

Effect of Knee Position on Hip and Knee Torques During the Barbell Squat

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ABSTRACT

Some recommendations suggest keeping the shank as vertical as possible during the barbell squat, thus keeping the knees from moving past the toes. This study examined joint kinetics occurring when forward displacement of the knees is restricted vs. when such movement is not restricted. Seven weight-trained men (mean \pm SD; age = 27.9 ± 5.2 years) were videotaped while performing 2 variations of parallel barbell squats (barbell load = body weight). Either the knees were permitted to move anteriorly past the toes (unrestricted) or a wooden barrier prevented the knees from moving anteriorly past the toes (restricted). Differences resulted between static knee and hip torques for both types of squat as well as when both squat variations were compared with each other ($p < 0.05$). For the unrestricted squat, knee torque (N·m; mean \pm SD) = 150.1 ± 50.8 and hip torque = 28.2 ± 65.0 . For the restricted squat, knee torque = 117.3 ± 34.2 and hip torque = 302.7 ± 71.2 . Restricted squats also produced more anterior lean of the trunk and shank and a greater internal angle at the knees and ankles. The squat technique used can affect the distribution of forces between the knees and hips and on the kinematic properties of the exercise. Practical applications: Although restricting forward movement of the knees may minimize stress on the knees, it is likely that forces are inappropriately transferred to the hips and low-back region. Thus, appropriate joint loading during this exercise may require the knees to move slightly past the toes.

Key Words: resistance exercise, weight training, kinetics, forces

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Introduction

The parallel squat exercise has become an important resistance-training exercise in sports training, general weight training, and physical rehabilitation (8). Although controversy exists concerning the safety of the squat exercise, the majority of research agrees that this exercise is both safe and effective if performed

correctly (5, 6, 8, 14, 15). For example, in the clinical setting, the superior efficacy of using the parallel squat vs. the commonly used knee-extension exercise has been established on several occasions (5, 23). Regarding safety, it has been suggested that improper exercise technique is one of the most important factors contributing to injury while performing the squat exercise. The knees and back appear to be most at risk of injury based on empirical reports (8). To date, only 1 scientific study has demonstrated a relationship between the squat exercise and knee instability, which could contribute to injury (13). Although these conclusions have since been repeatedly refuted (6), the parallel barbell squat exercise continues to be labeled by some as an exercise to be avoided (3).

From a biomechanical perspective, it has been reported that the forward movement of the knees during the squat exercise is associated with greater shearing forces on the knee (2). It was suggested that this knee excursion could contribute to knee injury. When national-level power lifters were studied, it was reported that, when compared with the most successful squatters, less skilled squatters had a greater tendency to lean forward, thus developing greater trunk torque (14). Furthermore, the more successful lifters also moved their knees anteriorly to a lesser extent during the squat, thus generating lower knee extensor torque (15). Although not reported, it should be noted that competitive power lifters usually utilize a low-bar barbell position (5, 11), which would influence squat kinematics and kinetics. Although trunk inclination during the squat undoubtedly contributes to trunk torque, it has been suggested that these torques are not influenced by the type of barbell squat (i.e., front or back squat) (20), although these findings have been disputed (11). What is clear is that maximal torques for the knee during a parallel squat occurs in the bottom position (i.e., greatest knee flexion), while the maximal torque for the hips occur during the second half of the concentric phase (16).

Numerous experts have suggested that proper squat technique is necessary to reduce the risk of injury to the knees and back (5, 6, 8, 14, 15). Based on

the findings of McLaughlin et al. (15), commonly accepted guidelines for proper technique when performing the squat exercise have included keeping the shin as vertical as possible in order to reduce the shear stress on the knee (5). From a practical standpoint, these guidelines suggest avoiding letting the knees travel anteriorly past the toes (8). Because no study to date has compared the magnitude of torque forces acting on the knee and hip joints when the knees travel anteriorly past the toes vs. when the knees are restricted behind the toes, the purpose of the present study was to compare the torques acting at the knee and hip joints during these 2 technique variations of the parallel barbell squat exercise.

Methods

Experimental Approach to the Problem

To compare the kinetic properties when either restricting or not restricting anterior movement of the knees during a barbell parallel squat, joint torques were determined for the knees and hips for both squat techniques.

Subjects

Recreationally weight-trained men who were currently using the high-bar parallel squat exercise volunteered for this study ($n = 7$; mean \pm SD; age = 27.9 ± 5.2 years), and provided informed consent for participation in the study. All subjects had utilized the barbell squat exercise for at least 1 year, were currently using the exercise in their training, and could lift a minimum of $1.5 \times$ body weight for the exercise.

Barbell Squat Exercise

The high-bar parallel squat consists of the barbell being placed on the superior aspect of the trapezius, while the feet are placed shoulder-width apart and are angled laterally approximately $15\text{--}30^\circ$ (5). Parallel squat depth for this study consisted of the inguinal fold at the same level as the superior aspect of the knee (11). Three unrestricted and 3 restricted high-bar squat lifts to parallel were performed by each subject. Unrestricted high-bar squat lifts consisted of a shoulder-width foot stance with no shims under the heels. In this condition, the anterior movement of the knees during the squat was unimpeded. Restricted high-bar squat lifts consisted of the same positioning and movement except that a wooden board was placed immediately distal to the first digit of both feet (see Figure 1). The wooden board, measuring 60 cm in width, restricted forward knee movement.

Data Collection

To assist in quantifying segmental and joint positions, reflective markers were placed on the base of the 5th metatarsal, the left lateral malleolus, 1 cm superior to the fibular head, the greater trochanter, and the end of

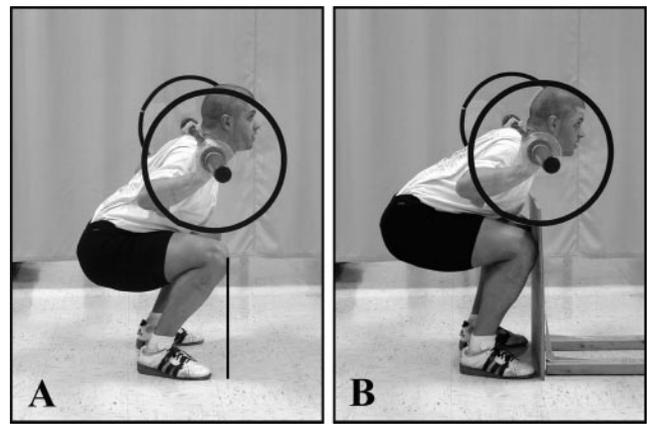


Figure 1. The 2 squat conditions used. (A) Unrestricted squat, where the knees are able to move anteriorly as far as necessary. Note the line illustrating the amount of anterior displacement of the knees relative to the toes. (B) Restricted squat, where a vertical board restricts anterior knee displacement.

the barbell. It was assumed that the end of the barbell represented the terminal end of the torso (14). Each repetition of both squat techniques was recorded on video tape. The video camera was placed 11.1 m away from the proximal end of the barbell, resulting in a sagittal view of the subjects. A Panasonic VHS movie system (Matsushita Electric Industrial Co., Okayama City, Japan) was used for data collection. Shutter speed was $1/250$, and the iris was closed to optimize visualization of the reflective markers. Additionally, a light source in direct alignment with the camera helped visualize the reflective markers. The field of view was calibrated with a meter stick both before and after each test session. Each subject was filmed for 1 set \times 3 repetitions of unrestricted and 1 set \times 3 repetitions of restricted high-bar squat lifts. One repetition from each set of squats was used for calculation purposes. The repetition chosen was based on the best overall body alignment of each subject as determined by the primary investigator.

Kinetic Analyses

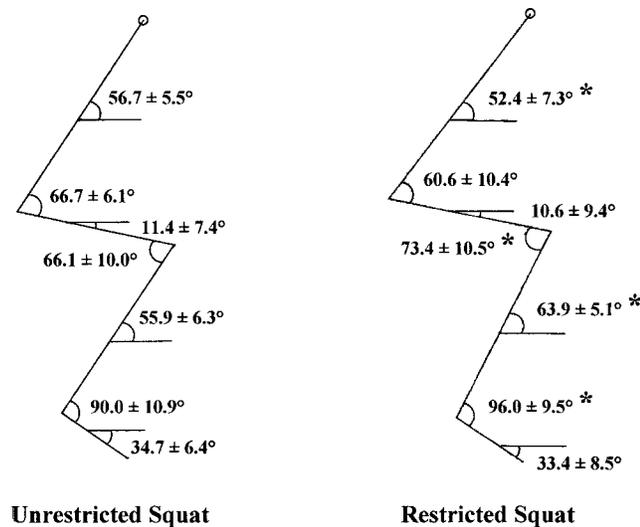
Static torque at the hip and knee (zero velocity and acceleration) was determined at the lowest position of the squat movement using the segmental dimensions of Dempster (7) and the methods described by Hamilton and Lutgens for determining kinetics using a static model (12). Segment angles relative to horizontal were determined for the trunk, thigh, shank, and foot segments and internal joint angles were determined for the hip, knee, and ankle.

Statistical Analyses

Statistical analyses were performed on the torque data with a 2×2 repeated measures analysis of variance (squat condition \times joint torque). Kinematic data were compared with dependent *t*-tests. Significance for all

Table 1. Hip and knee torques for both squat conditions (mean \pm SD).

Variable	Unrestricted	Restricted
Knee torque (N·m)	150.1 \pm 50.8	117.3 \pm 34.2*
Hip torque (N·m)	28.2 \pm 65.0**	302.7 \pm 71.2**.*

* Different from unrestricted squats ($p < 0.05$).** Different from knee torque ($p < 0.05$).**Figure 2.** Segmental angles relative to horizontal and internal joint angles for the restricted and unrestricted squat conditions (mean \pm SD). * $p < 0.05$.

analyses was $p \leq 0.05$. All data are reported as mean \pm SD.

Results

There was a significant difference between the 2 squat conditions for torques at both the hips and the knees. For both squat conditions, hip torque was significantly different from knee torque (see Table 1). The relationship between these joint torques was different for each type of squat. For the unrestricted squat, knee torque was greater than hip torque, while for the restricted squat, knee torque was less than hip torque. The restricted squat resulted in a more vertical shank and a more inclined torso when compared with an unrestricted squat. The restricted squat also exhibited less knee and ankle flexion (see Figure 2).

Discussion

The primary finding of this study was that significantly greater torque was produced at the hips and significantly less torque was produced at the knees in the restricted squat when compared with the unrestricted squat in recreationally weight-trained men. Al-

though not reported in the present study, this is certainly due to an increased moment arm at the hips in the restricted squat. This increased moment arm is due to a decreased torso angle relative to horizontal, thus maintaining the center of mass over the base of support (see Figures 1 and 2). The present study also reported a significantly greater internal angle at the ankle in the restricted squat, indicating that the shank was more upright, as has been suggested for proper squat technique (5, 8, 14). The more vertical shank, however, is accompanied by greater anterior lean of the torso, which is not reflective of highly skilled lifters who maintain a more erect posture and a greater extensor dominant thigh torque (14, 15). It has also been reported that excessive forward lean of the trunk is a common error for novice lifters performing the barbell squat (5, 8). It is likely that one cause of this technique error may be a result of the novice lifter attempting to restrict anterior movement of the knees, thus resulting in excessive forward lean of the trunk and the accompanying increase in hip torques.

Because it has been noted that lumbar shear forces increase with greater forward lean (20) and that less skillful lifters exhibited greater forward lean (14), it is important to note that the restricted squats required a smaller torso angle relative to horizontal (i.e., greater anterior lean). It thus becomes a trade-off between optimal knee positioning and optimal hip and back positioning. While it is critical to protect the knees from unnecessary forces, it is also important to avoid unnecessary forces acting at the hips. These hip forces will ultimately be transferred through the lower back and therefore must be carefully applied. The net result is that proper lifting technique must create the most optimal kinetic environment for all the joints involved. Exercise technique guidelines should not be based primarily on force characteristics for only 1 involved joint (e.g., knees) while ignoring other anatomical areas (e.g., hips and low back).

From a methodological perspective, it should be noted that, when both external and muscular forces are considered, calculations of only external forces, such as performed in the present study, will underestimate the actual forces acting at the knee (10). When knee forces during a squat are normalized for the mass of the system (i.e., body + barbell), compressive forces have ranged from 50 to 275% of the load lifted, while shear forces have ranged from 30 to 80% of the load lifted (9, 10, 16). It should also be noted that compressive knee forces of up to 8,000 N have been reported for the squat, but these values were associated with a point higher in the range of motion (74° knee flexion) than was used in the present study (2). In general, these forces become greater with increasing depth of the squat motion (9), although it is not known if this pattern continues when performing the squat through the range of motion used in the present study.

Although it is well known that shear forces also contribute to knee forces during the squat motion, it is not always appreciated that the greatest shear forces are posterior (9, 16). These shear forces, however, are well below the capacity of a healthy posterior or anterior cruciate ligament (1, 17, 19, 21). As the knees move anteriorly during the descent for the squat, the shear forces increase (2). Furthermore, the velocity of the squat motion appears to be positively related to the knee shear forces (1). An often overlooked variable is patellar compressive force, which increases with decreasing knee angle (9, 16). This compressive force is influenced by the placement of the barbell in either the high-bar position such as typically used by lifters or the low-bar position such as typically used by power lifters (11, 22). It has been suggested that the low-bar squat is used primarily for development of hip and trunk extensor strength, while the high-bar squat primarily develops quadriceps strength (10). While evidence indicates that the low-bar position would decrease anterior cruciate ligament strain, patellar compressive force, and shear forces (10), these forces are consistently well within the capacities of these structures with either bar position (17, 19, 21). While increasing the forward tilt of the torso may decrease the forces at the knee, it is likely to also increase the forces in the lumbar muscles and ligaments (4, 10, 18).

The biomechanical analysis used in this study was a static model. McLaughlin et al. (15) have shown that because the parallel squat is a relatively slow movement, a static model yields results within 10% of a dynamic model. The barbell center of mass (COM) was used as the terminus of the torso segment as suggested by McLaughlin et al. (14). Any systematic error in determining segmental positions via the barbell COM would be consistent across all subjects. It should be noted that this study did not examine the actual lumbar forces nor were loads heavier than body weight examined. As a result, greater barbell masses may alter the results. Although not measured in the present study, greater absolute loads would likely result in altered anterior torso lean, especially for the restricted squat. Further study would be necessary to determine the role of different relative loads on the kinetic and kinematic variables measured. It should also be noted that, in the present study, the head and arms were not accounted for in the calculations of COM and body segment weight; thus, the hip forces may be underestimated. The results of the present study are also limited to the type of squats described in the Methods section. Additional study would be required to determine the roles of other variations of the exercise (i.e., width of stance, foot positioning, use of heel shims or elevated heels, barbell position, depth of squat, etc.).

In summary, the results of this study indicate that, when performing a restricted squat where the knees are not permitted to move anteriorly past the toes,

greater torque is generated at the hips and less torque at the knees than when performing an unrestricted squat in recreationally weight-trained men. Although not measured in the present study, it is likely that use of greater relative loads for a restricted squat could produce excessive forces at the hips and low back. Barbell squat technique should incorporate techniques that optimize forces at all the involved joints. As such, we suggest that it is appropriate to permit forward displacement of the knees past the toes during this exercise to permit proper positioning of the torso. Obviously, this forward displacement must not be excessive, but instead should be carefully regulated to permit a mechanically sound exercise to be performed.

Practical Applications

Barbell squat exercise guidelines, including those published by the National Strength and Conditioning Association, cite the need to keep the knees from moving forward past the toes or to keep the shank as vertical as possible, when performing the exercise. However, in order to optimize the forces at all involved joints, it may be advantageous to permit the knees to move slightly past the toes when in a parallel squat position. This suggestion assumes that the individual performing the squat does not possess any pathological conditions of the involved joints such as chondromalacia, patellar tracking disorders, anterior or posterior cruciate ligament injuries, injuries of the meniscus, or related conditions. A more thorough study of knee mechanics would be necessary to determine the effect of squat technique in the presence of these conditions.

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