SQUAT DEPTH IN RELATION TO POTENTIAL INJURY OF THE KNEES AND LUMBAR

A THESIS

SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

BY

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Declaration

The thesis is described presently unless acknowledged otherwise to the best of my knowledge original, and the document has not been submitted to another institution for requirements of another degree.

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John Ethan Andamasaris Date

Acknowledgments

This project is designed to help and educate people on the biomechanics of squatting in different depths. I would like to thank all my classmates that helped me with completing this, I could not have done it without them. I would also like to thank Dr. Henry Wang for all the help and guidance he gave me while completing this. He set aside lots of his time to help me make this project come to life. I would also like to thank Dr. Clark Dickin and Dr. Lawrence Judge for all their support and guidance.

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Abstract

Introduction: Squats are one of the most widely used exercises in the strength and conditioning community. It is considered to have superior biomechanical similarities to athletic movements which could help enhance performance. It is also proven to be effective in improving leg strength and physical functioning in the general population. Although squatting is an exceedingly popular exercise, it is associated with an elevated risk of overuse injury in the low back and the knees. The purpose of the study is to examine the mechanics and muscle activation patterns in the knee and lumbar region during different squatting depths (deep, parallel, and partial). The main research question is how squatting at different depths affects the biomechanics in the knee and lumbar regions. Specifically, does performing a deep squat place a greater mechanical load on the knees and lumbar compared to a partial or parallel squat? Also asking the question of which muscle groups will be most active in the deep squat. It is hypothesized that the deep squat will put a higher mechanical load on the knees and lumbar. It is also hypothesized that EMG readings will show the highest quadriceps, hamstring, and erector spinae activation in the deep squat position. But show no difference in gluteus maximus activity between conditions.

Methods: Testing was broken down into two collection days. On the first day, participants performed a three-repetition max (3RM) barbell back squat in the deep squat position. Their 3RM was used to give a predictive 1RM that was used for the main collection. On the second day, participants performed squats with three different depths in a randomized order with a resistance level set at 75% of their predictive 1RM. Performing each squat in one set of three repetitions. 3D motion capture with force plates was used to determine the mechanics of the squat movements to determine mechanical load. Electromyography (EMG) was also used to assess activation patterns of muscles in the leg and lumbar region. **Results:** The main findings suggest that higher knee flexion will influence more moments and quadricep/hamstring muscle activation in both the concentric and eccentric phases of the squat. Trunk flexion did show an increase as the knee flexion increased between depths. The erector spinae and gluteus maximus muscle activation did not show to be greater as knee flexion increased but instead stay consistent between each condition. **Conclusion:** Muscle activation in the lower back stayed the same through each condition. There was increased mechanical load put onto the knee region as depth increased, these increased moments will also contribute to increased muscle activation on the quadriceps and hamstrings.

Chapter 1: Introduction

The benefits gained from the squat are not limited to just the athletic population (Schoenfeld, 2010). The squat has a connection to many muscle groups and given that most activities throughout the day require those muscles it makes the squat an important movement for the general population to perform and become proficient in. Squatting is considered one of the best exercises to improve quality of life and is also becoming more popular in clinical settings, helping strengthen lower body muscles after injuries. (Schoenfeld, 2010). Squats are used to enhance both strength and hypertrophy of the lower body and improve functional performance. It is one of the building blocks of exercises yet so many people do not know the details that go into the squat. It has been an ongoing debate in the exercise community about which range of motion (ROM) is most optimal when squatting (Schoenfeld, 2012). As there are many different opinions among experts about which squat is the best to perform for their bodies. Research states that the parallel squat is best and can reduce injury (Escamilla, 2001). While other research states that the deep squat is safe to perform, and the body can adapt to more force in the lower extremities (Hartmann et. al., 2013).

When looking into existing literature the two most common injury spots were the knee and spine/lumbar region. Professional powerlifters in many situations were documented to have the back and knee as the top two injury locations. Having over one thousand hours of training it occurred in several cases that over fifty percent of the time the back was the main location, followed by the knees (Aasa et. al., 2016). It was determined that 3.3 injuries per 1000 training hours happen over six years in Olympic weightlifters. These injuries were not long-lasting and were related to tendinitis in the knee due to overuse. A limited amount showed acute or muscle strain injuries over this time compared to chronic injuries (Calhoon et. al. 1999). The majority of the public does not complete squats with the load and intensity of Olympic weightlifters, but it can be speculated that forces will still be applied to the knees and lumbar. Research states that avoiding deep knee flexion is recommended to minimize forces on the lumbar and knee joints (Escamilla, 2001). But no factual evidence is presented that deep knee flexion exerts a significantly greater number of forces in those areas to cause injury. It was found that there were no high knee joint forces for knee flexion beyond 50 degrees. But the highest compressive forces and stresses can be found at 85 degrees in the ascent phase. This is due to where the load is being placed putting the most stress on that area (Hartmann et. al., 2013). Also, with this increasing flexion with the deep squat, there is more load distribution and force transfer within the lower retro patellar compressive forces which is termed the wrapping effect (Hartmann et. al., 2013). ACL and PCL loading forces have been shown to reduce when the knee becomes more highly flexed. The force in the ACL is greatest around 15-30 degrees of flexion and significantly decreases at 60 degrees. While the PCL maxes out around 90 degrees (Schoenfeld, 2012). It was also found that increased trunk flexion in the squat reduces the tolerance of compressive loads and transfer of the load from the muscles to the passive tissues. Having the increased forward lean increases the amount of shear force being put onto the lower back region (Yavuz et. Al., 2015). The amount of literature on the lower back region within squat depth is limited and seeing the forces produced could build solid data to share.

Neuromuscular activation has been seen to be inconsistent when comparing depths of squats. Studies have shown different activation patterns when comparing different depths between participants (Gorsuch et. al., 2013, Da Silva et. al., 2017, Contreras et. al., 2016). This can be due to different weights, and repetitions performed as well as the type of individuals that participated. This becomes problematic and is difficult to tell which study is showing the right information for someone to use. Comparing all three depths with a consistent load and looking at both eccentric and concentric phases of the squat will give accurate information on the muscles being used during each condition. Being able to show the angles produced, with forces made in those angles will be able to show the trends made with muscular activation. There is a need for updated neuromuscular activation data in healthy adults that perform the squat. This current study aims to produce accurate information for the public on muscle activation in different squat depths.

Using all three squatting conditions can be beneficial to all types of different people. Dependent on their goals, and limitations. One squat does not fit all people, developing an understanding of all three conditions and how they differ will allow people to educate themselves and choose what is right for them. A basketball player wanting to work on sport-specific jumping may not use as much of the deep squat as an Olympic weightlifter. A basketball player would want to work in a squat depth that they would perform in a game and that would be a partial squat. A limitation a person may have to their knees may also decide which depth to perform, as someone with a recently torn ACL should not perform a deep squat as it can produce more force in those areas (Escamilla, 2001). Injuries can happen when exercising by having an overabundance of stress and forces being put onto the body. Having research that can teach people what they should be avoiding and minimizing injury is an important topic to explore and share. Specifically exploring knee and back injuries and why injuries happen while squatting and how to avoid them. Squatting should be a safe and effective exercise to develop the lower extremities.

Thus, the purpose of the study was to examine the mechanics and muscle activation patterns in the knee and lumbar region during squats with different depths (deep, parallel, and partial). The parallel squat can be defined as having the femur parallel to the ground. The deep squat is ~twenty degrees lower from the parallel position and the partial squat is ~twenty degrees higher from the parallel position (Cotter et. al., 2013). Squats were broken down into eccentric and concentric phases. The eccentric phase is from the standing position to the bottom position, while the concentric is from the bottom position to the standing position. The main research question was how squatting at different depths affects the biomechanics in the knee and lumbar regions.

Specifically, does performing a deep squat place a greater mechanical load on the knees and lumbar compared to a partial or parallel squat? This study planned to investigate the biomechanics of the squat and how it affects the body. It was hypothesized that the deep squat would put a higher mechanical load on the knees and lumbar. It has been seen in past studies that there is a trend of higher forces in the knee when knee flexion is increased (Escamilla, 2001). It was also seen that with increased knee flexion the trunk would increase in flexion as well. This increased trunk flexion would produce more force on the lumbar (Yanagisawa et. al., 2020). It was hypothesized this trend will continue and data will show an increase in moments and power to the knee with increased knee flexion. It is also hypothesized that electromyography (EMG) readings will show the highest quadriceps, hamstring, and erector spinae activation in the deep squat position. Past studies have been inconsistent in their findings, but with other data, research has shown increased knee moments in the deep squat position (Escamilla, 2001). It is hypothesized that the increased moments will show higher quadriceps and hamstring EMG activity. It was shown in a study that trunk flexion can cause increased activation in the erector spinae muscles (Yanagisawa et. al., 2020). It is also hypothesized that the gluteus maximus muscle activation will show no change between conditions. As the gluteus maximus findings have shown to also be inconsistent. As a past study shows parallel produces the highest activation in the gluteus maximus (Marchetti et. al., 2016). But another previous study found the gluteus maximus to have no change. This study is more closely related to my procedures, and it is hypothesized this current study will produce similar results (Contreras et. al., 2016). The outcome of this study will improve our understanding of the effect of squatting on the knee and lumbar health, as well as enable practitioners to develop customized squat exercise programs for athletes and the general population.

Chapter 2: Literature Review

2.1 Overview and Benefits

The squat is one of the most essential and efficient movement patterns to improve performance and build resilience to injuries if done correctly. It is one of the most effective exercises because performing a squat takes the coordinated interaction of many muscle groups and strengthens prime mover muscles that give people the ability to be explosive in certain movements like jumping and running. This also translates to everyday life where performing the squat supports those muscles to be able to perform everyday tasks like squatting over to pick up a large object. It is a major benefit to be strong in that position to improve the quality of life among people. Squats are also helpful in the clinical setting providing a movement that can strengthen the lower body with minimal harm to the connective tissue after a joint-related injury (Myer, 2014). Squats are also an exercise to be used for rehabilitation. As the squat is a closed kinetic chain exercise that provides excessive strain that can be placed on the ACL (Myer, 2014). The depth of the squat is a major component in getting the full benefit of the activity. Training in deeper depth will help benefit motor control positions that would be more present in most sports. It was also stated that no evidence indicates the deep squat effects potential injury to the cruciate and collateral ligaments. But the squat in fact may enhance knee stability if performed correctly and may reduce injury risks (Myer, 2014). Looking into practical applications of depth in the squat can be dependent on what goal the individual sets. Past research has shown that individuals involved in sports who want to exert maximal power through a limited range should perform near-maximal partial squats to improve performance (Drinkwater, 2012). Past research has shown that the anterior cruciate ligament (ACL) is loaded more in the 10–50-degree knee flexion range and peaks in force between 10-30 degrees (Escamilla, 2012). This information provides rehabilitation methods to be used to reduce swelling and pain and increase recovery in patients. As it is common for research to state that it is recommended to engage in quarter to parallel squats to avoid degenerative problems in the knee region. It is shown that the cartilage tissue receives inadequate stresses that would lead to fighting degradation around the knee (Morscher, 1978).

2.2 Structure of the Body

The deep or full squat can be performed by having the knee angle around ~120 degrees, the parallel squat around ~90 degrees, and the quarter or parietal squat ~60 degrees. (Kubo et. al., 2019). The parallel squat can be defined as having the knees flexed until the inguinal fold is in a straight horizontal line with the top of the knee (Hartmann, 2013). By performing these several types of squat depths different things happen to the body. Different muscle activation occurs, and stress is put onto joints. For this, looking into the different depths will give information on what gives people a safer way of squatting and reducing injury. The amount of force that can be loaded safely differs from individual to individual. But research has shown that for individuals under 26 years old, the PCL tensile strength was 4,000 N. While the ACL tensile strength for ages 16 to 35 was 1,730 ± 660 N (Noyes, 1976). While the vertebral column was shown to have a compressive force strength of 11,000 N. It was also shown that specifically in the L4/L5 in a 22-year-old male it would have a compressive strength of 8,800 N (Brinckmann, 1989). Understanding the key components of the knee and spine/lumbar region and what they are made up of will give insight into what research is looking at. The knee joint consists of the tibiofemoral which gives people the ability to have a range of motion of 0 to 160 degrees of flexion. This joint is a hinge joint comprising the articulation of the tibia and femur. Assisting this joint is the patellofemoral joint, a gliding joint that provides mechanical leverage in extension and reduces wear on the quadriceps and patellar tendon (Schoenfeld, 2010). The knee is also supported by many different ligaments and cartilage which stabilize and support the entire knee. While the spine is made up of 24 vertebral segments, all displaying some degree of freedom in them. As a whole unit, it is capable of flexion and extension in the sagittal plane, lateral flexion in the frontal plane, and rotation in the transverse (Schoenfeld, 2010). It is also supported by many different muscles like the erector spinae. The lumbar is particularly important during a squat because it helps resist any shear forces and maintain spinal integrity. (Schoenfeld, 2010) This can cause the spine, lumbar region, and any other supporting muscles to be exposed to many internal forces during the squat. All these joints, ligaments, and muscles can be put under great stress while performing the squat. Finding the correct depth for an individual will provide optimized performance and reduced injury.

2.3 Neuromuscular Activation

When looking into the squat electromyography (EMG) the main muscles being read where the hip, thigh, and trunk muscles more specifically the gluteus maximus (GM), biceps femoris (BF), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), and erector spinae (ES). The muscle activation shown in the different depths did vary from study to study. Comparing the parallel squat to the partial squat it was shown that the RF was higher in the parallel squat. It also, shows the ES activity was higher in the parallel squat as well. BF activity was shown to have similar activity between both the parallel and partial (Gorsuch et. al., 2013). Another study compared the full and partial squats, and it was shown that the partial squat had significantly greater activation in the GM. There were no other differences in muscle activation between the other muscles (Da Silva et. al., 2017). This study that was looked at showed no difference in the GM, BF, and VM between the full and parallel squats. They both showed similar EMG readings throughout the whole motion (Contreras et. al., 2016). Another study observing the thigh muscles in a bodyweight squat in different depths showed no change in VM, VL, and BF among conditions. It was stated that the thigh muscles did not go under any change, but the GM did change between conditions in the concentric phase of the squat (Caterisano et. al., 2002). The last study looked at all three depths at 20, 90, and 140 degrees in an isometric squat. In general, the most muscle activation was found at 90 for the three quadriceps muscles. Muscle activation of the GM was found greater at 20 and 90 degrees. The BF showed similar activity along all joint angles. Overall, the knee position alters muscle activation of the quadriceps and GM muscles (Marchetti et. al., 2016). Another previous study looking at EMG activation of the VM, BF, and GM found that the VM was most active in the concentric phase of the parallel squat. It also found the BF to have the lowest activity in that depth and phase. The GM findings suggested that the parallel squat maximizes EMG activation to that squat depth (Hammond, 2016).

2.4 Kinematics/Kinetics

The kinematics and kinetics of the squat are especially important in deciding which squat will fit each person. Many studies have looked at the whole leg going from the ankle, knee, hip, and lumbar. They are all connected and contribute in some way to one another. To this, narrowing down and looking at the knee and spine/lumbar region will provide information on the two most common injury spots. Having a strong and stable knee is key for all types of people. Understanding how the knee works and how it takes on different loads in various positions is helpful. When examining the knee in all types of depths there was a low to moderate posterior shear force that was restrained by the posterior cruciate ligament (PCL). While there were also low anterior shear forces restrained by the anterior cruciate ligament (ACL) but were only found between the knee flexion of 0-60 degrees. There were also patellofemoral compressive forces, tibiofemoral compressive forces, and shear forces that progressively increased as the knees flexed and decreased as the knees extended. The knees were reaching peak values near maximum knee flexion. It is said training between 0-50 degrees of knee flexion will provide the least amount of knee force in that range (Escamilla, 2001). Since it has been shown that both tibiofemoral and patellofemoral compression has been shown to increase with increasing knee angles. These forces then provide a protective function at the knee by contracting the quadriceps and hamstring muscles. The hamstrings send a counter force on the tibia by pulling on it posteriorly, causing a counteraction of a shear force being put onto the knee (Schoenfeld, 2010).

The spine having flexion and extension has been shown to impact joint kinetics during the squatting motion. During that squatting motion, a flexed lumbar spine decreases the moment arm for the lumbar ES. This reduces the spine's tolerance to hold a compressive load which then transfers those forces from the muscles to the passive tissues resulting in disc herniation. So, the shear focus is much higher as the lumbar flexion increases as the spine cannot take on that type of shear force resulting in some type of injury. Another key point is the lumbar forces increase in the forward lean of a squat, maintaining an upright posture is always important (Schoenfeld, 2010). Another component of the lumbar spine is the compressive load that happens in the L3-L5 region. As more weight is added to the bar when squatting, a more compressive load will come from it. The body does an excellent job over time of adapting to these forces and creating a more rigid system to take on more weight. That it does not prevent any such injuries from happening (Hartmann et. al., 2013). It was seen that the parallel or deep squat presented greater mechanical stress on the lower lumbar. This is caused by having an anterior pelvic tilt angle at the bottom position of a deeper squat. The loading of the spine can be a significant injury if not done correctly. As this study did state that the training effects are greater in the parallel and deep squat, it does carry that precaution of that stress being put into the spine. As the weight continues to go up and the depth is low there is more risk of injury (Yanagisawa et. al., 2020).

2.5 Injury

When the debate of squat depth comes up with the squat, people have many opinions about what is right and what is wrong. It has been stated in past research that going into a deep squat will put a peak mechanical load on the knees to the point that injury can occur (Escamilla, 2001). It has also been stated that these forces might be high, but the body will learn to adapt to them (Hartmann et. al., 2013). Looking into key injury spots and seeing what forces are being produced will give data to verify if those forces are too much for the body to take on. When looking at professional powerlifters the two most common injuries that were found were the knee and spine/lumbar region. The injury occurs in the knees and lumbar when shear and compressive forces overtake the normal capacity that it normally will stand. So even when looking at professional powerlifters who have an excellent technique that they have been practicing for many years, injury can occur and especially in those two areas (Aasa et. al., 2016). Before looking into squat depth, having the correct technique, and using the correct amount of weight can be key factors in reducing injury while squatting. Not having these two things could lead to severe injury even if they are performed at the correct depth for that person.

The main concern that has been talked about is deep squats could have an increased risk of injury to the knees and spine/lumbar region. It is stated that avoiding deep knee flexion is recommended to minimize forces on the lumbar and knee joints (Escamilla, 2001) (Yanagisawa et. al., 2020). But this is no factual evidence that deep knee flexion exerts forces that would be detrimental to the body. It was found that there were no high knee joint forces for knee flexion beyond 50 degrees. But in fact, the highest compressive forces and stresses can be found at around 90 degrees. When observing how much force was produced throughout the squat it was shown to have the highest patellofemoral compressive forces (4,548 ± 1,395 N, 4.99 9 bw) present in the ascent phase at 95 degrees. In the decent phase, it was recorded at 85 degrees to have the highest compressive forces (4,042 ± 955 N, 4.43 9 bw) (Escamilla, 2001). Research has also shown tibiofemoral and patellofemoral compressive in three different positions. At approximately 50 degrees forces of 6,750 and 7,000, Newton (N) was produced. At 90 degrees 6,000, and 6,250 N, and at the top, at 120 degrees it decreased to 5,000 and 5,550 N (Nisell, 1986). Therefore, much past research has stated that going into a deep squat puts this increased force on people's knees. It does but it is not proven that these forces are too much for individuals. Also, with this increasing flexion with the deep squat, there is more load distribution and force transfer within the lower retro patellar compressive forces which is termed the wrapping effect. This wrapping effect is a protective mechanism that increases the thickness of the quadriceps tendon causing more compression in that tendon (Hartmann et. al., 2013). ACL and PCL forces have been shown to go down as high knee flexion is present. The force in the ACL maxes out around 15-30 degrees of flexion and takes a big decrease at 60 degrees. While the PCL maxes out around 90 degrees (Schoenfeld, 2012).

As stated earlier (Yanagisawa et. al. 2020), the spine/ lumbar region does have slightly more stress when put into a deeper squat with a large load. Research has presented that those subjects with a greater forward lean showed the highest tibiofemoral shear forces (Ariel, 1972). These restrictions on forward knee displacement will cause a change in knee-hip coordination McKean et. al., 2010). This displacement will cause greater forward flexion of the lumbar spine (List, et. al., 2013). This movement will cause an increase in greater anterior shear forces on the intervertebral ligaments and discs (Potvin, 1991). This data has been provided and it has been instructed to avoid forward knee placement. This information is not valid and does not calculate which direction these shear forces are going in and if it is too much for the body (Ariel, 1972)

(Hartmann et. Al., 2013). It was calculated that the anterior shear force and ACL forces with loads 1.16-to-2.27-fold bodyweight in parallel and deep squats. The parallel and deep squats accounted for 11.62 and 28.9% of tensile strength. The partial squat presented anterior shear forces with a load of 1.16-fold body weight between 33.29-41.56%. Seen from these studies the deep squat does not present shear forces to the PCL and ACL that could cause any harm (Noyes, et. al., 1976) (Woo et. al., 1991). How much of a load is being put onto the bar and how the technique is when going into a deeper squat is a precaution all should take. When performing the deep squat, a lighter load will be required to perform it. Paired with normal strength training the body will adapt its passive tissues to be able to go into that position and take on those forces (Eckstein et. al., 2005). If there is too much of a load going into a deep squat it could result in injury to both the lumbar and spine. If going into a deep squat compromise form, it should be avoided to limit injury in the lumbar and knees. The stress put onto the lower lumbar is most present with forwarding trunk lean. As form starts to give out with a heavier load forward trunk lean will become present putting most of the stress on the lower lumbar region and hamstrings. Forward trunk lean can become present in all depths during the squat, but it is unknown if having a deeper depth will increase forward trunk lean in individuals (Yavuz, 2015). It is hypothesized the deep squat will not pose a threat to the knee joints and lumbar region if done correctly. Having the correct technique and weight will allow people to perform a deep squat correctly and safely.

A squat is a complex movement and knowing how to perform the squat movement correctly is something that should not be overlooked. As seen in the EMG findings the biggest difference in muscle activation between knee flexion angles was the quadriceps activated more in the parallel squat compared to full and partial squats, and the hamstring muscles did not see a meaningful change between the three depths (Marchetti et. al., 2016). If an individual has the correct form and mobility to be able to perform a deep squat there is no reason for them to avoid that depth. The deep squat requires a higher level of joint stability to be performed correctly with no compensations to form (Butler, 2010). Also, if an individual has any present or preexisting injuries to the knee/lumbar, that will hinder mobility and stability it would be recommended to stay away from the deep squat. As those angles could affect the integrity of the knee joint and lumbar to a point that would injure them. For an average person performing a squatting exercise that is healthy, it is recommended to perform a squat with their goals in mind. As it is hypothesized that the deep squat will not cause significant problems. If an individual cannot perform the deep squat staying at the 90-degree mark will give good muscle activation through the lower extremities and put people's bodies in the correct position to reduce any injuries and still increase performance (Escamilla, 2001). If an individual can perform the deep or full squat correctly with no previous injuries, it would not be of concern when performing it. It comes down to what that person feels comfortable with and what they want to work on, with the body that they have. Every person is built differently, and some might not be able to perform the deep squat correctly.

2.6 Conclusion

Squatting in the safest and most optimal position is what every person should strive for. Providing this information will contribute to anyone that is into weightlifting doing some type of squatting movement. Giving them the best possible way to do it to minimize injury and enhance performance in the process. This topic is relative and can contribute to all weightlifting populations. Previous research gives a great basis for what the several types of squats depths are, and how it affects people's bodies, breaking them down into kinetics and kinematics (Escamilla,

2001) (Schoenfeld, 2012). Having this base can give other researchers other opportunities to add on top of it. Studies have shown that going into a deep squat can increase the mechanical load on the lumbar and knees. With this information, this study aims to see the biomechanical differences between each squat depth while looking into the benefits each depths give individuals while performing them.

Gaps that are seen in preexisting literature are looking at different body types when squatting. People all have different body types; some people have much longer femurs and tibias. While other people have a much longer torso, and that all goes into how those people perform the squat. By looking at the different body types in different depths one could see how the forces and stress talked about earlier might change from person to person. Different body types of different genders could be explored as well. As the female and male body types are different it may affect how one squats. Information was found on different genders but could not find much information on body types in general and both can be persuaded in the future. Another gap that was present is the amount of information on the spine/lumbar. There was a good amount of research on the squat as a whole and looking at the compression forces. But there was not enough information on how different depths might affect the spine/lumbar region. Most of the research that was conducted was done on the knee and ligaments in and around the knee. This could be another avenue to pursue since the research is so limited. Another avenue that could be persuasive is a more in-depth investigation of how different angles of the ankle affected the knee. Specifically looking into increased dorsiflexion during the squatting motion and how that would affect the mechanical load on the knee. Even though this is an exceedingly popular topic there are still many big gaps that could be filled. Giving people as much information on injury in squatting should be particularly important to keep people healthy and active.

Chapter 3: Methodology

3.1 Participants

There were 10 males (age: 22± 1.25, height: 177.03cm± 7.55, weight: 83.72kg± 13.85) and 7 females (age: 23.86± 1.57, height: 166.86cm± 3.59, weight: 73.04± 8.74) that volunteered to participate in this study. All participants had at least a one-year experience performing the barbell back squat three times a month. All participants had no lower extremity or lower back injuries or surgeries in the last six months and were between the ages of 18 to 35. The number of participants was calculated using an a- priori power analysis (alpha level= 0.05 and power of .08) showing that a minimum of 12 participants were needed to reach an alpha level of 0.05 (Da Silva, 2017). From these studies the range of participants was 9-17, this current study was based on those numbers (Contreras et. al., 2016, Da Silva et. al., 2017, Endo et. al., 2020, Gorsuch et. al., 2013, Kubo et. al., 2019).

3.2 Sampling Procedure

Participants were recruited from the Delaware County area, mostly students attending Ball State University. Flyers were posted in the health and physical activity building with all the information from the study on them. The communications center sent out emails to Ball State students informing them of the opportunity to participate in this study. Recruitment continued until the required number was reached for this study and used university-approved consent documentation.

3.3 Participant Preparation

This study was broken down into two separate collection days. On the first day, participants were asked to fill out an informed consent form and a health history questionnaire. After that complete anthropometrics were taken of each participant. This included height (mm), mass (kg), inter-ASIS distance (mm), leg length (mm), knee width (mm), and ankle width (mm). An anthropometer (Lafayette Instrument Company, IN, USA) was used to measure ankle, knee, and hip width. Next, participants walked through a 5–10-minute dynamic warmup of the lower extremities. The dynamic warmup consisted of 1 set x 20 repetitions of jumping jacks, 1x10 body weight squats, 1x5 (each leg) reverse lunge, 1x5 (each leg) hip rotations, and a 20-second isometric lunge on each leg. Once that was complete participants began with the barbell and ascended in weight until their 3RM was reached. Participants were asked to guess their 3RM and 25% increments were based on it. Participants were given a three-minute break in between sets. Degree measurements for knee flexion were measured using a goniometer (Zimmer, USA) to ensure consistency. The 3RM was performed in the deep squat position, and there was a 3-minute break in between each ascending set. If the participant was unable to complete the squat while keeping the correct form that participant performed the 3RM at a lower weight. Their 3RM was used to give a predictive 1RM that was used for the main collection (Richens, 2014). After their 3RM was complete, they were asked to return in 5-10 days (6.12 days) to complete the second trial.

Before any participants entered the room for the second day the motion capture system and electromyography (EMG) were prepared. Each participant was asked to change into a tight compression shirt and shorts that were provided. They were also asked to change standardized footwear (Puma Inc., Herzogenaurach, Germany). Before application, the EMG sensors were placed on participants, and the sites being applied were cleaned, shaved, and abraded to ensure optimal data collection. EMG sensors were placed on the erector spinae, rectus femoris, vastus medialis, vastus lateralis, biceps femoris, and gluteus maximus on both limbs. The placement of the erector spinae was two inches laterally of the L1 spinal process (De Nooij, 2008). The rectus femoris was placed on the anterior aspect of the thigh, midway between the superior border of the patella and the anterior superior iliac spine (Delagi,1981). The vastus medialis was placed four fingerbreadths proximal to the superomedial angle of the patella. The vastus lateralis was placed over the lateral aspect of the thigh, one fingerbreadth above the patella (Delagi,1981). The biceps femoris placement was at the midpoint of a line between the fibula head and ischial tuberosity (Delagi,1981). The gluteus maximus was placed three inches midway between the greater trochanter and sacrum (Delagi,1981). Participants were then asked to perform a 5–10-minute dynamic warmup before moving on to retroreflective marker placement. Motion capture retroreflective markers were then placed on the anatomical bony landmarks on the trunk and lower extremity following a modified Plug-in-Gait marker set available the participant then had several bony landmarks marked in the correct spots. The modification made to the Plug-in-gait included the additions of a T2 and T10 marker. For the upper half of the body, markers were placed on the acromion process, clavicle, and sternum. The lower half of the body was placed on the anterior-posterior iliac spine (cluster of two markers), iliac crest, lateral and medial femoral epicondyles, posterior superior iliac spine, lateral aspect of the shank, and thigh (cluster of four markers), calcaneal tuberosity, second metatarsal head, the base of the fifth metatarsal head, and medial and lateral malleoli. Retroreflective markers were placed on the participant using double-sided tape and both EMG sensors and retroreflective markers were then secured using PowerFlex

(Andover Healthcare, Inc., Salisbury, MA, USA) cohesive bandage. After completion of participant preparation, they were then ready to complete the different squatting conditions.

3.4 Instruments

1. Vicon Nexus Motion Capture System

Any kinematic data that was collected was using 13 VICON infrared cameras (Oxford Metrics, Oxford, UK) sampling at 100 Hz.

2. Electromyography (EMG)

12 Delsys Trigno wireless electromyography (EMG) sensors (Delsys Inc., Boston, MA, USA.) were used to collect EMG data. The data were collected at a rate of 2000 Hz and bandpass filtered between 20-400 Hz. The muscle activity of the erector spinae, rectus femoris, vastus medialis, biceps femoris, and gluteus maximus on both limbs was collected for each trial of the squat.

3. AMTI Force Plate

Squats were performed on two AMTI force plates (AMTI Inc., Watertown, MA USA.) sampling at 2000 Hz. Force plate data was used to analyze moments and joint reaction forces during the squatting trials.

3.5 Data Collection Procedure

Before the primary collection starts participants needed to perform static and range of motion trials. This included a static calibration which involves participants standing on the force plate centered in the middle of the room and performing an anatomical position, having arms out to their sides and thumbs pointing down. After that was complete, they were asked to perform a range of motion calibration which involved them standing on a 30cm (11.81 in) box located on top of the force plate. They then were asked to complete a five-star movement pattern followed by a half circle on each leg. Lastly, still, on the box, they were asked to complete a knee ROM (range of motion) trial which consists of the participants extending their leg back and flexing and extending five times. They were asked to do this for both legs. In preparation for data collection, participants performed squats starting with the bar and added 25% of their weight until they reached their marked weight of 75% predictive 1RM for deep, parallel, and partial squats. They then performed one set x three repetitions at each condition with a three-minute rest period between each set. The three squat conditions were randomized to avoid fatigue and produce the best results. All squats were under a raw condition which includes no bracing belt, knee sleeves, or weightlifting shoes. All participants were asked to use the high bar method and remain in that position throughout the squat. These conditions were used on both days of collection to ensure consistency throughout the study. After the completion of all squatting conditions, participants were then asked to complete maximal voluntary isometric contractions (MVC) of the quadriceps, and hamstrings, using a Cybex Norm isokinetic dynamometer (Lumex Corporation, Ronkonkoma, NY, USA). Subjects completed separate bilateral isometric strength measurements on the isokinetic dynamometer. Hook-and-loop straps were used to stabilize the trunk, waist, and thighs. Strength measurements were used to monitor fatigue levels during the data collection period by using maximal torque values. Three maximal voluntary isometric contractions were performed at 30° of flexion for the hamstring tests and at 60° of flexion for the quadriceps tests. The gluteus maximus was tested by doing an isometric maximal contraction of a glute bridge. Participants would lay on their backs and have a strap fastened to their waist for resistance. Lastly, the erector spinae muscles were tested by having the participants perform a Superman pose in the prone position while pressure was applied to their backs for resistance. The gluteus maximus and erector spinae did not capture the force produced in these motions but gathered

EMG signals to normalize data. All MVC exercises were done for three sets x one rep for 3-5 seconds, with a 1-minute break in between sets.

3.6 Data Processing

VICON Nexus 2.12.1 (Oxford Metrics, Oxford, UK) was used to label and construct figures from the retroreflective markers. After that was completed, data were further processed using the program Visual 3D (2021x64) (C-Motion, Inc., Germantown, MD, USA). A Butterworth lowpass filter was used to filter motion capture marker data at 8hz. This same filter was also used at 50hz to filter ground reaction forces collected from the force plates. Raw data from the motion capture system includes marker data, ground reaction forces, and muscle activity. This data was used to calculate link model-based computations to develop angles moments, and power. Raw EMG signals were rectified and processed using a root mean squared low pass filter with a time window of .1 seconds.

3.7 Experimental Design

Grouping variables of deep, parallel, and partial squat were used to compare the three different depths. There was no control group, and participants completed the same tasks, but in a randomized order.

3.8 Statistical Analysis

The program used to complete the statistical analysis of the project was SPSS v28 (IBM, Armonk, NY, USA). The independent variable was the different squat depths. The dependent variables included the trunk, and lower extremity joint angles, moments, and power during the eccentric and concentric phases of the squat. Dependent variables also include normalized root mean square EMG data during eccentric and concentric phases of the squat. Data were normalized by MVC data to give a percentage of EMG activity during squatting. Multiple one-way repeated measures ANOVA was conducted, with the significance level set at .05. When there were significant main effects Bonferroni corrections were used to adjust for multiple tests during pairwise comparisons between conditions. If Mauchly's test of sphericity was significant Greenhouse-Geisser was used for tests of within-subjects effects. Additionally, partial eta squared was used to present the effect size for each variable measured.

Chapter 4: Results

4.1 Kinematics

Eccentric

There were significant differences in knee flexion among participants as depth changed. There were also significant differences in truck flexion as the depth changed as well. Observed in the sagittal plane the eccentric and concentric phases showed significant results between conditions (Table 1). Trunk flexion in the eccentric phase showed significant differences between the deep squat and the partial squat (<.001). There was no significant difference between the deep and parallel squats during the eccentric phase. Ankle dorsiflexion during the eccentric phase of the squat showed to be significantly different in all ranges of motions of the squat. As the ankle in the deep squat was more than both parallel and partial squats. The parallel squat was also greater than the partial squat (p<.001). Knee flexion during the eccentric phase of the squat also showed the deep squat to be highest when compared to parallel and partial squats (p<.001). Hip flexion in the eccentric phase of the squat showed the deep squat to have the highest angle when compared to parallel and partial squats (p<.001).

Concentric

There was significantly more trunk flexion in the deep squat when compared to the parallel and partial squats during the concentric phase (p<.001). At the deepest angle performed in each squat, the trunk angle was greater in both deep and parallel when compared to partial (p<.001). The trunk angle between deep and parallel had no significant difference. During the concentric phase, ankle dorsiflexion underwent significant differences. Showing the deep squat was greater than both parallel and partial squats. The parallel squat was also greater than the partial squat when compared (p<.001). Knee flexion in the concentric phase presented the deep squat to be the highest when compared to parallel and partial ($p<.001$). Hip flexion in the concentric phase of the squat showed the deep squat to have the highest flexion when compared to parallel and partial ($p<.001$).

4.2 Kinetics

Eccentric

There were significant differences in knee moments among participants as depth changed. Observed in the sagittal plane the eccentric and concentric phases of the squat showed significant average peak moment differences between conditions (Table 2). The highest peak plantar flexion moment was shown in the deep squat when compared to the partial squat. The parallel squat did show to have more peak plantar flexion moments when compared to the partial squat, but there was no significant difference between the deep and parallel squats ($p<.001$). The knee during the eccentric phase of the squat showed to have greater peak knee extensor moments in the deep squat when compared to parallel and partial squats ($p<.004$). There was no significant difference between parallel and partial squats. The hip also presented greater peak hip extensor moments in the deep squat when compared to partial during the eccentric phase of the squat ($p<.001$). There was no significant difference between the deep and parallel squats.

Concentric

The concentric phase showed the highest peak plantar flexion moments to be shown in the deep squat when compared to the partial squat. The parallel squat had significantly higher peak plantar flexion than the partial squat ($p<.001$). The deep squat and parallel squat were shown to have no significant difference. The knee in the concentric phase showed the deep squat was significantly greater than both parallel and partial squats during knee extension ($p<.006$). There was no significant difference between the parallel and partial squats. The hip in the concentric phase showed similar results for peak hip extensor moments as the deep squat was significantly greater than the partial squat ($p<.001$). There was no significant difference between the deep and parallel squats.

Eccentric

Observed in the sagittal plane the eccentric and concentric phases of the squat showed significant power absorption and production differences between conditions (Table 3). The deep squat showed to have the greatest power absorption in the ankle during the deep squat when compared to the parallel and partial squats ($p<.004$). It was not shown that the parallel and partial squats had a significant difference in power absorption. The knee was shown to have significantly greater power absorption in the deep squat when compared to the other two conditions. The parallel squat also showed greater power absorption when compared to the partial squat ($p<.001$). The hip during power absorption showed to be greatest in the deep squat among all conditions. The parallel squat was also significantly greater in power absorption than the partial squat ($p<.001$).

Concentric

The ankle was shown to have significantly greater peak power production in the deep squat when compared to the partial squat. The parallel squat also showed to have greater peak power production when compared to the partial squat ($p<.001$). There was no significant difference in power production between the deep and parallel squats. Hip peak power propulsion was also shown to be significantly greater in the deep squat when compared to the partial squat. Results showed the same for the parallel squat as it was greater than the partial squat in power production ($p<.001$). There was no significant difference between the deep squat and the partial squat.

4.3 Electromyography

Eccentric

There were significant differences in EMG activity to the VMO, VL, RF, and BF as depth changed among participants. Average peak EMG activity observed in both concentric and eccentric phases of the squat showed significant results in quadricep and hamstring activity (Table 4). EMG activity was shown in peak activity which was the highest activity recorded during that each phase of the squat. The VM showed the most peak activity concentrically in the deep squat when compared to the partial squat. The parallel squat also showed greater peak activation concentrically when compared to the partial squat ($p<.019$). There was no significant difference between deep and parallel activation concentrically in the VM. The VL showed similar results as the VM as the deep squat presented the most peak activation when compared to parallel and partial squats in the concentric phase. The parallel squat was also greater when compared to the partial squat ($p<.001$). The RF presented the most peak activation in the deep squat during the concentric phase when compared to the partial squat. The parallel squat was also significantly greater than the partial squat ($p<.001$). There was no significant difference between peak activation concentrically between deep and parallel squats.

Concentric

The BF in the concentric phase of the squat showed to have the highest peak activity in the deep squat among the other conditions. The parallel squat was also significantly greater than the partial squat ($p<.004$). The erector spinae and gluteus maximus did not show enough significance between the three squats to show a major difference. Both muscles have a large amount of activation in all three squats but do not show a difference when compared to each other.

The muscle activity during the eccentric phase of the squats showed minimal significance between conditions. The RF did show the main effect ($p<.045$) to be significant but pairwise comparisons between conditions do not have significance. The BF also showed the main effect ($p<.015$) to be significant and showed eccentric peak activation between conditions to be significant between the deep squat and parallel to also be significant. There was a trend between the deep squat and partial squat ($p<.015$).

Overall, the main findings suggest that the deep squat will influence more moments in both the concentric and eccentric phases of the squat. The quadriceps muscles showed activation results that match with the moments around the knee. As the angle of the knee increases the muscle activation and moments were increased in the quadricep and knee region showing how the contribution between the muscles worked and the magnitude of moments created in the knee. The quadriceps muscle group showed to have the most difference between the three conditions, as the activation is shown to be greatest in the deep position. Trunk flexion did show an increase as the knee angle increased but did not show more muscle activation patterns. The erector spinae did not show more muscle activation as the knee angle increased but instead stay consistent between each condition.

Chapter 5: Discussion

The main research question that was asked for this study was how different squatting depths affect the knee and lumbar. But more specifically does a deep squat place a greater mechanical load on the knee and lumbar region of the spine? As well as what muscles activate the most in the deep squat position. It was hypothesized that the deep squat will put a greater mechanical load on the knees and the lumbar spine. This current study shows that increased knee flexion, achieved during the deep squat, does put a greater mechanical load on the knees. The increased knee flexion also resulted in an increased amount of trunk flexion and potentially loading on the lumbar spine. Elevated levels of EMG activity in the quadriceps, BF, and ES were hypothesized in response to the deeper squatting depths, with no changes predicted for the GM across all squatting conditions. This hypothesis was partially supported as the quadriceps, and hamstring muscle activity was highest in the deep squat. The GM was also supported as it stayed consistent between conditions. The ES activity was not supported and showed the activity to be consistent between conditions.

The main findings of this current study suggest a significant impact on trunk flexion, knee moments, and EMG activation of the quadriceps when squatting at different depths. There was significantly more trunk flexion in the deep squat when compared to the parallel and partial squats during the concentric phase. At the deepest angle of knee flexion performed in each squat, the trunk angle was greater in both deep and parallel when compared to partial. The knee in the concentric phase showed the deep squat was significantly greater than both parallel and partial squats in producing knee extension moments. The VM, VL, and RF showed the most peak activity concentrically in the deep squat when compared to the partial squat. The parallel squat also showed greater peak activation concentrically when compared to the partial squat. The BF in the concentric phase of the squat showed to have the highest peak activity in the deep squat among the other conditions. The parallel squat was also significantly greater than the partial squat.

The squat is seen as one of the most popular and effective exercises for lower extremity development. The back squat aims to gain strength, size, and function in a person's lower extremities. Using the back squat as a resistance training exercise has been shown to facilitate strength gains in the lower extremities through increased levels of muscle activation (Myer, 2014). Prior research has different perspectives on the different depths of the squat and what to do and what to avoid. Prior research has suggested the parallel squat is the safest and most optimal squat to be performed (Escamilla, 2001). Findings from this current study can help illustrate the kinematic, kinetic, and EMG data that can help inform individuals on what squat they should be performing.

The damage to knee cartilage, when observed in different squat positions, shows that having more depth in the squat will not exert a greater amount of force to hurt someone. When compared to one study the data on knee forces seemed to be similar. This is not a surprise as many other studies have found the same trend of increased knee flexion will contribute to increased forces on the knee (Escamilla, 2001). This current study matched and showed significant differences in both phases of the squat in which the deep squat showed greater peak moments during knee extension. Another study has shown that in the concentric phase of the squat, the highest forces were found at 85 degrees of knee flexion. With this finding the claim of only performing squats above 85 degrees is recommended (Escamilla, 2001). As this study had participants complete loaded deep squats and showed similar findings in forces of the knee to this current study's data. This study had concerns that these higher forces can have negative effects on the knee region (Escamilla, 2001). These high forces should not be viewed as a negative or something to avoid as two studies calculated the anterior shear force and ACL forces with loads 1.16-to-2.27-fold bodyweight in parallel and deep squats. The parallel and deep squats accounted for 11.62 and 28.9% of tensile strength. The partial squat presented anterior shear forces with a load of 1.16-fold body weight between 33.29-41.56%. Seen from these studies the deep squat does not present shear forces to the PCL and ACL that could cause any harm. These studies were also done on healthy individuals ages (16-35) with no prior injuries to the knee region (Noyes, et. al., 1976) (Woo et. al., 1991). This should be considered when deciding which squat is best for that individual. It was seen in another study that these high forces on the knee may correspond with retro patellar cartilage thickness. The higher forces if done correctly can help build the strengthen the cartilage. The thickness of the cartilage decides the mechanical stress tolerance of the knee (Tiderius et.al., 2004). This study compared non-lifters, runners, and lifters and saw a significant increase in cartilage. It showed that knee cartilage adapts and strengthens as an exercise with high forces is applied to it (Tiderius et.al., 2004). Another study showed that cartilage tissues surrounding the knee, if not stressed enough, will receive insufficient force to build the cartilage which could lead to degeneration and atrophy (Morscher, 1978). These forces are needed to build and strengthen the knee to make it more resilient. This makes the argument if performed correctly increased forces can make the knee stronger and more resilient to injuries. The deep squat can be seen as something that can help strengthen and develop the knee region instead of avoiding it (Schoenfeld, 2010).

A study provided information that a flexed spine will decrease the moment arm for the lumbar. This will reduce the tolerance to hold a compressive load, which then transfers those loads to the passive tissues (Schoenfeld, 2010). It is also stated that minimal trunk flexion is necessary to maintain stability when performing a deep squat (Schoenfeld, 2010). The lumbar in this current study was shown to have more flexion as knee flexion increased. As this current study did calculate the muscle activity indicated and showed that the erector spinae muscles in the L 2-3 region were highly activated across all squat phases and depths but were not different between the three squat depths. When regarding erector spinae muscles it was shown that different results from this current study's data presented that the parallel squat had the highest amount of activation (Gorsuch et. al. 2013). This previous research did only compare parallel and partial squats in cross-country runners who did a lesser load with higher repetitions. These factors could affect the results and show different activation from this current study's data. In this current study data, no indication of increased squat depth with showing more activation in the lumbar between any condition.

When looking into other EMG activity through the lower extremities the findings from one study showed different results. The BF femoris was shown to stay consistent between parallel and partial squats (Gorsuch et. al. 2013). This previous research did use collegiate cross-country runners and used a lighter load compared to this current study's load. Under these conditions, it could have caused a difference in results. Previous research comparing the deep and partial squats showed that the BF activation did not change throughout conditions as well. (Da Silva et. al., 2017). A lighter load and higher repetitions were used to test muscle activation. These changes could affect the results and show the BF to not change between conditions. In a past study, isometric squats were tested at deep, parallel, and partial, and the BF did not show any difference (Marchetti et. al., 2016). This research did not complete the full phases of the squat, the isometric squat could present different results from a dynamic movement. This is not to be found in this current study as in the concentric phase of the squat there was a significant difference between every condition, showing the deep squat to have the most BF activation. One study used young women, that performed 10 repetitions in each condition. It showed the deep and parallel squats to have similar VM activation throughout each condition. A past study shows different EMG activation and the cause of this could be attributed to a different load between conditions. As the parallel squat had a greater load than the deep squat, causing a different variable to change results (Contreras et. al., 2016). Having a heavier load in the parallel squat (53.1 ± 17.0 kg) compared to the deep squat (46.7 ± 17.1 kg) when squatting can cause a change in the biomechanics of the body and change muscle activity. Another study observing the thigh muscles in a bodyweight squat in different depths showed no change in VM, VL, and BF among conditions. These results could be different from this current study, as there was no load added in the squat (Caterisano et. al., 2002). This current study did not find the same results and saw all quadricep muscles to be more active in the deep squat. The GM results from this current study followed the same findings showing no change in activation between different squatting depths (Marchetti et. al., 2016). The GM was still activated in a large amount while performing the squat but did not show a significant change between the squats. A previous study looking into the EMG activity of the VM, BF, and GM during a five-repetition maximum load in different depths found that the VM was most active in the concentric phase of the parallel squat. It also found the BF to have the lowest activity in that depth and phase. The GM findings suggested that the parallel squat maximizes EMG activation to the GM, as it is possible this happens because of a higher external moment arm or reduction or neural drive. These can change between studies as the load the participants are doing can affect those factors and have a change in results (Hammond, 2016).

There are pros and cons to every depth of the squat, and all can be beneficial to people depending on personal goals and limitations of the body. As squat depth increases, so do the moments, power, and angles. If a person were to want the most muscular activation and is not worried about the forces being put onto their knees the deep squat would be the best squat for them. Injury risk can be present at any depth of the squat, loading up a barbell with weight and performing a squat comes with risks regardless of the depth. But knowing which one could fit someone's body and goals is beneficial. This current study showed that an increased squat depth did not increase activation in lower back muscles. The risk of injuring muscular tissue when performing a squat does not show to be a main concern when squatting in different depths but instead, the squat as there was an equal amount of muscular activation when performing the squat. A person with a concern about injuring their lower back while squatting should not focus on the different depths of the squat but look at the squat as a whole and see if that movement is right for them. Injury risk associated with the knee is dependent on what that individual can perform correctly and any recent injuries that might come into effect. This current data showed that the knee had more force being put into the knee when the depth increased. If a person had previous knee pain or injuries the deep squat could be a movement to avoid as those increased forces could cause harm. The deep squat should not be seen as something that could injure a healthy individual or something to be avoided. Provided with the correct technique the deep squat can be a great tool to protect and strengthen the lower extremities.

Practical applications to the squat can be used to develop evidence-based guidelines for squat depth in different populations and activities. This will enable sports teams and individuals to have information to know what depth will help improve performance and keep them healthy. Dependent on the sport the appropriate squat depth should be selected to improve those athlete's performance. As an Olympic lifter will be performing different squats as a basketball player would. The basketball player would want to focus more on partial depth as they load up into that position while playing. But an Olympic lifter would want to focus on deep depth to strengthen their lower extremities as much as possible and get used to being in that depth. Another practical application that could be used with this information is investigating the role of squat depth in the rehabilitation and prevention of lower extremity injuries. Knowing what depth could help strengthen and develop the lower extremities to help avoid injuries to the ACL, patellofemoral pain, and hamstring strains. Training athletes in the right depth can be something to help avoid these injuries before they happen. Preparing athletes to be able to take on the loads that they may see during a match can prepare their bodies to know what that feels like and have a sense of how to handle it. A practical application that can be further researched is the effect of performance and muscle activation during different squat depths in different populations such as older adults, and beginner lifters. Comparing data from this current study to other populations can show how different populations handle change in depth and how it affects their bodies.

This current study was aimed at the public and wanted to simulate the movements and weights used by everyday weightlifters. The different results found from other studies were tested under different conditions and still gave important information. This data can be used to produce programs for many types of people performing the squat. It gives information to be able to decide which squat is right for that individual and what benefits they will get from it. This current study uses EMG paired with kinetics to show the moments created in the joints to back up muscle activity found during testing. This current study's EMG data was also collected using general young healthy participants, that went to the gym regularly and knew how to squat correctly. The load was also adjusted to a weight that normal gymgoers would use regularly and stayed consistent through all conditions to give consistent results through all depths. All of this was put into account to give the public information so they can be educated and select the right squat for them.

Limitations

One limitation that was present that may have influenced the results of this study was the squat depth. It was monitored by using a goniometer and setting a bungy cord to the correct height. The height of the cord and angles were set correctly but there were times when participants would exceed the cord. This would normally happen on the first rep, and they would only exceed it in a small amount. Even with familiarization trials, participants seemed to still take a rep to get used to it. This did not happen for every participant but was seen to happen at times. I think there could be a better way in the future to set it, where this did not happen. The tempo of the squat was not controlled as well, so the velocity of squats may have varied from participant to participant. Each participant was asked to perform squats at a preferred pace and keep that consistent through each squat. This could have influenced moments and power due to different velocities. We did want to make this a real simulation of squatting in everyday life, where a metronome would not be used. But having more control over the velocity could result in more consistent results in the future.

Conclusion

This study analyzed the kinematics, kinetics, and muscle activation patterns of the lower extremities while performing different squatting depths in young healthy adults to determine the performance and injury risk associated with each depth. From the results, participants showed increased knee and trunk flexion as the squat depth increased, and this was associated with increased force in the knee region and greater activation of the quadriceps and hamstrings. Within the kinematic results, the relationship between the increased knee flexion and trunk flexion did match. As when knee flexion increased so did trunk flexion. With that, it was seen that muscle activation did not change between depths but instead stayed consistent. This showed that going deep will not put a significantly more amount of muscular strain on the lower back. The kinetics showed that having an increased knee flexion will induce more force in the knee region. With that, it also increases muscle activation in the quadriceps and hamstrings. People with knee issues may want to avoid deep squats, while those with lower back issues may want to consider the deep squat as it places less strain on the lower back. Knowing your body and practicing form will aid in the decision of what squat position an individual may do. This information is to guide individuals to choose the appropriate squat depth.

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Tables and Graphs

Sagittal Plane Trunk, Ankle, Knee, and Hip Angles (°)					
	Deep	Parallel	Partial	p-value	Effect Size
Trunk Concentric Peak Angle	11.3± 3.9†	11.8± 3.7	12.3± 4.6†	0.053	.168
Trunk Concentric Minimum Angle	44.9± 6.2†Ᵽ	41.5± 7.3‡Ᵽ	35.2± 6.3†‡	<.001	.792
Trunk Eccentric Peak Angle	13.8± 7.5	14.1± 7.7	14.2± 7.2	0.571	.034
Trunk Eccentric Minimum Angle	38.5± 8.8†	38.2± 9.7‡	33.5± 7.8†‡	<.001	.686
Trunk Angle at Highest Knee Flexion	35.3± 20.4†	35.2± 20.5‡	30.5± 18.7 †‡	<.001	.687
Ankle Concentric Peak Angle	30.5± 5.8†Ᵽ	28.9± 4.5‡Ᵽ	25.7± 4.7†‡	<.001	.716
Ankle Concentric Minimum Angle	.50± 3.7	.80± 3.7	1.4± 3.8	0.56	.035
Ankle Eccentric Peak Angle	30.8± 5.7†Ᵽ	28.9± 4.6‡Ᵽ	25.9± 4.6†‡	<.001	.716
Ankle Eccentric Minimum Angle	1.9± 3.1	2.1± 3.6	2.3± 3.8	0.567	.075
Knee Concentric Peak Angle	125.1 ± 7.0†Ᵽ	110.6± 6.9 ‡Ᵽ	89.8± 6.7†‡	<.001	.930
Knee Concentric Minimum Angle	3.8± 5.7 †	4.2± 6.5	6.4± 6.5†	0.004	.289
Knee Eccentric Peak Angle	124.9± 7.4†Ᵽ	110.5± 6.9‡Ᵽ	89.9± 6.8†‡	<.001	.967
Knee Eccentric Minimum Angle	6.4± 6.0	6.9± 7.0	8.1± 6.6	0.126	.262
Hip Concentric Peak Angle	109.4± 7.0†Ᵽ	104.4± 6.8‡Ᵽ	90.8± 8.9†‡	<.001	.859
Hip Concentric Minimum Angle	9.7± 9.7†	12.8± 8.8‡	16.7± 10.3†‡	<.001	.486
Hip Eccentric Peak Angle	109.5± 7.2†Ᵽ	104.5± 6.8‡Ᵽ	90.9± 8.6†‡	<.001	.859
Hip Eccentric Minimum Angle	12.7± 9.2†Ᵽ	15.0± 9.9‡Ᵽ	17.9± 8.9†‡	<.001	.473

Table 1: The kinematics of the trunk, ankle, knee, and hip were observed in the sagittal plane (X-Axis) and showed the average peak angles in both eccentric and concentric phases of each condition of the squat. Trunk angle at highest knee flexion is defined as the trunk flexion at the highest point of knee flexion during the squat. The significance level was set at .05, and the symbols show significant differences between the three conditions. †: deep and partial ‡: parallel and partial Ᵽ: deep and parallel

Moments in the Sagittal Plane for Ankle, Knee, and Hip Joints (N*m/Kg)					
	Deep	**Parallel**	**Partial**	**p-value**	**Effect Size**
Ankle Plantar Flexion Peak Moment During Concentric	1.05± .21†	.98± .28‡	.74± .26†‡	<.001	.795
Ankle Plantar Flexion Minimum Moment During Concentric	.12± .17	.21± .20	.18± .20	0.123	.077
Ankle Plantar Flexion Peak Moment During Eccentric	.96± .27†	.92± .26‡	.63± .25†‡	<.001	.795
Ankle Plantar Flexion Minimum Moment During Eccentric	.11± .17	.15± .16	.13± .17	0.275	.077
Knee Extensor Peak Moment During Concentric	2.10± .50†Ꝑ	1.82± .35Ꝑ	1.81± .30†	0.006	.327
Knee Extensor Minimum Moment During Concentric	.33± .30	.31± .30	.24± .33	0.076	.149
Knee Extensor Peak Moment During Eccentric	2.06± .45†Ꝑ	1.83± .31Ꝑ	1.82± .30†	0.004	.361
Knee Extensor Minimum Moment During Eccentric	.18± .32	.20± .30	.13± .31	0.155	.110
Hip Extensor Peak Moment During Concentric	2.50± .47†	2.45± .54‡	2.20± .52†‡	<.001	.539
Hip Extensor Minimum Moment During Concentric	.02± .19†	.09± .22	.20± .22†	0.006	.275
Hip Extensor Peak Moment During Eccentric	2.38± .47†	2.43± .52‡	2.16± .50†‡	<.001	.594
Hip Extensor Minimum Moment During Eccentric	.14± .18†	.21± .24	.27± .21†	0.21	.258

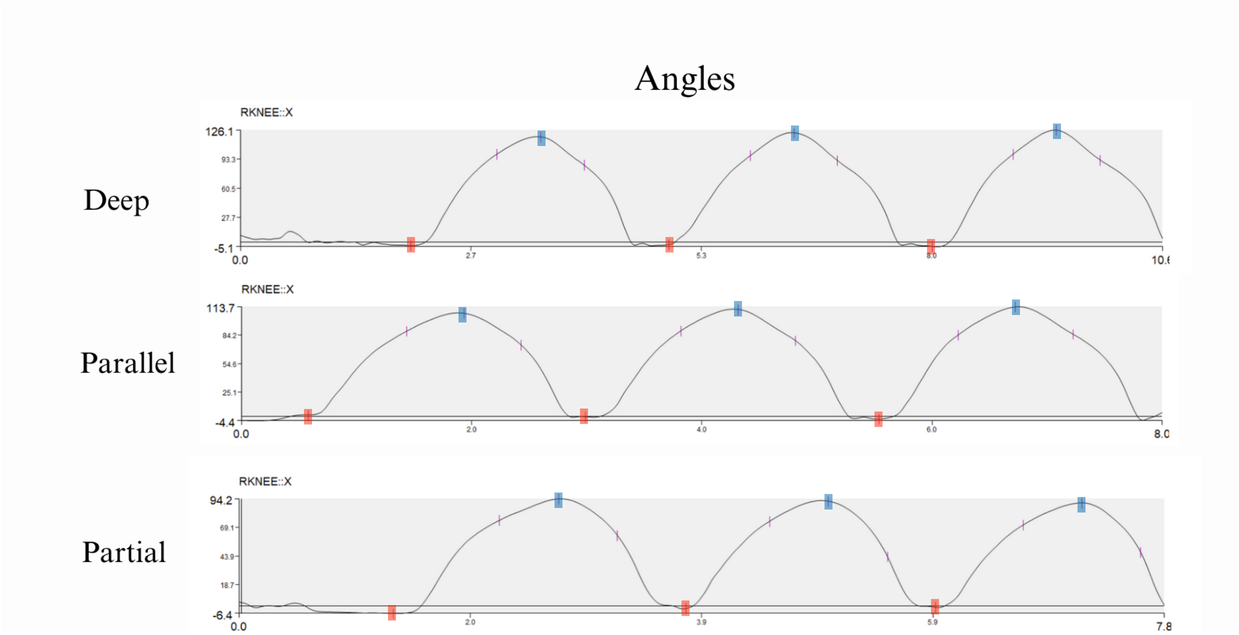
Table 2: The average peak moments in the ankle, knee, and hip were observed in the sagittal plane (X-axis), during both concentric and eccentric movements through all conditions. The significance level was set at .05, and the symbols shows the significant differences between the three conditions. †: deep and partial ‡: parallel and partial Ꝑ: deep and parallel

Power for Ankle, Knee, and Hip Joints (W/kg)					
	Deep	**Parallel**	**Partial**	**p-value**	**Effect Size**
Ankle Peak Power Production	.72± .24†	.67± .33‡	.52± .30†‡	<.001	.291
Ankle Minimum Power Production	.18± .10†	.15± .12	.08± .06†	0.005	.401
Ankle Minimum Power Absorption	.14± .09†	.10± .05	.08± .04†	0.004	.291
Ankle Peak Power Absorption	.49± .21†‽	.38± .14‽	.34± .19†	<.001	.401
Knee Peak Power Production	3.00± .89	2.71± .84	2.59± .71	0.052	.169
Knee Minimum Power Production	.48± .41	.45± .43	.30± .26	0.024	.208
Knee Minimum Power Absorption	.43± .35	.34± .32	.33± .30	0.146	.113
Knee Peak Power Absorption	3.22± .52†‽	2.85± .55‡‽	2.29± .40†‡	<.001	.729
Hip Peak Power Production	3.32± 1.00†	3.41± 1.23‡	2.84± 1.04†‡	<.001	.503
Hip Minimum Power Production	.24± .19	.23± .14	.19± .16	0.544	.037
Hip Minimum Power Absorption	.17± .14	.07± .11	.15± .18	0.133	.118
Hip Peak Power Absorption	2.60± .61 †‽	2.40± .65‡‽	1.93± .54†‡	<.001	.671

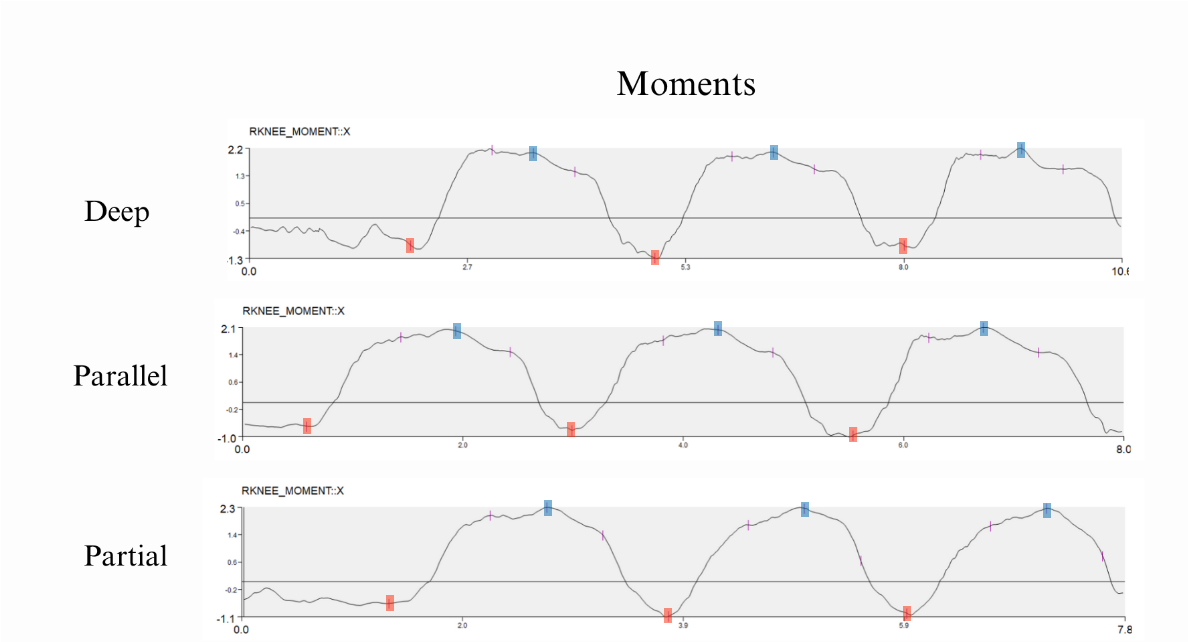
Table 3: The power of the ankle, knee, and hip are broken down into absorption and production. Absorption is during the eccentric phase of the squat and shows how much intake of force there is for that joint region. Production is during the concentric phase of the squat and shows how much power is being exerted in that joint region. The significance level was set at .05, and the symbols show the significant differences the three conditions. †: deep and partial ‡: parallel and partial ‽: deep and parallel

Electromyography of Lower Extremity Muscles (% of MVC)					
	Deep	**Parallel**	**Partial**	**p-value**	**Effect Size**
Vastus Medialis Concentric Peak Activation	239± 136.6†	183± 49.6‡	158± 45.8†‡	0.019	.286
Vastus Medialis Eccentric Peak Activation	144± 57.9	142± 47.9	136± 41.1	0.405	.050
Rectus Femoris Concentric Peak Activation	193± 101.3†	176± 79.4‡	134± 63.2†‡	<.001	.421
Rectus Femoris Eccentric Peak Activation	143± 97.4	137± 76.3	125± 77.9	0.045	.176
Vastus Lateralis Concentric Peak Activation	193± 87.9†Ꝥ	169± 70.7‡Ꝥ	144± 66.4†‡	<.001	.538
Vastus Lateralis Eccentric Peak Activation	146± 77.4	143± 69.3	133± 54.2	0.229	.088
Biceps Femoris Concentric Peak Activation	98± 65.8†Ꝥ	79± 46.4‡Ꝥ	62± 33.3†‡	0.004	.418
Biceps Femoris Eccentric Peak Activation	52± 26.2Ꝥ	43± 19.5Ꝥ	42± 23	0.015	.297
Gluteus Maximus Concentric Peak Activation	181± 101.9†	145± 69.4	135± 104.0†	0.126	.138
Gluteus Maximus Eccentric Peak Activation	136± 266.3	72± 32.3	89± 84.1	0.325	.061
Erector Spinae Concentric Peak Activation	256± 106.0	287± 253.0	250± 281.0	0.686	.018
Erector Spinae Eccentric Peak Activation	222± 134.9	321± 437.9	219± 232.4	0.324	.070

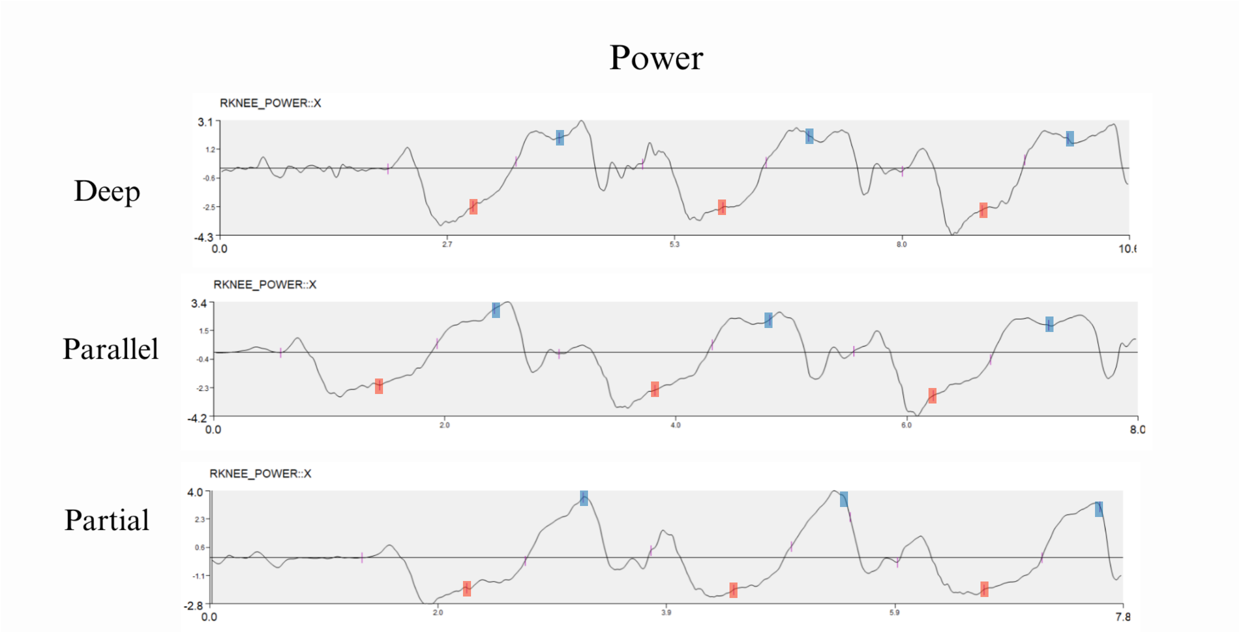
Table 3: Lower extremity muscular activity shown in average peak activation in the concentric and eccentric phases of the squat. Peak activity is the highest recorded signal in that phase of the squat. The numbers presented are the percent of MVC in each condition. The significance level was set at .05, and the symbols show significant differences between the three conditions. †: deep and partial ‡: parallel and partial Ꝥ: deep and parallel



Graph 1: The deep, parallel, and partial squat knee flexion angles on the right leg during both eccentric and concentric phases of the squat. Red indicates the standing portion of the squat, while blue represents the bottom portion of the squat.



Graph 2: The deep, parallel, and partial squat knee moments on the right leg during both eccentric and concentric phases of the squat. Red indicates the standing portion of the squat, while blue represents the bottom portion of the squat.



Graph 3: The deep, parallel, and partial squat knee powers on the right leg during both eccentric and concentric phases of the squat. Red indicates the standing portion of the squat, while blue represents the bottom portion of the squat.

Appendix

SQUATTING HISTORY QUESTIONNAIRE
"Squat Depth in Relation to Potential Injury of the Knees and Lumbar"
IRB # 1977455-1

All answers and information will be kept confidential, and no names or identifiers will be revealed in the results of this study. For participants that do not qualify based on this questionnaire, any responses will be destroyed. Please follow the question instructions carefully. Please note your selection with an "x" or circle your selection to represent your answer.

Subject Information:
Full Name: ____
Biological Sex: __ Male __ Female
Age: _______
Emergency Contact _____________________
Emergency Contact Phone # (_____) _______ _________

Squatting History

How many times per month do you squat?	1 2 3 4 5 6 7
How many days per week do you train your lower body?	1 2 3 4 5 6 7
Do you have a minimum of 1 year of experience in barbell back squats?	__ Yes __No
Which type of squat do you perform most often?	__ Deep __Parallel __ Partial
Can you perform a deep squat (>60 degrees)?	__ Yes __No

Injury Related

Have you been hurt squatting in the last 6 months? If yes include the area of injury.	__ Yes __________________ __ No
Have you experienced pain or discomfort in the last 6 months while squatting? If yes, please explain.	__ Yes __________________ __ No
Have you had any surgeries of the lower extremity? If yes, please explain.	__ Yes __________________ __ No

Other Information:

Is there any additional information that you feel the investigators should know prior to your participation?	
Do you have any concerns about your participation?	

INFORMED CONSENT FORM

Study Title

Squat Depth in Relation to Potential Injury of the Knees and Lumbar
IRB Net Number: 1977455-1

Funding/Sponsor

This research is supported/sponsored/funded by Ball State University Sponsored Projects Administration ASPiRE grant.

Study Purpose and Rationale

The purpose of the study is to examine the mechanics and muscle activation patterns in the knee and lumbar region during squats with different range of motion (ROMs) (120º, 90º, and 60º knee angles).

Inclusion/Exclusion Criteria

You must be between the ages of 18-35, have a one-year minimum of experience doing the barbell back squat 3x a month, and be able to perform a deep squat (<60 degrees). You must also have had no reconstructive surgeries or any lower extremity/ lower back injuries in the last 2 months that would prohibit squatting.

Participation Procedures and Duration

If you qualify and you would like to participate in this study, you will participate in two separate sessions lasting 30-45 minutes and 45 minutes to 1 hour, respectively. On the first collection day, you will begin with a dynamic warmup and complete a functional movement system (FMS). Beginning with the barbell you will ascend in weight until your three-rep max (3RM) is reached. Your 3RM will be used to produce a predictive one rep max. The 3RM will be performed in the deep squat position, and there will be a 3-minute break between each ascending set. If you cannot complete the squat while keeping the correct form, you will perform the 3RM at a lower weight. After your 3RM is complete, you will be asked to return in 5 days to complete the second trial. For the second session of motion capture, retroreflective markers, and electromyography sensors (EMG) will be placed on the anatomical bony landmarks on the trunk and lower extremities. Starting with the bar you will add 25% of your weight until you reach your marked weight of 75% of your predictive 1RM for deep, parallel, and partial squats. You will then perform 1x3 at each ROM, there will be a 3-minute break given after each set. The ROMs will be randomized to avoid fatigue and produce the best results. You will be under the same conditions as other participants. All squats will be under the raw condition which includes no bracing belt, knee sleeves, or weightlifting shoes. You will be asked to use the high bar method to ensure consistency throughout the study.

Data Confidentiality or Anonymity

All data will be maintained as confidential, and names will be collected and assigned a numeric identifier during data collection.

Data Security, Storage, and Retention Period (How will the researchers protect my information?)

Only members of the research team will have access to the data. All electronic data will be stored on a password-protected computer and kept indefinitely for potential future research and publication purposes. If you withdraw, your data will be deleted.

Risks or Discomforts
All the assessments to be performed in this study are standard assessments used in physical exercise and have been used in numerous studies with the Biomechanics program with no incidents of injury. You may experience minimal fatigue and minor discomfort toward the end of the test session, or on the following day. It is expected that this soreness will lessen and disappear over the next few days. Additionally, as in any sport or exercise, there is a small possibility that you could sprain a ligament, strain a muscle, or experience other mild, moderate, or severe injuries.

Compensation/Incentives
After completion of the study, participants will receive a $20 Tango gift card. Emails will be used to receive the gift card from Tango.

Voluntary Participation
Your participation in this study is completely voluntary and you are free to withdraw your permission at any time for any reason without penalty or prejudice from the investigator. Please feel free to ask any questions of the investigator before signing this form and at any time during the study.

Your decision will not affect your relationship with John Ethan Andamasaris.

If you decide to withdraw from this study, any data already collected from you will be destroyed.

IRB Contact Information
For questions about your rights as a research subject, please contact the Office of Research Integrity, Ball State University, Muncie, IN 47306, (765) 285-5052, or at orihelp@bsu.edu.

Consent Statement
Squat Depth in Relation to Potential Injury of the Knees and Lumbar

Consent
I, ___________________, agree to participate in this research project entitled, Squat Depth in Relation to Potential Injury of the Knees and Lumbar. I have had the study explained to me and my questions have been answered to my satisfaction. I have read the description of this project and give my consent to participate. I understand that I will receive a copy of this informed consent form to keep for future reference.

To the best of my knowledge, I meet the inclusion/exclusion criteria for participation (described on the previous page) in this study.

____

Participant's Signature Date

Researcher Contact Information

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