal squats and 2) reduced integrated gluteus maximums activation during the ascent phase of both maximal and submaximal squats.

Surprisingly, knee sleeves did not significantly improve weight lifted compared to no-sleeves. On a subject-specific basis, 1-RM results were quite erratic: six participants exhibited a greater 1-RM with sleeves (range: 2.3 - 13.6 kg), three participants a lower 1-RM with sleeves (each 4.5 kg), and six participants matched 1-RM in both conditions. In addition, perceived exertion was not significantly impacted for 1-RM or submaximal lifts with knee sleeves. Therefore, it appears knee sleeves do not provide any advantage from a weight-lifting perspective, at least among individuals with substantial resistance training experience.

Given the effects of squat depth on difficulty in lifting similar loads (Calhoon et al., 1999; Hamill et al., 1994; Kulund et al., 1978, Wretenberg et al., 1996), we chose to control squat depth during 1-RM and sub-maximal testing. Our knee angle results suggest our

methodology of assessing an acceptable squat (full-depth: thigh-calf contact; and parallel: thighs parallel to ground) was sufficient. Maximum knee flexion angles were not statistically different between conditions (sleeve/no sleeve) and were statistically greater in full-depth compared to parallel squats. Thus, it appears our methods were sufficient to control knee flexion.

Although no other research exists on knee sleeves during weight-lifting exercises, knee wraps are well-researched and are a somewhat similar knee support device. Previous research demonstrated that wearing knee wraps increased 1-RM for lifters and that was a main reason for powerlifters to wear them in training and competition (Marchetti et al., 2015). Although knee sleeves should, theoretically, provide a similar elastic response and increase in weight lifted, it is likely the elastic properties of knee sleeves are inferior to knee wraps. It is possible that knee sleeves weren't as effective as knee wraps due to their thickness and are not worn as tight (assuming persons follow the fit guidelines). The elastic material in both sleeves and wraps should spring back to its original shape after being deformed or stretched, thus assisting the lifter. According to Gomes et al., 2014, the elastic energy stored in the knee wrap is transferred into kinetic energy and added to the lifter (Gomes et al., 2014). However, this was likely not provided by knee sleeves, as there was no significant increase in weight lifted. A perceived advantage of knee sleeves is the sleeves do not lead to occlusion and pain, a known negative of the knee wraps due to their intense and tight application (Gomes et al., 2015; Harman & Frykman, 1990), which may be a factor of their popularity. Other research with knee wraps has found increased mechanical output and increased vertical impulse with decreased lowering and lifting phase durations (Lake et al., 2012). Our study did not find meaningful knee kinematic or kinetic differences between wearing knee sleeves or no knee sleeves at maximal or sub-maximal loads. Various studies have found carry-over, or additional weight lifted, with knee wraps to be

anywhere from 10-13% to 20-25% while squatting to 90° (Gomes et al., 2014; Harman & Frykman, 1990, Marchetti et al., 2015). Although 1-RMs were not performed at 90° knee angles, our comparisons of sub-maximal squats to both full-depth and parallel suggest no "carry-over" effect would occur at small knee angles. Similar to our study, Marchetti et al. and Gomes et al. both found no RPE differences with/without knee wraps. Therefore, although knee sleeves may be easier to wear/utilize as they do not require intense wrapping procedures, knee sleeves are not as effective as knee wraps.

Only one significant difference in muscle activations between conditions was found. Integrated gluteus maximus activity during the ascent phase of squatting was significantly greater in both maximal and submaximal squats using the no-sleeve condition. Coupled with the lack of differences in joint mechanics, it is evident that knee sleeves do not markedly alter squat technique or muscle recruitment. We also did not see a change in barbell patterns while wearing knee sleeves as was reported using knee wraps (Lake et al., 2012). The previous study found a significant reduction in horizontal displacement during the lowering phase of a squat while wearing knee wraps (Lake et al., 2012). We did not track barbell trajectory; however, a change in barbell path should have resulted in alterations to lower extremity joint loads/patterns.

Previous work utilizing neoprene knee sleeves suggest knee sleeves are useful as knee supports during various physical tasks involving the knee joint (Bryk et al., 2011; Schween et al. 2015; Csaspo et al. 2016). This body of work analyzes similar support devices such as thinner knee sleeves or braces with the primary population having knee injuries and typically in a rehabilitation setting. Bryk et al., 2011, found their KOA patients felt less pain while wearing knee sleeves, using a visual analog scale, and two of the three physical tests utilized significantly improved with sleeves, the 6-meter walk and timed up and go assessments. With no significant

differences in RPE or 1-RM in a healthy population, our results do not concur with a reduced pain scale or enhanced performance. Previous reports of knee sleeves have detailed walking with an elastic knee sleeve reduced knee adduction angles, moments and impulse in persons with KOA (Schween et al., 2015). In addition, knee sleeves have limited the amount of anterior tibial translation in healthy female athletes during passive tibial translation tests (Csaspo et al., 2016). Contrarily to these studies, we found no changes in knee angles, moments, powers, or activation patterns in muscles surrounding the knee joint while wearing knee sleeves. Although these several benefits have been associated with wearing supportive knee sleeves in unloaded movements, these improvements do not translate to loaded back squats.

A previous comparison of low bar and high bar placement found that both low and high bar back squats produced greater peak hip moments during deep compared to parallel squats (Wretenberg et al., 1996). Comparing our deep and parallel squats, we found no significant differences in knee mechanics. Although hip and ankle mechanics were not a primary aspect of this study, no marked ankle/hip mechanic differences were found between conditions. Since all subjects were required to use high-bar back squats in this study, we cannot address the previous results in regards to low-bar back squats.

The lack of muscle recruitment differences in primary knee muscles (RF, VM, and biceps femoris) during 1-RM or submaximal squats was quite surprising. If knee sleeves provided any discernable mechanical advantage, submaximal squats while wearing knee sleeves should have resulted in reduced quadricep muscle activations due to an added elastic effect from the knee sleeves. However, coupled with the lack of increased 1-RM weight lifted, the lack of alterations in quadricep or hamstring muscle activations suggest knee sleeves provided no advantaged to the neuromuscular system. Contrary to our findings, wearing knee wraps at 90% 1-RM squats

resulted in lower activation of the VL, but no difference in integrated gluteus maximus activity compared to no knee wraps (Gomes et al., 2014). Therefore, despite similarities in usage, it is apparent that knee sleeves do not provide the same effects as knee wraps.

VI. CONCLUSION

Within a population of experienced, healthy weight lifters, wearing knee sleeves while back squatting does not significantly increase weight lifted, reduce RPE, impact the muscle activations, knee joint angles, or knee joint loads. Biomechanically, wearing knee sleeves also does not appear to have an impact on maximal or submaximal deep back squats.

Recommendations

With no significant differences in muscle activation or joint loads while wearing knee sleeves during back squats, there are no recommendations for or against knee sleeves. This recommendation only applies to those with healthy knees, as no subjects with knee injuries were included in our study. Those desiring to lift heavy and do have a knee injury, past or present, are encouraged to listen to their physical therapists and medical professionals when deciding to wear or not wear any type of knee support.

Future research addressing knee sleeves could consider subjects that currently have knee injuries. Additional research could be performed to compare the different thicknesses of knee sleeves (3mm, 5mm, and 7mm), different types and/or brands of knee sleeves, as well as a direct comparison between the knee wrap and knee sleeve. The current study examined the high bar back squat at full depth and at parallel; however, future studies could address other variants of squats to include alternate load placement (front squats, low bar back squat), varying stance width or a wider variety of depths.

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