Deep Squats and Knee Health: A Scientific Review

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Squat strength has been linked to success in a variety of athletic movements (e.g. sprinting speed, vertical jump height, etc.), but major disagreement exists regarding how performance benefits and health risks are influenced by specific squatting techniques (22). Evidence suggests deep squats promote greater muscle mass and strength development compared to partial range of motion squats, but controversy exists over the safety of deep squatting. When applied to healthy individuals, the existing body of literature suggest that squatting below parallel is not detrimental to knee health. This article reviews the scientific research on how squat depth affects knee health, specifically related to sheer and compressive forces.

For the sake of simplicity, we will refer to squat depth in reference to parallel (~90° knee flexion, where 0° is full extension), with shallow squats being performed above parallel and deep squats performed below parallel. Recent evidence has shown that while shallow squats (60° knee angle) improve lower-body strength and vertical jump performance, deep squats (120° knee angle) are more efficacious (1). However, the safety of deep squatting remains highly questioned. The foundation of this controversy stems from the argument that squatting depth directly affects knee joint health (5). The National Strength and Conditioning Association (NSCA) published an evidence-based position statement in 1991 that stated squats are not only safe, but have the potential to improve knee health and decrease the likelihood of knee injury (5). However, this was published nearly 25 years ago and did not specifically include recommendations about squat depth.

The knee joint accepts both shear and compressive forces when loaded and mobilized (i.e. a squat). Ligaments (primarily the anterior (ACL) and posterior (PCL) cruciate ligaments) stabilize the joint by regulating shear forces, while the soft tissue (i.e. cartilage) absorbs compression and stabilizes the interaction of the tibia and femur. Shear and compressive forces in the knee are typically inversely related and can be both helpful and harmful. For example, as the flexion angle increases (as in the case of a squat), shear forces decrease (due to increased compressive forces). In this case compression is desirable as it works to stabilize the tissues in the joint.

Therefore, damage likely only occurs when the shear/compressive forces become excessive and surpass the normal capacity of the ligaments/cartilage. Squatting deeper than parallel has been labeled unfavorable on that exact premise (7). Others argue that while these forces are large, they are not damaging (5). This argument is contingent upon two basic questions: *1)* What are the shear and compressive forces during the squat? and *2)* Are these forces detrimental to the joint?

Shear Forces

Most shear forces on the knee joint during squats happen in the transverse (i.e. rotational) and sagittal (i.e. front to back) planes. These forces are primarily absorbed by the ACL and PCL. Thus, restricting shear forces limits ACL and PCL stress. Li *et al.* (2004) examined the rotational and translational forces in a series of experiments by analyzing the kinematics and kinetics of the knee under both passive and loaded flexion. The investigators reported the anatomical structures of the tibiofemoral joint increased tibial rotation and translation (anterior-posterior movement) when the knee was passively flexed. However, this did not occur when the knee joint muscles were active and loaded. Tibial rotation and translation actually remained unchanged between 50-120° of flexion and even decreased between 120-150° (14). Maximum anterior tibial translation and internal rotation surprisingly occurred at 30° and 90° of flexion, respectively. In concert, ACL forces peaked between 0-30°, significantly decreased at 60°, and remained constant through maximal knee flexion (15). PCL forces increased with increasing flexion angles before peaking at 90° and significantly decreasing with higher angles of flexion (15). This indicates that even though the flexion angle increases and the knees translate forward when squats progress past parallel, the shear forces and consequential ligament stress do not increase. Thus, the available evidence does not support the thought that squatting with vertical shins is necessary to minimize shear forces.

These data also collectively suggest that when compared to knee flexion angles at or above parallel, deep squatting actually results in less rotational and translational movement between the tibia and femur; placing less stress on the ACL and PCL. Tissue such as the menisci (which are built to absorb tibiofemoral compression, but are susceptible to shear forces) would therefore be at greater risk during the portion of the squat when knee flexion is ~90°. The reason for this phenomenon is unknown, though speculation ranges from non-modifiable (i.e. structural surfaces of the knee) to modifiable (e.g. squatting technique/muscular activation patterns) factors. For example, tibia axial rotation and patellofemoral contact forces change significantly when quadriceps muscle loading patterns shift. Medial dominant patterns result in greater internal rotation and patellofemoral compression than lateral loading patterns (27). This indicates neutral or lateral loading squatting limits shear-induced stress.

Positioning of the ankles, knees, and hips directly influences loading patterns, as the angle of these joints affects activation of the quadriceps, hamstrings (12), and glutes (4). Research has shown peak activity of the quadriceps and hamstrings occurs at, or prior to, parallel and does not decrease past parallel (4). Furthermore, the relative contribution and activation of these muscles is unaltered by depth (4). Conversely, activation of the gluteus maximus increases as squat depth increases (4). This collectively suggests that when compared to parallel squatting, squatting below parallel presents no alterations in quadriceps/hamstring activation, increases glute activation and knee joint stability, and decreases shear forces and ACL/PCL strain.

Compressive Forces

Compressive forces during squatting are found at both the patellofemoral and tibiofemoral joints (7, 24, 25). These forces increase as muscle activation (26), load (19), velocity, and loading-duration increase (17). Although increased compressive forces (associated with increased squat depth) functions to neutralize shear forces (16), excessive compression could lead to the breakdown of menisci/articular cartilage. This may accelerate the development of osteoarthritis or other maladies (17). Therefore, the challenge in determining the risk of compressive forces lies in defining the line between necessary, and excessive force. These data currently do not exist. Complicating the matter, the magnitude of compressive stress is a function of the amount of force divided by the articular cartilage, tibia, femur, and patella contact area (6).

Increases in patellofemoral force during knee flexion are likely met with increases in contact area, assuaging, or possibly even diminishing the compressive stress (24). Patellofemoral compressive forces peak between 70°-100° of knee flexion (7, 21), yet the patellofemoral contact area continues to increase with increased knee flexion. In fact, because of this, patellofemoral stress actually decreases when knee flexion angles exceed 90°-100° (6, 24). The magnitude of this effect is well illustrated by Thambyah and colleagues (2005), who found that patellofemoral stress elicited by a 4 fold body mass load at 90° of knee flexion was equal to a 5 fold body mass load at 120° of knee flexion. These findings mirror the conclusions reported regarding shear forces; that patellofemoral stress does not increase when squats exceed parallel.

Existing evidence suggests compressive forces at the tibiofemoral joint are the only forces that increase when squats are performed past parallel (7). This is a legitimate concern, as adult articular cartilage is not likely to regenerate effectively when damaged. Yet, recent data suggest individuals free of neuromuscular injury are capable of accommodating the increased compressive force (8), making it safe for them to squat below parallel. Since the technology required to measure articular cartilage structure/composition in the body is relatively new, only a few long-term studies related to this topic exist; none of which have assessed squatting.

The most relatable study which directly measured cartilage found that six months of training for a marathon did not result in a clinically relevant loss of tibiofemoral cartilage (13). Although running and squatting are astoundingly different, a 78 kg male running at a reasonable speed of 3.85 m/s results in peak tibiofemoral compressive forces (~6382 N) (2) comparable to those of deep squatting at an incredibly heavy load (250 kg) (~7000 N) (18). This suggests running likely results in greater tibiofemoral compressive stress than full depth squatting, even at excessively high loads. However, neither of these activities appears to produce compressive forces that exceed the capacity of the joint, acutely or chronically.

Data from athletes who regularly engage in deep squats further supports this contention. A group of elite male weightlifters training at the U.S. Olympic Training Centers [who are the most likely to obtain a compression injury as they regularly engage in full depth and high *1)* vertical load, *2)* quadricep/patellar tendon tension, and *3)* velocity squatting] reported a remarkably low acute and recurring injury rate (3.3 injuries per 1000 hours of training) over a six-year period (3). Only one of the 107 knee injuries required more than one week of recommended rest, and none longer than three weeks (3). The instantaneous high compression probably functions to stabilize the knee; decreasing the likelihood of shear-induced ligament damage. This enhanced stability does not appear to come at the expense of compression-induced injuries. In fact, a certain level of mechanical stress may be necessary to maintain cartilage function as vigorous activity actually decreases the rate of articular cartilage degradation in adults without existing cartilage defects (23). The same may or may not be true of deep knee squatting.

While the load itself may not be an issue, it may alter knee health as a function of changing squatting technique. McKean *et al.* (2010) observed a significant increase in forward movement of the knee during loaded squats (body weight + 50% 1RM) compared to body weight squats. Along the same lines, deep back squats inherently result in greater anterior translation of the knees than parallel squats (10). However, hip moments and forward trunk lean increase when squats are restricted so that the knees do not pass the toes and some form of counter balance is not applied (10). This increase in forward trunk lean leads to increased lumbar shear forces (20). Considering the previously discussed data suggesting high degrees of knee flexion are not deleterious to knee health, allowing the knees to translate past the toes will not result in knee injury, but will allow for a more upright torso, which can decrease low-back stress (20). Load placement can also affect the knee joint as Lynn and Noffal (2012) found that counterbalanced squats result in lesser knee and greater hip moments than regular squats. Furthermore, both average maximal compression and knee moments are higher in the back squat when compared to the front squat, even though muscle utilization does not differ (11). This suggests the counterbalanced/front squat allows the exerciser to minimize compressive forces and moment on the knee while maintaining lower limb muscle activation.

Contraindications of Squatting

Individuals with current injuries or other contraindications may need to be given special consideration. Although shear forces and patellofemoral compressive stress decrease when squats are performed past parallel, individuals with current tibiofemoral and/or patellofemoral joint injuries may need to refraining from squatting into angles deeper than ~60° as it requires them to pass through the area of the highest forces (~60-80° of flexion) (11, 24, 25). Contraindications may also exist among apparently healthy individuals with dysfunctional movement patterns or flexibility/mobility limitations. Anecdotal and empirical evidence highlights the particular importance of adequate ankle mobility for squat safety as impairments may promote a valgus knee, which has been linked to knee injury risk. Additional research has observed the average net joint moments at the left and right knee joint during the barbell squat to differ by an average of ~14% (9). Asymmetrical movement patterns such as this could theoretically lead to injury as it results uneven distribution of forces.

Conclusion

Deep squats result in greater activation of lower-body musculature compared to shallow squats. Squatting past parallel does not result in greater shear forces, which means ACL and PCL stress does not increase past parallel. Although squatting below parallel also does not result in greater patellofemoral compressive stress, deeper squats may result in greater tibiofemoral compressive forces, which stresses the articular cartilage of the tibia and the femur at the knee joint. However, recent data suggests the articular cartilage at the tibiofemoral joint (in individuals without existing knee injuries) is capable of enduring the magnitude of compressive forces that are encountered during heavy deep squats. Moreover, it may actually be an effective method of preserving joint health. Therefore, squatting below parallel is safe for individuals without any contraindications, assuming it is performed at a load and velocity consistent with the exercisers ability to maintain symmetry and position.

Perspective

Squatting depth is one of the many technique variables that affect knee stress during the squat exercise. You must be aware of all the technique variables (some of which are beyond the scope of this article) that affect knee stress during the squat exercise. Under the supervision of a qualified professional, healthy athletes/clients may perform the deep squat exercise to maximize lower-body musculature development without unnecessary concern of knee injury. However, athletes/clients with any contraindications should not perform deep squats and instead either perform squats in the physiologic range (0°-50° of knee flexion) (6), or choose one/some of the many other exercises that can be used to develop the musculature of the lower body. The current review focused entirely on the knee joint, but we recognize many other structures are involved in the squatting process (e.g. lumbar spine, ankle, etc.) and thus deserve equal consideration.

References

1. Bloomquist K, Langberg H, Karlsen S, Madsgaard S, Boesen M, and Raastad T. Effect of range of motion in heavy load squatting on muscle and tendon adaptations. *European Journal of Applied Physiology*: 1-10, 2013.
2. Boocock M, McNair P, Cicuttini F, Stuart A, and Sinclair T. The short-term effects of running on the deformation of knee articular cartilage and its relationship to biomechanical loads at the knee. *Osteoarthritis and Cartilage* 17: 883-890, 2009.
3. Calhoon G and Fry AC. Injury rates and profiles of elite competitive weightlifters. *Journal of Athletic Training* 34: 232, 1999.
4. Caterisano A, Moss RE, Pellinger TK, Woodruff K, Lewis VC, Booth W, and Khadra T. The effect of back squat depth on the EMG activity of 4 superficial hip and thigh muscles. *The Journal of Strength & Conditioning Research* 16: 428-432, 2002.
5. Chandler TJ and Stone MH. The squat exercise in athletic conditioning: A position statement and review of the literature. *Chiropractic Sports Medicine* 6: 105-105, 1992.
6. Escamilla RF. Knee biomechanics of the dynamic squat exercise. *Medicine and Science in Sports and Exercise* 33: 127-141, 2001.
7. Escamilla RF, Fleisig GS, Zheng N, Lander JE, Barrentine SW, Andrews JR, Bergemann BW, and Moorman CT. Effects of technique variations on knee biomechanics during the squat and leg press. *Medicine and Science in Sports and Exercise* 33: 1552-1566, 2001.
8. Farrokhi S, Colletti PM, and Powers CM. Differences in Patellar Cartilage Thickness, Transverse Relaxation Time, and Deformational Behavior A Comparison of Young Women With and Without Patellofemoral Pain. *The American Journal of Sports Medicine* 39: 384-391, 2011.
9. Flanagan SP and Salem GJ. Bilateral differences in the net joint torques during the squat exercise, in: *J Strength Cond Res*. United States, 2007, pp 1220-1226.
10. Fry AC, Smith JC, and Schilling BK. Effect of knee position on hip and knee torques during the barbell squat. *The Journal of Strength & Conditioning Research* 17: 629-633, 2003.
11. Gullett JC, Tillman MD, Gutierrez GM, and Chow JW. A biomechanical comparison of back and front squats in healthy trained individuals. *J Strength Cond Res* 23: 284-292, 2009.
12. Hahn D. Lower extremity extension force and electromyography properties as a function of knee angle and their relation to joint torques: implications for strength diagnostics. *The Journal of Strength & Conditioning Research* 25: 1622-1631, 2011.
13. Hinterwimmer S, Feucht MJ, Steinbrech C, Graichen H, and von Eisenhart-Rothe R. The effect of a six-month training program followed by a marathon run on knee joint cartilage volume and thickness in marathon beginners. *Knee Surgery, Sports Traumatology, Arthroscopy*: 1-7, 2013.
14. Li G, Zayontz S, DeFrate LE, Most E, Suggs JF, and Rubash HE. Kinematics of the knee at high flexion angles: an in vitro investigation. *Journal of Orthopaedic Research* 22: 90-95, 2004.

15. Li G, Zayontz S, Most E, DeFrate LE, Suggs JF, and Rubash HE. In situ forces of the anterior and posterior cruciate ligaments in high knee flexion: an in vitro investigation. *Journal of Orthopaedic Research* 22: 293-297, 2004.
16. Lynn SK, Noffal GJ. Lower extremity biomechanics during a regular and counterbalanced squat. *J Strength Cond Res* 26: 2417-2425, 2012.
17. Markolf KL, Bargar WL, Shoemaker SC, and Amstutz HC. The role of joint load in knee stability. *The Journal of bone and joint surgery American volume* 63: 570, 1981.
18. McCormack T and Mansour JM. Reduction in tensile strength of cartilage precedes surface damage under repeated compressive loading in vitro. *Journal of biomechanics* 31: 55-61, 1997.
19. McKean MR, Dunn PK, Burkett BJ. Quantifying the movement and the influence of load in the back squat exercise. *J Strength Cond Res* 24: 1671-1679, 2010.
20. Nisell R. Joint load during the parallel squat in powerlifting and force analysis of in vivo bilateral quadriceps tendon rupture. *Scand J Sports Sci*, 1986.
21. Nisell R, Németh G, and Ohlsén H. Joint forces in extension of the knee: analysis of a mechanical model. *Acta Orthopaedica* 57: 41-46, 1986.
22. Russell PJ and Phillips SJ. A preliminary comparison of front and back squat exercises. *Research Quarterly for Exercise and Sport* 60: 201-208, 1989.
23. Salem GJ and Powers CM. Patellofemoral joint kinetics during squatting in collegiate women athletes. *Clinical Biomechanics* 16: 424-430, 2001.
24. Schoenfeld B and Williams M. Are Deep Squats a Safe and Viable Exercise? *Strength & Conditioning Journal* 34: 34-36, 2012.
25. Teichtahl AJ, Wluka AE, Forbes A, Wang Y, English DR, Giles GG, and Cicuttini FM. Longitudinal effect of vigorous physical activity on patella cartilage morphology in people without clinical knee disease. *Arthritis Care & Research* 61: 1095-1102, 2009.
26. Thambyah A, Goh JC, and De SD. Contact stresses in the knee joint in deep flexion. *Medical Engineering & Physics* 27: 329-335, 2005.
27. Trepczynski A, Kutzner I, Kornaropoulos E, Taylor WR, Duda GN, Bergmann G, and Heller MO. Patellofemoral joint contact forces during activities with high knee flexion. *Journal of Orthopaedic Research* 30: 408-415, 2012.
28. Tsai L-C and Powers CM. Increased hip and knee flexion during landing decreases tibiofemoral compressive forces in women who have undergone anterior cruciate ligament reconstruction. *The American journal of sports medicine* 41: 423-429, 2013.
29. Wünschel M, Leichtle U, Obloh C, Wülker N, and Müller O. The effect of different quadriceps loading patterns on tibiofemoral joint kinematics and patellofemoral contact pressure during simulated partial weight-bearing knee flexion. *Knee Surgery, Sports Traumatology, Arthroscopy* 19: 1099-1106, 2011.