The Effects of Squatting Mechanics on the Soft Tissues of the Knee Joint

The squat is one of the most common exercises used for the development of strength and muscular hypertrophy of the lower extremity. Popular in both the rehabilitation and strength and conditioning communities, it is an essential aspect of the competitive sports of weightlifting and powerlifting and is considered by many to be a fundamental movement skill.[1] The squatting movement pattern mimics many activities of daily living and sports-specific tasks, making it a useful exercise tool for a wide variety of populations, impairments, and athletic applications at all ages.[2] Additionally, the classification of the squat as a closed-chain compound movement—that is, one which utilizes multiple major muscle groups across multiple joints[3]—makes it an efficient exercise choice for the training of the entire body with nearly infinitely-variable loads and movement patterns, achieving adaptations in strength, neuromuscular control, flexibility, mobility, stability, and muscular hypertrophy throughout the body.[1] Some authors have estimated that nearly 200 muscles are active during a squat.[4]

This paper will largely focus on variations of the squat which are loaded through the use of an Olympic barbell. The barbell is a piece of exercise equipment commonly found in most private and commercial gyms and rehabilitation settings which allows for symmetrical loading via weighted plates. Most standard barbells weigh 20 kilograms (commonly rounded to 45 pounds in United States customary units) and are 2.2 meters in length, with rotating outer sleeves 50 millimeters in diameter which allow the loading of standardized weight plates.[5] Smaller barbells, colloquially referred to as "women's bars," are available at weights of 15 kilograms (or approximately 35 pounds) and are smaller in both length and diameter (2 meters and 25 millimeters, respectively).[5] Barbells allow for loads as low as 35 pounds to well over 1,000 pounds to be used for a wide variety of exercises, and their standardization of measurement and ubiquity in training environments allows for ease of tracking and measuring exercise progress. In the context of the barbell squat, multiple variations exist which are worth defining. In terms of barbell placement and positioning, three variations are typically considered in common practice: the "high-bar back squat" in which the barbell is positioned on the bulk of the upper trapezius; the "low-bar back squat" in which the barbell is positioned inferior to the spine of the scapula on the bulk of the posterior deltoids; and the "front squat" in which the barbell is positioned on the bulk of the anterior deltoids below the clavicles.[5] Visual examples of these three variations can be seen in Figure 1 of Appendix A. Other variations are worth briefly defining as related to depth and knee angle. While no unanimous definitions of squat depth exist in the literature, classifications of squat depth will be divided into four categories for the sake of this paper: the half-squat, the partial squat, the parallel squat, and the deep squat. Precise knee flexion angle measurements relating to these variations will be expanded on in later sections of this paper. However, it generally agreed upon that the parallel squat can be defined as the inguinal fold (or "hip crease") being positioned in sagittal alignment with the superior aspect of the patella, with deep squats defined as the inguinal fold being positioned inferior to the patella.[5–7] The illustrations in Figure 1 of Appendix A are all representative of parallel squats.

Safe and proper performance of the barbell squat can vary notably depending on the unique anthropometry of the subject performing the exercise. Leg lengths, bony segment proportions, and flexibility or mobility of the involved joints may all necessitate subtle variations in technique involving foot angle, foot placement width, and torso inclination angle.[8] Despite these individual variations, the standard squat exercise will almost always begin in an upright stance with knees and hips extended and feet flat on the floor, with the descent consisting of simultaneous hip, knee, and ankle flexion until desired depth is reach, and the ascent consisting of simultaneous hip, knee, and ankle extension until returning to the original upright position.[1,7] The squat concentrically and eccentrically involves most of the lower extremity musculature, including the quadriceps femoris, multiple hip extensors, hip adductors, hip abductors, hip external rotations, and triceps surae, and isometrically involve much of the core musculature, including the abdominals, spinal erectors, and even upper back musculature of the trapezius, rhomboids, and deltoids.[1,5,7,9]

All of the aforementioned variables of the squat exercise have implications regarding the kinetics, kinematics, and relative loading of the numerous tissues involved. Strength and conditioning specialists might modify these variables to bias adaptations towards or away from a specific muscle group or movement pattern. Rehabilitation specialists, such as the orthopedically-minded physical therapist, might modify these variables to consider injury potential or safe loading of damaged or painful tissues. The primary objective of this paper will be to perform a comprehensive analysis of the effects of these variables as they relate primarily to the tissues and structures of the knee joint from the perspective of a physical therapist.

The knee is one of the larger and more complex joints in the human body, acting as a modified hinge joint that primarily permits flexion and extension in the sagittal plane with slight internal and external rotation in the transverse plane.[10] It consists of two joints: the tibiofemoral (TF) joint, which connects the femur of the thigh to the tibia of the lower leg, and the patellofemoral (PF) joint, which consists of a sliding articulation between the patella (“knee cap”) and the trochlear groove of the femur. Additionally, numerous ligaments and cartilaginous structures can be found within the knee complex, including the anterior and posterior cruciate ligaments (ACL and PCL, respectively), the medial and lateral collateral ligaments (MCL and

LCL, respectively), the quadriceps tendon (connecting the quadriceps musculature to the patella) and the patellar ligament (connecting the patella to the tibia), menisci, and more. Mechanical loading patterns of interest on the knee during the squat exercise can be stratified between compressive and shearing forces on the tibiofemoral joint, compressive forces on the patellofemoral joint, as well as ligamentous stability in the sagittal (anteroposterior) and frontal (mediolateral) planes.

Tibiofemoral compressive forces are most implicated in cartilaginous soft tissue injuries including the menisci and articular cartilage. While these tissues resist and absorb axial compressive forces by design, it is theorized that excessive compressive forces (either via magnitude, frequency, or duration of loading) can lead to acute or chronic degenerative changes in these structures. Research suggests that tibiofemoral compressive forces in the squat increase fairly linearly with increased knee flexion angles,[11,12] leading some authors to caution against squatting to depths at or beyond 90 degrees of knee flexion to minimize tibiofemoral compression.[13] In a study calculating knee forces of a powerlifter squatting an astonishing 250 kilograms, compressive forces peaked at nearly 7,000 Newtons (N) at the initiation of the ascent phase with approximately 130 degrees of knee flexion, and were smallest at around 5,000 N with approximately 60 degrees of knee flexion.[9] However, two caveats to these findings must be noted. First, squatting to parallel with such astronomical loads is almost unheard of in most rehabilitation settings. Second, shallower squats have been shown to allow for greater loads, and greater loads are shown to contribute to greater tibiofemoral compressive forces.[14] It is therefore reasonable to hypothesize that deeper squats, which necessitate lighter loads due to increased range of motion, might result in similar compressive forces as shallower and heavier squats when considering proportionally altered loading—to the best of this author's knowledge, however, these data do not exist in the current literature. A final consideration regarding depth and tibiofemoral compression involves soft tissue contact between the posterior thigh and calf musculature during extreme squat depths. Zelle et al have hypothesized, and later confirmed, that tibiofemoral compressive forces are reduced with increased thigh-calf contact, shifting loads from inside the knee joint towards the soft tissue interface.[15] The effects of this on the cartilaginous tissues of the knee remain unclear.[6] Clinically, the evidence would currently suggest that squat depth should be limited if forces on the menisci and articular cartilage are of principal concern.

Tibiofemoral shearing forces involve contributions from musculature and ligamentous structures. The quadriceps exert an anterior shearing force on the tibia, and the hamstrings exert a counteracting posterior shearing force on the tibia. It has interestingly been shown that these two muscle groups typically co-contract and work synergistically throughout the squat, leading to increased knee stability and a net neutral shearing force.[7,13] In the absence of muscular injury or significant muscular strength imbalances, this leaves the cruciate ligaments of the knee as primarily implicated in the effects of shearing forces. The main role of the ACL is to resist anterior translation of the tibia on the femur in addition restricting motion in the frontal and transverse planes.[16] Anterior shearing forces on the knee have been demonstrated in numerous studies to peak within the first 30 to 60 degrees of knee flexion during the squat, decreasing linearly as depth increases.[6,13,14,17,18] It should again be underscored that tibiofemoral shearing forces and ACL tensile forces are not necessarily equivalent; contraction of the hamstrings provide a posterior shearing force that alleviates stress from the ACL, and EMG data suggest that hamstring activity remains constant throughout most variations of the squat.[19] These findings lead to two primary conclusions regarding tibiofemoral shearing forces and ACL stress: first, maximizing hamstring contraction during the squat is most likely protective of the ACL even in the face of large shearing forces; second, maximum anterior shear occurs during half and partial squat variants (with knee flexion angles between 30 and 60 degrees), and anterior shear is minimized during parallel and deep squats. A patient rehabilitating an ACL injury should therefore be coached towards deep squats and high degrees of knee flexion.

Posterior tibiofemoral shear presents in almost perfect contrast to the previous discussion. The PCL acts as the primary restraint against posterior shear within the knee.[16] Posterior shearing forces appear to peak around 90 degrees of knee flexion—approximating the position of a parallel squat—but seem to decrease as one ascends towards full knee extension or continues to descent into further depth.[11,13,17] Contrary to the discussion of the ACL, if one seeks to minimize tensile forces on the PCL, restricting depth to that approximating a half or partial squat appears to be most appropriate.

Similar to compression of the tibiofemoral joint, compressive forces of the patellofemoral joint appear to increase as knee flexion angle increases.[6,13,20] This retropatellar compressive force is the resultant force from the combined forces of the quadriceps tendon and the patellar ligament on the patella,[21] a biomechanical illustration of which can be seen in Figure 2 of Appendix A. At first glance, this would lead one to believe that risk of patellofemoral degeneration increases as knee flexion (and therefore squat depth) increases. However, at least four additional variables are worth exploring. First, since the patellofemoral articulation is sliding and dynamic throughout the range of motion, the contact area and contact pressures between the patella and trochlear groove change as well. As the knee joint flexes towards 90 degrees and beyond, cranial displacement of the patella results in increased contact surface area between the two articulating surfaces;[22,23] therefore, despite increasing compressive forces, concomitantly increasing contact area would result in a net neutral effect on patellofemoral contact pressures. Older studies have observed increasing contact areas at 120 degrees and beyond, though more recent authors have called these measurement techniques into question.[6,24] Second, it has been observed that as knee flexion angle increases, contact between the quadriceps tendon and the intercondylar notch increases, which appears to again distribute patellofemoral loads over a broader surface area (colloquially, this is referred to as the "wrapping effect."[6]) Thirdly, the load distribution effects of soft-tissue contact between the posterior thigh and calf—previously mentioned in the discussion on tibiofemoral compressive forces—likely apply to this discussion as well.[15] Lastly, a repeat discussion is warranted regarding the relationship between squat depth and load. As previously mentioned, shallower squats necessitate increased external loads to achieve similar adaptations due to the inverse relationship between range of motion and loading capabilities.[7] Higher external loads in the squat have been shown to result in increased patellofemoral compressive forces, even when range of motion is controlled.[25] The nuanced relationship between knee flexion angle, patellar mobility, external loading, and soft tissue influence ultimately appears to lead to ambiguous conclusions regarding appropriate application of squatting variables to patellofemoral pathology and rehabilitation.

The previous sections of this paper have focused primarily on the effects of loading, knee flexion angle, and squat depth on various biomechanical forces on the main knee joints and associated soft tissues. However, due to the complex nature of the squat, additional discussion is warranted regarding other variables that are often not considered by coaches or rehabilitation specialists. This include foot placement width and angle, torso inclination angle, and the position of external load.

Foot placement can be considered from two directions: width and angle. Traditional methodologies teach subjects to squat with heels placed at or around hip or shoulder width and with a comfortable toe angle that allows for the femur to track along a relative sagittal plane.[8] Adjustments beyond this beginner stance can be implemented for anthropomorphic or biomechanical reasons. In 2001, Escamilla et al analyzed the differences between standard, narrow, and wide stance squats as normalized by biacromial width.[26] Wide stance squats, where foot placement exceeded shoulder width, tended to result in increased hip flexion, hip adduction, and lower leg external rotation, in additional to greater hip extensor torque. Notably, the wide stance additionally resulted in significantly greater tibiofemoral and patellofemoral compressive forces. Contrastingly, a narrow stance squat, where foot placement was narrower than shoulder width, biased more knee extensor torque, reduced compressive force, but resulted in significantly greater anterior knee translation and therefore larger shearing forces on the tibiofemoral joint. Therefore, with regards to stance width, a wide squat might be preferred if the goal is to minimize shearing forces, but should avoided if compressive forces are of concern; in contrast, a narrow stance squat should be utilized in compressive forces want to be minimized, but ought to be avoided if anterior shearing forces are of concern. No significant effects of stance width were seen on torso angle, quadriceps, or hamstring involvement; however, multiple studies have observed increased adductor and glute activity in wider stance squats, which has implications for the rehabilitation of adductor, groin, or hip injuries.[26–28]

The effects of tibial rotation, or toe-out angle, in the squat remains a contentious but relatively understudied subject. The consensus of multiple studies and reviews is that toe-out angle has minimal effect on muscular recruitment during the squat, and that in general extreme angles should be avoided.[8,29,30] A 2018 study by Lorenzetti et al analyzed the effects of foot position angles (0°, 21°, and 42°) on knee displacement in various planes.[8] The authors observed significantly greater displacement in the frontal plane (that is, varus and valgus moments) with increased out-toe angle, though the most knee displacement was observed in both narrow, out-toeing stances and wide, straight-footed stances. These positions should be avoided if varus or valgus loading is of concern. Furthermore, the authors observed the least valgus and varus displacements in straight-toed hip-width stances and wide stances with approximately 21 degrees of out-toeing. Thus it appears that toe angle is principally responsible for controlling frontal plane motion of the knee, which has numerous implications involving cruciate and collateral ligaments, menisci, contact pressure distribution, and more. Clinically, special care should be taken to avoid extreme internal or external tibial rotation and to ensure that proper hinge-joint tracking of the knee is encouraged.

The position of external load and trunk inclination angle have an intimate relationship and will therefore be discussed simultaneously. Reference to Figure 1 in Appendix will provide an illustrated visual on the effects of load placement and resultant torso angle. With the reasonable assumption that load placement will approximate the body's center of mass over the middle of the foot, trunk inclination angle becomes progressive more horizontal as one progresses from the front squat towards the high-bar and low-bar back squat variations.[5] More horizontal trunk angles have been shown to result in more vertical shin angles and decreased knee flexion angles when depth is controlled.[5,7] Furthermore, recent EMG studies have observed increased internal hip extensor torque with horizontal trunk angles (e.g., the low-bar back squat) due to increased external hip flexion torque, and more vertical trunk angles. (e.g., the front squat) tend to result in greater internal knee extensor torque due to larger external knee flexion torque.[5,7] This relationship between load placement, trunk inclination angle, and knee flexion angle has multiple implications. The low-bar back squat, with its horizontal trunk angle and decreased knee flexion angle, is likely to result in decreased tibiofemoral and patellofemoral compressive forces as well as decreased anterior shearing and ACL stressors, in addition to biasing muscular loads towards hip extensors and adductors and away from the knee extensors. (Additional stress is placed on the spinal erectors and spinal joints, but that discussion is beyond the scope of this paper.) In contrast, more upright squatting variants such as the front squat or high-bar back squat are likely to bias muscular recruitment more towards the quadriceps and knee extensors, though the increased knee flexion angle required from these variations might place increased shearing and compressive stress on the structures of the knee. At least one study has directly compared kinetics between the front squat and back squat, and the results appear somewhat paradoxical at first glance. Gullett et al found significantly smaller compressive forces in the knee during the front squat, with no differences observed in shearing forces between exercises. Additionally, overall muscular recruitment appeared to be similar between both variations.[31] Once again, however, discussion of external load differences between variations is warranted. In the study, similar *relative* loads were used (70 percent of one-repetition maximum of each exercise), but these proved to drastically different *absolute* loads— 61.8 +/ 18.6 kg and 48.5 +/- 14.1 kg for the back squat and front squat, respectively. Differences in muscular recruitment and mechanical advantages tend to necessitate significantly reduced loading in upright squatting variations. (The reasons behind this are numerous, many of which are beyond the scope of this paper. In short, the demands of trunk and core musculature tend to increase as the squat becomes more upright. Horizontal back angle variations of the squat often have the biomechanical advantage of relying on the stronger spinal extensors and related back musculature. As already mentioned, this places additional stress on the tissues of the back and spine; with regards to the lower extremities and knee joint, however, the athlete is capable of lifting more external load. This explains why the low-bar back squat is popular among powerlifters, whose goal is lift as much as load as possible.) While some studies indicate reduced forces on the knee joint during front squats, these studies do not account for differences in external loading. Similar to previous discussions on the effects of squat depth on knee forces, the effects of trunk angle and load placement must be considered alongside the magnitude of external load used.

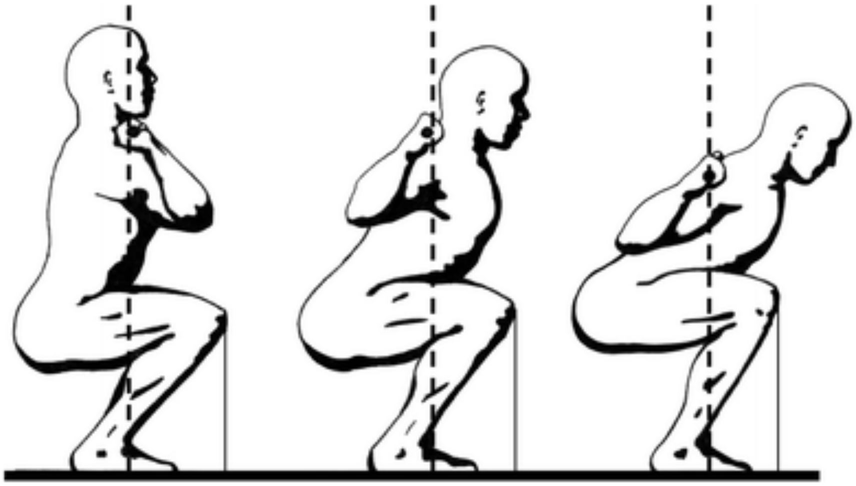
Much of this paper has focused the discussion on various passive soft tissues, such as ligaments and cartilage, and joint forces, with only occasional mention of contributing muscular forces. It has been previously noted that over 200 muscles are active during the barbell squat; due to the emphasis of this paper on the knee joint, only lower extremity muscles relevant to the knee will be discussed in this section. These include the quadriceps, hamstrings, and triceps surae, but also the rotators, abductors, adductors, and extensors of the hip. The effects of range of motion on muscular hypertrophy are well-documented; in almost every instance, when viewing the muscle in a vacuum, a longer range of motion (i.e., a parallel or deep squat) will result in greater hypertrophy of the involved musculature, even after accounting for the necessity of decreased load.[32,33] As previously mentioned, it is reasonable to conclude that wide-stance squats bias towards the development of the hip extensors and hip adductors, while narrow-stance squats might emphasize the knee extensors and triceps surae. A more horizontal trunk inclination angle, by altering external hip flexion torque, will necessarily result in increased internal hip extensor torque demands. Increasing squat depth also appears to linearly increase internal hip extensor torque demands, and quadriceps force appears to peak with parallel squatting variations.[7] Functional knowledge of the effects of these technique variations on muscular contribution will allow a skilled clinician to shift the effects of the squat towards or away from an injured tissue. For example, in the acute stages of an adductor sprain, a patient might be encouraged to squat in a narrower stance to minimize contribution, and therefore irritation, of the adductors; later in the rehabilitation process, when specific strengthening of the injured muscle is desired, the patient might transition to a wider squat variation to increase demands on the adductors.

Two useful musculature-related tangents are worth briefly examining. A 2019 study by Kubo et al[33] suggests that the hip extensor torque during deep squats is shared rather equally between the adductor magnus and the glutes. This conclusion was drawn via hypertrophy observations after ten weeks of squat training, and the subjects experienced an average increase in cross-sectional area of 6.2% and 6.7% percent of the adductors and glutes, respectively. This is supported biomechanically as well; the internal moment arms of the glutes and adductors, alongside EMG data, suggest that the glutes contribute more to hip extension in the squat as the lifter approaches full hip extension, whereas the adductors are the primary hip extensors at or below parallel in deeper squats.[34,35] An additional brief discussion is warranted with regards to the rectus femoris, a biarticular quadriceps muscle that contributes to both hip flexion and knee extension, and the biceps femoris, a biarticular hamstring muscle that contributes to both hip extension and knee flexion. The Kubo et al study observed astonishingly low hypertrophic effects in these muscles at squat training, lending one to conclude that the squat is not an effective exercise for the training of these muscles. This seems to occur for at least three main reasons. First, EMG data show that the hamstrings are one of the least active muscle groups during the squat, and that they mostly work isometrically.[36] Second, contraction of the hamstrings results in inhibition of the quadriceps due to their antagonistic nature, which would not be helpful in the squat given the high knee extension torque demands. Lastly, a concept referred to as Lombard's paradox explains how these two biarticular muscles are able to contract simultaneous—and isometrically—as the hips and knees simultaneously flex and extend during the squat; in brief, each muscle is able to shorten and contract from opposite ends simultaneously, resulting in a net isometric contraction that enables the muscles to contribute to hip and knee flexion without effectively changing in length.[37] To rephrase in brief: the squat is probably a better adductor exercise than most would belief, and is a rather ineffective hamstring and rectus femoris exercise than most would assume.

The barbell squat is an immensely popular and useful exercise for the closed-chain strengthening of the lower extremity. Involving over 200 muscles and almost every joint in the body to some degree, it has nearly unlimited potential in terms of loading, progression, regression, and customization. This paper sought to provide a thorough overview of a multitude of technical variables relating to the safe performance of the barbell squat exercise and their effects specific to the knee joint and its related tissues. These include squat depth, knee flexion angle, tibial translation, torso inclination angle, external load placement, foot placement, toe angle, and magnitude of external load. These variables have been analyzed in terms of their effects on compressive, tensile, and shearing stresses of the tibiofemoral and patellofemoral joints, associated ligaments, cartilaginous tissues, and nearby musculature. An in-depth and functional knowledge of how to effectively modify these variables to bias stressors and exercise-induced adaptations towards or away from injured or affected tissues is a critical skill for the strength and conditioning specialist or rehabilitation professional. It is this author's hope that this paper has left the reader with a greater appreciation and understanding of practical applications and clinical utility of the barbell squat exercise.

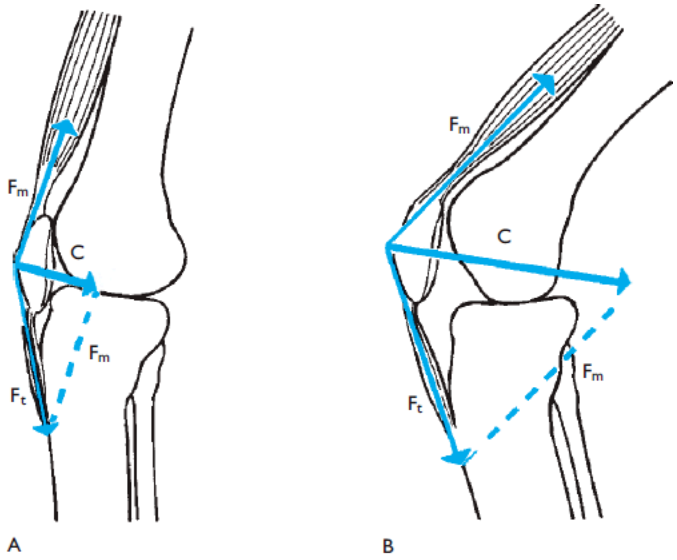
APPENDIX A

Figure 1



Illustrated representations of (from left to right) the parallel front squat, parallel high-bar back squat, and parallel low-bar back squat.[5]

Figure 2



Illustrated biomechanical representation of the relationship between the force of the quadriceps tendon, the patellar ligament, and the resultant retropatellar compressive force with increasing knee flexion angles.[38]

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