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Clinical Commentary/Current Concept Review

A Biomechanical Review of the Squat Exercise: Implications for Clinical Practice

Rachel K Straub, Christopher M Powers[a]

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The squat is one of the most frequently prescribed exercises in the rehabilitative setting. Performance of the squat can be modified by changing parameters such as stance width, foot rotation, trunk position, tibia position, and depth. An understanding of how the various squatting techniques can influence joint loading and muscular demands is important for the proper prescription of this exercise for various clinical conditions. The purpose of this clinical commentary is to discuss how the biomechanical demands of the squat can be influenced by various modifiable parameters. General recommendations for specific clinical conditions are presented.

Level of Evidence

5

INTRODUCTION

Squatting is an essential movement pattern for activities of daily living (i.e., toileting and getting into or out of a chair) and various athletic tasks. As such, the squat exercise is commonly used in rehabilitation and sport performance settings to strengthen the primary lower extremity muscle groups (i.e., hip extensors and knee extensors).[1-5] In addition, the squat exercise requires a high level of recruitment from the trunk muscles to provide stabilization for the spine and torso.[4,6,7]

The squat exercise can be highly variable in its execution. For example, the squat can be adapted by modifying trunk position, tibia position, foot rotation, stance width, and depth. Given that each modifiable factor can influence the biomechanics of the squat (i.e., muscular demands, joint loading, etc.), it is not surprising that the literature is conflicting when recommending various squatting techniques for different clinical situations.[4,8] Interpretation of research related to squatting is difficult owing to the fact that many studies fail to control for the various modifiable parameters when assessing the influence of a specific variable.

It is important that clinicians be mindful of the various interactions among the modifiable parameters so that correct clinical recommendations can be made. As such, the purpose of this clinical commentary is to discuss how the biomechanical demands of the squat can be influenced by various modifiable parameters. General recommendations for specific clinical conditions are presented. It is hoped that the information presented will assist clinicians in the appropriate prescription of the squat exercise for patients with various diagnoses.

MODIFIABLE SQUAT PARAMETERS

TRUNK INCLINATION

The moments at the hip and knee during squatting are highly influenced by the orientation of the trunk, which in turn affects the center of mass of the body.[9,10] During a typical squat, the resultant ground reaction force vector passes anterior to the hip and posterior to the knee, thereby creating flexion moments at both joints (Figure 1).[9] Muscular actions of the hip and knee extensors are required to generate extensor moments to counteract these external moments. Moving the trunk from a more upright position (Figure 1A) to more forward position (Figure 1B) shifts the resultant

a Corresponding Author:
Christopher M. Powers, PT, PhD, FACSM, FAPTA
USC Division of Biokinesiology & Physical Therapy
1540 E. Alcazar St. CHP-155
Los Angeles, CA 90089-9006
Phone: 323.442.1928
Fax: 323.442.1515
Email: powers@usc.edu

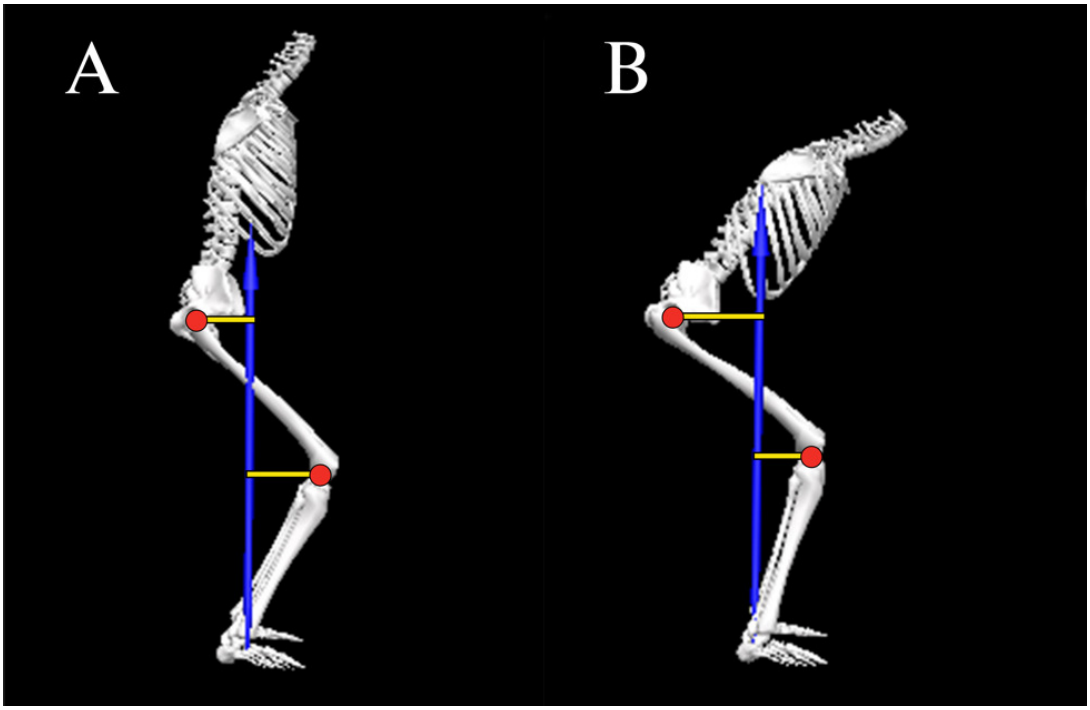

Figure 1. Sagittal plane orientation of the trunk influences the external moments at the hip and knee.

(A) Squatting with the trunk in a more upright position increases the knee flexion moment while decreasing the hip flexion moment. (B) Moving the trunk forward increases the hip flexion moment while decreasing the knee flexion moment.

ground reaction force vector anteriorly, resulting in an increase in the hip flexion moment while simultaneously decreasing the knee flexion moment.[11] Conversely, moving the trunk from a forward position (Figure 1B) to more upright position (Figure 1A) shifts the resultant ground reaction force vector posteriorly, thereby decreasing the hip flexion moment while simultaneously increasing the knee flexion moment.[11]

Apart from its influence on the hip and knee flexion moments, squatting with a forward trunk has an impact on the lumbar spine flexion moment. Generally speaking, the greater the forward trunk inclination, the greater the muscular demand on the back extensors to stabilize the trunk.[12] It should be noted however, that forward inclination of the trunk can be obtained through flexion of the hip or flexion of the lumbar spine (Figure 2).[13] Attainment of a forward trunk position using lumbar spine flexion (Figure 2A) results in decreased tolerance to compressive loads[14] and lumber spine anterior shear forces as compared to when forward trunk inclination is achieved with a neutral spine position (Figure 2B).[15] Maintaining a neutral spine position increases the moment arm for the spinal extensors thereby allowing better control of compressive loads and shear forces.[14,15]

TIBIA INCLINATION

Compared to trunk inclination, inclination of the tibia during squatting has an opposite influence on the knee flexion moment.[9,10,16-18] Moving the tibia from a more upright position (Figure 3A) to more forward position (Figure 3B) shifts the knee joint center further away from the resultant ground reaction force vector, thereby increasing the knee flexion moment. Conversely, moving the tibia from a forward position (Figure 3B) to more upright position (Figure 3A) shifts the knee joint center closer to the resultant ground reaction force vector, thereby decreasing the knee flexion moment.

Forward tibia inclination can be achieved by either ankle dorsiflexion (with the foot flat on the floor) or squatting with the heels off the floor (i.e., using an external lift under the rearfoot or weightlifting shoes with an elevated heel).[19] In general, elevating the heels during squatting facilitates a greater degree of forward tibia inclination, thereby increasing the knee flexion moment and the demand on the quadriceps.[19,20] It should be noted however, that the forward tibia position when squatting with the heels elevated can occur without a corresponding increase in ankle dorsiflexion.

FOOT ROTATION

The degree of foot rotation during squatting can be accomplished by hip external rotation, knee external rotation, or a combination of both. The degree of toe out influences the frontal and transverse plane moments at the knee while having a negligible effect on the sagittal plane moments. For example, rotating the feet outward 30° has been reported to decrease the valgus moment at the knee by 50% while simultaneously increasing the varus moment by 80%.[21] In addition, rotating the feet outward 30° decreases the external rotation moment at the knee by 20% when compared to a neutral stance.[21]

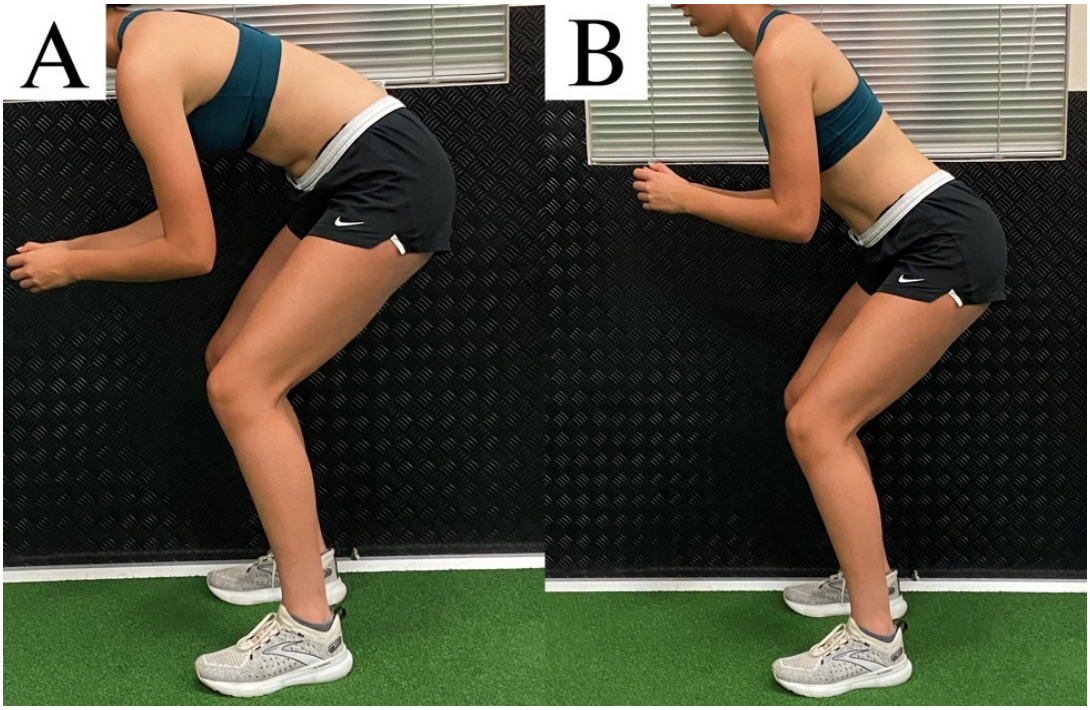

Figure 2. Forward inclination of the trunk that is achieved by spine flexion (A) results in decreased tolerance to compressive loads and less control of anterior shear forces as compared to when forward trunk inclination is achieved with a neutral spine position (B).

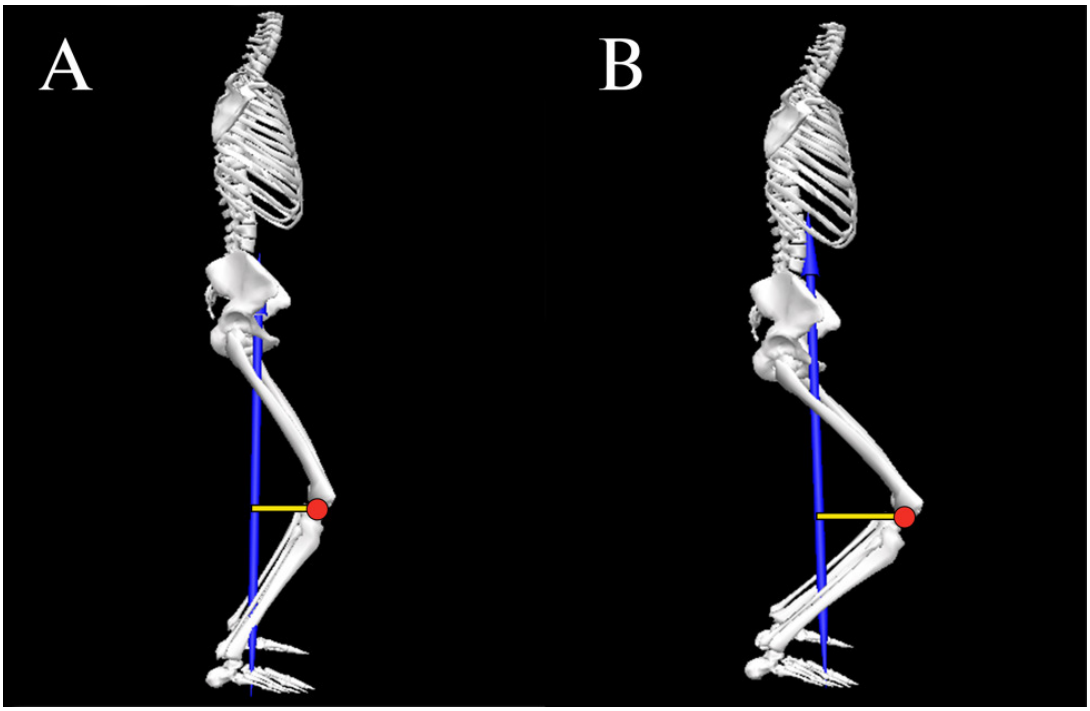

Figure 3. Sagittal plane orientation of the tibia influences the external moment at the knee.

(A) Squatting with the tibia in a more upright position decreases the knee flexion moment. (B) Moving the tibia forward increases the knee flexion moment.

From a muscle recruitment standpoint, rotation of the foot outward 30° has no effect on activation of the quadriceps, hamstrings, or gastrocnemius when compared to a neutral foot position.[2,22] Similarly, varying rotations of the tibia and femur from 30° inward to 80° outward has no effect on quadriceps activity.[23] However, squatting with the hip externally rotated 30° to 50° has been reported to increase hip adductor activity compared to a neutral stance by 17% and 23% respectively (neutral: 13% of maximum

voluntary isometric contraction [MVIC] vs. 17% and 23% MVIC for 30° and 50° rotation, respectively).[24]

STANCE WIDTH

For the purposes of this perspective, the authors operationally define stance width as narrow (75% to 100% shoulder width), medium (100% to 150% shoulder width), or wide (150% to 200% shoulder width). With respect to the frontal and transverse planes, a wide stance results in greater knee valgus moments (23%)[25] and higher hip external rotation moments (19%-37%) when compared to narrow/medium stance squats.[26] In terms of the sagittal plane, however, the impact of stance width is conflicting.[25-27] Compared to a narrow/medium stance, the knee flexion moment during wide stance squatting has been reported to be higher (69%-80%),[27] lower (11%),[25] or not different.[26] Similarly, the hip flexion moment during wide stance squatting has been reported to be higher (10%-48%)[26,27] or not different compared to narrow/medium stance squatting.[25] The conflicting results among studies can be explained by how authors controlled for other modifiable factors such as trunk and tibia orientation. For example, performing a wide stance squat with the trunk inclined would yield a different result than if the squat was performed with the trunk more upright.

From a muscle recruitment standpoint, a medium/wide stance squat has been reported to result in higher gluteus maximus activity (13%-61%)[28,29] and 18% lower gastrocnemius activity (14% vs. 17% MVIC) compared to narrow/medium stance squats.[2] Stance width does not appear to influence hamstring,[28,29] quadriceps,[28,29] or gluteus medius activity.[29] In regards to hip adductor recruitment, stance width does not influence overall muscle activation.[29] However, if the descending and ascending phases are analyzed separately, a wider stance increases hip adductor activity during the accent phase of squatting compared to the descent phase by approximately 50%.[28]

SQUAT DEPTH

For the purposes of this perspective, the authors operationally define squat depth as partial/shallow (0°-90° knee flexion), medium (90°-110° knee flexion or thigh parallel to floor), or full/deep (110°-135° knee flexion). Generally speaking, the knee flexion moment tends to steadily increase from an upright position to maximum knee flexion during squatting.[30-32] Similarly, the hip flexion moment also increases with squat depth.[32] However, the increase in the knee flexion moment with greater squat depth is not consistent across studies,[33,34] and can be affected by the trunk and tibia orientation. For example, if the increase in trunk inclination with increasing depth is more pronounced than the increase in tibia inclination, this could potentially result in a relatively higher hip flexion moment relative to the knee flexion moment at higher depths. Conversely, if the increase in tibia inclination with increasing depth is more pronounced than the increase in trunk inclination, this could potentially result in a higher knee flexion moment relative to the hip flexion moment at greater squatting depths.

Apart from the influence of squat depth on hip and knee moments, studies examining muscle recruitment with increasing depth are conflicting. In regards to quadriceps activity, some studies have reported an increase in EMG activity with squat depth (29%),[35] while others have not.[1,5,36] Similarly, evidence related to hamstring activity also is conflicting, as studies have reported no change[1,5,35] or a slight decrease in activation (absolute difference: 12% MVIC) with increasing squat depth.[36] With respect to gluteus maximus, activity has been shown to increase from shallow to medium depth squatting by 65%[1] but what happens thereafter is controversial. Compared to medium depth squats, gluteus maximus activity has been reported to be similar,[5] or 25% greater with deep squats (28% vs. 35% MVIC).[1] When comparing partial to deep squats, gluteus maximus activity has been reported to be higher with partial depths (absolute difference: 29% MVIC).[36] As noted above, failure to account for trunk and tibia position with deep squatting likely underlies the inconsistent findings among studies.

From a joint motion standpoint, the primary limitation to deep squatting is the amount of available hip flexion. When end range of hip flexion is reached during squatting, a posterior pelvic tilt will occur (Figure 4). The posterior rotation of the pelvis is the result of the femur compressing into the acetabulum.[37] Given that posterior pelvic tilt is coupled with lumbar spine flexion,[37,38] compressive and shear forces occur at the lumbar spine.[14,15,39] The fact that lumbar erector spinae activity does not increase beyond 90° of knee flexion,[36] suggests that passive structures (i.e., posterior longitudinal ligament) provide the resistance to the spine flexion moment.

KNEE VS. HIP EXTENSOR BIASED SQUATTING

As noted above, inclination of the trunk and tibia have opposite effects on the knee flexion moments and therefore the demand on the quadriceps. Forward inclination of the tibia increases the knee flexion moment, while forward trunk inclination decreases the knee flexion moment. As such, considering the degree of tibia inclination without considering the degree of trunk inclination can result in erroneous interpretation of the biomechanical demand at the knee. For example, the increase in the knee flexion moment resulting from inclination of the tibia could be offset by forward inclination of the trunk.[10] Therefore, the relationship between trunk and tibia inclination may be a better way to characterize the biomechanical demands of the knee extensors during squatting.

Evidence in support of this premise is provided by Barrack et al., who demonstrated that the relative demand of the hip and knee extensors during squatting could be predicted based on the relative inclination of the trunk and tibia.[11] Specifically, the authors reported that the difference between sagittal plane inclination of the trunk and sagittal plane inclination of the tibia (i.e., trunk-tibia angle) at peak knee flexion was predictive of the average hip/

Figure 4. Squatting to a depth that exceeds available hip flexion results in a posterior pelvic tilt.

knee flexion moment ratio during the decent phase of squatting. The regression model indicated that a trunk-tibia angle of -8° resulted in a hip/knee flexion moment ratio equal to 1.0.[11] When the degree of trunk inclination exceeded the degree of tibia inclination (i.e., trunk-tibia angle > 0), a hip extensor bias squat was observed (i.e., hip/knee flexion moment ratio > 1.0). Conversely, when tibia inclination exceeded trunk inclination (by at least 8°), the squat became knee extensor biased (i.e., hip/knee flexion moment ratio < 1.0).[11]

Based on the findings of Barrack et al., it is possible to characterize the relative demand of the hip and knee extensors using the trunk-tibia inclination difference.[11] When the degree of trunk inclination exceeds the degree of tibia inclination by 10°, a hip extensor bias can be inferred (Figure 5A). When the degree of tibia inclination exceeds the degree of trunk inclination by 10°, a knee extensor bias squat can be inferred (Figure 5B). In situations where the degree of trunk and tibia inclination are within 10° or each other, the relative demands on the hip and knee extensors can be considered equal (i.e., neutral bias) (Figure 5C).

The orientation of the trunk relative to the tibia (and therefore the hip/knee flexion moment ratio) can be influenced by the location of the applied load. For example, when the load is placed anteriorly (i.e., barbell front squat or goblet squat), the trunk is typically held in a more upright position. Conversely, a traditional barbell back squat typically is performed with greater trunk flexion.[4,40] Therefore, it is not surprising that studies have reported differing muscular demands during these squat types. Back squats are associated with higher hip flexion moments, whereas front squats exhibit higher knee flexion moments, assuming the same absolute load.[40]

CLINICAL APPLICATIONS

When prescribing the squat as a therapeutic exercise, the desired clinical outcome needs to be considered. For example, knee extensor bias squatting may be indicated for patients with quadriceps weakness. In contrast, performing the squat with a hip extensor bias may be preferred if the goal is to the increase strength of the hip musculature. Based on the literature reviewed above, recommendations for performing the squat exercise for various clinical conditions are presented below (Table 1).

PATELLOFEMORAL PAIN (PFP)

Clinical guidelines for persons with PFP advocate for hip and knee extensor strengthening.[41] During the acute phase of the rehabilitation process, hip biased squats should be considered to reduce the demand on the quadriceps. This is important as quadriceps force contributes directly to patellofemoral joint reaction force and patellofemoral joint stress.[42] During the sub-acute or recovery phase, squats can be progressed as tolerated to be more neutral biased or even quadriceps biased by modifying the trunk-tibia relationship.

During the acute phase, gluteus maximus activation should be emphasized as this muscle controls hip adduction and internal rotation, motions known to contribute to patellofemoral joint stress and PFP.[43,44] Increased gluteus maximus activation can be achieved through the use of wider stance squats,[26-29] as well as external band resistance around the thighs.[45,46] However, a squat stance that exceeds 150% shoulder width may result in elevated knee valgus moments.[25] During the sub-acute or recovery phase, transitioning to more narrow/medium stance squats will

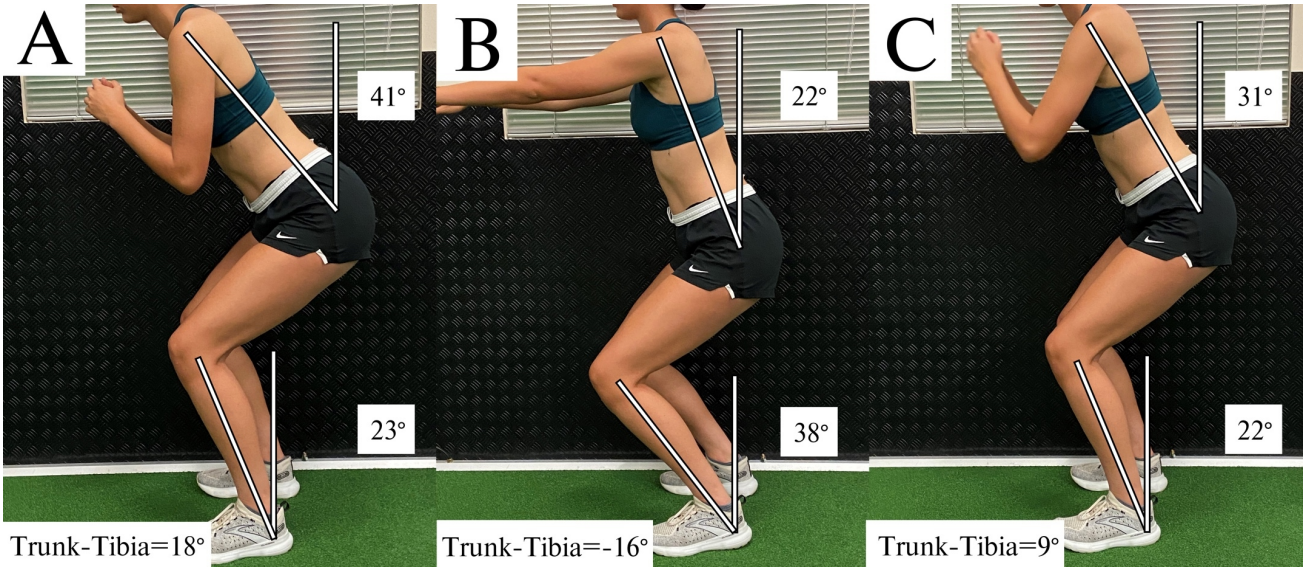

Figure 5. Trunk-tibia angle (bottom left).

(A) Hip extensor bias with trunk-tibia angle > 10°; (B) Knee extensor bias with trunk-tibia angle < -10°; (C) Neutral bias with -10° ≤ trunk-tibia angle ≤ 10°.

promote greater tibial inclination[47] and a quadriceps bias. Regardless of phase, a toe out position should be considered as this will result in a decrease in the knee valgus moment.[21]

Another important consideration for the patient with patellofemoral pain is squat depth. Patellofemoral joint stress steadily increases from partial to medium depth squatting (0° to 90°).[42] The increase in patellofemoral joint stress is the result of a steadily increasing patellofemoral joint reaction force that is more pronounced than the increase in contact area as the knee flexes.[42] Generally speaking, shallow-medium depth squats should be prescribed for the patient with patellofemoral pain to minimize joint stress. Furthermore, there is evidence that shallow squats may be more desirable for gluteus maximus activation compared to deep squats.[36]

POST ANTERIOR CRUCIATE LIGAMENT (ACL) RECONSTRUCTION

Clinical guidelines for persons post ACL reconstruction advocate for the restoration of knee extensor strength and symmetry.[48,49] Patients with patellar tendon or quadriceps tendon autografts regain quadriceps strength more slowly and are more prone to anterior knee pain.[50] Thus, slow and progressive loading of the quadriceps should be the focus. For patients with donor-site pain, slower rates of loading/tempo may be better tolerated to stimulate tendon remodeling and muscular strengthening.[50] Given that patients post ACL reconstruction are susceptible to anterior knee pain, hip biased squatting should be considered to lower the demand on the quadriceps using the trunk-tibia relationship recommendations above. Secondary considerations for hip bias squatting early in the recovery process include external band resistance around the thighs to promote gluteus maximus and gluteus medius activation[45,46] and avoidance of deep squats (i.e., recommendations highlighted above for PFP). Medium stance squats are preferred over wide stance squats to minimize the knee valgus moment.

As tolerance to donor site loading improves, squats should be modified to progressively emphasize quadriceps loading (i.e., knee biased squatting). This can be achieved by either modifying the trunk position (more upright), promoting greater tibial inclination, or a combination of both. Secondary considerations for the introduction of more knee bias squatting include the use of deeper squats to increase quadriceps demands (moments)[30,32] and narrow/medium stance widths. Regardless of squat type utilized (hip vs. knee bias), care should be taken to avoid valgus and transverse plane moments at the knee by promoting some degree of toe out.[21]

FEMOROACETABULAR IMPINGEMENT (FAI)

FAI, or abutment or impingement of the femoral neck against the acetabular labrum, can result in chondrolabral damage, thereby contributing to early onset of hip osteoarthritis.[51,52] Persons with FAI exhibit impaired mobility at the hip (specifically hip flexion) and deficits in gluteal muscle activation.[51,53] As such, selecting squatting mechanics that emphasize gluteus maximus and medius activation is prudent by optimizing the trunk-tibia relationship, utilizing a wider stance, and external band resistance around the thighs (see recommendations above).

Squat depth should be limited to avoid hip flexion beyond the patient's available range of motion. This is important as patients with FAI have limited ability to posteriorly tilt the pelvis during squatting, which places them at greater risk for impingement.[54] Deep squats (even if pain free) should be avoided. Although up to 25% of patients with FAI can perform deep squats without pain,[55] it is important to note that deep squats impose large amplitudes of hip joint stress[56] and increase the requirements for hip

Table 1. Summary of Squat Parameters for Clinical Conditions

Patellofemoral pain	• Avoid deep squats (limits patellofemoral joint stress) • Outward toe rotation (decreases knee valgus moment) *Acute Phase (hip bias)* • Trunk-Tibia angle >10° • Wider stance • External band resistance around thighs *Sub-Acute Phase (progress to neutral and/or knee bias squat)* • -10° <= Trunk-Tibia angle <= 10° (neutral bias) OR Trunk-Tibia angle < -10° (knee bias) • Narrow/medium stance
Post Anterior Cruciate Ligament Reconstruction	• Outward toe rotation (decreases knee valgus moment and knee transverse moment) • Medium stance preferred over wide (decreases knee valgus moment) *Acute Phase (hip bias)* • Trunk-Tibia angle >10° • External band resistance around thighs • Avoid deep squats *Sub-Acute Phase (progress to knee bias squat)* • Trunk-Tibia angle < -10° • Deeper squats • Narrow/medium stance
Femoroacetabular impingement	• Trunk-Tibia angle >10° (hip bias) • Wider stance (hip bias) • External band resistance around thighs (hip bias) • Avoid deep squats (protects against hip impingement) • Outward toe rotation to promote hip external rotation (protects against hip impingement)
Low Back Pain	• Minimize trunk inclination (protects against lumbar muscle strain) • Trunk-Tibia angle >10° (hip bias) • Wider stance (minimizes lumbar loading) • External band resistance around thighs (hip bias) • Avoid deep squats (facilitates neutral spine)
Tibiofemoral Osteoarthritis	• Avoid deep squats (minimizes tibiofemoral compressive forces) • Outward toe rotation (if lateral compartment osteoarthritis) • Neutral foot (if medial compartment osteoarthritis) *Acute Phase (hip bias)* • Trunk-Tibia angle >10° • Wider stance • External band resistance around thighs *Sub-Acute Phase (progress to knee bias squat)* • Trunk-Tibia angle < -10° • Narrow/medium stance

flexion and hip internal rotation,[54,57] the hallmark movements that contribute to impingement. A toe out stance also should be considered as this will promote a greater degree of hip external rotation and gluteal activation, thereby minimizing the potential for impingment.[54,58]

LOW BACK PAIN

Hip weakness (abductors, adductors, and extensors) is a common finding in persons with low back pain.[59] As such, squatting recommendations for low back pain should aim to minimize the compressive and shear loads on the lumbar spine, while simultaneously promoting adequate hip muscle activation. However, trunk inclination should be limited to avoid excessive lumbar muscle strain. To obtain a hip bias squat with limited forward trunk lean, a wider stance width can be used. A wider stance will reduce ankle dorsiflexion,[47] which will facilitate a more favorable trunk-tibia relationship to produce a hip bias. Additionally, a wider stance during squatting reduces lumbar loading[26] and permits a more upright lumbar (less kyphosis).[60] Secondary considerations for hip bias squatting include external band resistance around the thighs to promote gluteus maximus and gluteus medius activation.[45,46]

Similar to what was described above for FAI, squat depth should be limited to avoid flexing the hip beyond the available range of motion, thereby limiting posterior pelvic tilt. That is, squat depth should be limited to a depth in which a neutral spine can be maintained. As noted above, posterior pelvic tilt is coupled with lumbar spine flexion,[37,38] resulting in compressive and shear forces occur at the lumbar spine.[14,15,39]

TIBIOFEMORAL OSTEOARTHRITIS

Osteoarthritis is the most common joint disease,[61] primarily affecting the tibiofemoral joint.[62,63] Lower-extremity strength deficits are common in patients with knee osteoarthritis,[64] highlighting the importance of appropriate squatting for overall lower extremity strength. High compressive loads in the tibiofemoral joint can worsen osteoarthritis by increasing stress/strain on internal structures (e.g., articular cartilage and menisci).[65,66] Therefore, squatting recommendations for tibiofemoral osteoarthritis should prioritize lower extremity strengthening while reducing tibiofemoral loading. Similar to PFP and ACL recommendations above, patients with tibiofemoral joint arthritis should progress from a hip bias to knee bias using the trunk-tibia relationship recommendations.

As for the tibiofemoral joint, compressive forces steadily increase when squatting from a partial to a deep position.[3,67] Since tibiofemoral contact area decreases with increasing knee flexion, contact stresses also increase.[68,69] Therefore, deep squats should be avoided. Additional considerations for hip bias squatting early in the rehabilitation process to improve gluteal activation include external band resistance around the thighs[45,46] and a wider stance.[28,29] However, tibiofemoral compressive forces during a wide squat (compared to narrow squat) are approximately 15% higher.[2]

Considerations for knee bias squatting later in the rehabilitation process include transitioning to more narrow/medium stance squats to promote greater tibial inclination[47] and a quadriceps bias. Regardless of squat type (hip vs. knee bias), outward foot rotation may need to be limited in the presence of medial compartment osteoarthritis but advised in the presence of lateral compartment osteoarthritis. An outwardly rotated foot decreases loading in the lateral compartment (by decreasing the knee valgus moment) but increases loading in the medial compartment (by increasing the knee varus moment).[21]

CONCLUSION

The squat can be a safe and effective exercise if properly executed for both rehabilitation and sport performance purposes. However, selection of specific squatting parameters requires a thorough understanding of their impact on muscle activity and joint loading. The preceding review examines these factors in detail and provides evidence to guide clinical decision making. It is important for clinicians to prescribe appropriate squatting parameters based on the individual needs of the patient to maximize the effectiveness of the exercise. Additional work is necessary to establish the appropriateness and effectiveness of squat exercise for patients with various musculoskeletal conditions. While the current review summarizes important research in this area, it should be noted that comparisons across the numerous studies cited (particularly those related to EMG) should be approached with caution owing to differences in data reduction/analysis (including normalization) and how various confounding factors were controlled.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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