Journal of Orthopaedic & Sports Physical Therapy
Official Publication of the Orthopaedic and Sports Physical Therapy Sections of the American Physical Therapy Association

Patellofemoral Joint Kinetics While Squatting With and Without an External Load

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RESEARCH REPORT

Study Design: Single-group repeated measures design.
Objective: To quantify patellofemoral joint reaction forces and stress while squatting with and without an external load.
Background: Although squatting exercises in the rehabilitation setting are often executed to a relatively shallow depth in order to avoid the higher joint forces associated with increased knee flexion, objective criteria for ranges of motion have not been established.
Methods and Measures: Fifteen healthy adults performed single-repetition squats to 90° of knee flexion without an external load and with an external load (35% of the subject's body weight [BW]). Anthropometric data, three-dimensional kinematics, and ground reaction forces were used to calculate knee extensor moments (inverse dynamics approach), while a biomechanical model of the patellofemoral joint was used to quantify the patellofemoral joint reaction forces and patellofemoral joint stress. Data were analyzed during the eccentric (0–90°) and concentric (90–0°) phases of the squat maneuver.
Results: In both conditions, knee extensor moments, patellofemoral joint reaction forces, and patellofemoral joint stress increased significantly with greater knee flexion angles ($P < 0.05$). Peak patellofemoral joint force and stress was observed at 90° of knee flexion. Patellofemoral joint stress at 45°, 60°, 75°, and 90° of knee flexion during the eccentric phase, and at 75° and 90° during the concentric phase, was significantly greater in the loaded trials versus the unloaded trials.
Conclusion: The data indicate that during squatting, patellofemoral joint stress increases as the knee flexion angle increases, and that the addition of external resistance further increases patellofemoral joint stress. These findings suggest that in order to limit patellofemoral joint stress during squatting activities, clinicians should consider limiting terminal joint flexion angles and resistance loads. *J Orthop Sports Phys Ther 2002;32:141–148.*

Key Words: *biomechanics, knee, patellofemoral joint reaction force, patellofemoral joint stress*

The dynamic squat is commonly used in the clinical setting for lower-extremity strengthening. Studies have shown that this exercise effectively recruits the quadriceps, hamstrings, and gastrocnemius muscles.[5,26] Squat exercises have also been advocated for their functionality. Most daily activities (eg, walking and stair climbing) require the synchronous contraction of multiple muscle groups. Only multiple-joint movement exercises such as squatting are able to effectively recruit the necessary muscle groups within a single maneuver.[13,16]

In the rehabilitation setting, squatting exercises are often executed to relatively shallow depths (eg, 0–60° of knee flexion) to avoid the higher joint forces associated with increased ranges of motion.[1,8] This is particularly true in the treatment of patellofemoral pain, where the goal is to strengthen the knee extensors and minimize patellofemoral joint compression forces and stress.[17] Although clinicians intuitively limit squatting depth during their treatment programs, objective criteria for squatting depths based on biomechanical data have not been established.

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This research report was approved by the Institutional Review Board of the Health Science Campus at the University of Southern California. Research for this study was supported by the California Physical Therapy Fund 99-14.
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Few studies have investigated the effects of weight-bearing activities on patellofemoral joint stress. Steinkamp et al[21] compared patellofemoral joint stress while performing an isometric leg press and non–weight-bearing knee extension and reported that patellofemoral joint stress during the leg press was less than that observed during the knee extension from 0° to 48° of knee flexion.[21] Based on this finding, the authors advocate the performance of the leg press within the said range of knee angles.

Excessive joint stress has been linked to articular cartilage degradation and may contribute to knee pathologies such as osteoarthritis, chondromalacia, and patellofemoral pain.[6,7] Patellofemoral joint stress is defined as patellofemoral joint reaction force divided by area of contact between the articular surfaces of the patella and femur.[11] The patellofemoral joint reaction force, a measurement of patellar compression against the femur, is influenced by the knee angle as well as the quadriceps force.[23] Biomechanical studies of the patellofemoral joint have demonstrated that during squatting maneuvers, the patellofemoral joint reaction force is relatively minimal when the knee is extended, but increases steadily as the knee is progressively flexed.[3,5,19] The addition of an external resistance could therefore increase the patellofemoral joint reaction force and stress throughout the squatting range of motion.

Cadaveric studies have shown that patellofemoral contact area increases steadily from 0° to 60° of knee flexion, but remains fairly constant from 60° to 90° of knee flexion.[2,10,18] While squatting from 0° to 60°, increases in patellofemoral joint reaction force may be offset by increases in contact area; thereby limiting patellofemoral joint stresses within acceptable ranges. However, squatting to a depth greater than 60° may be problematic as contact area changes very little beyond this point.

The purpose of the study was to quantify patellofemoral joint reaction forces and patellofemoral joint stress while squatting with and without an external load. We hypothesized that while squatting from 0° to 90° of knee flexion, the patellofemoral joint stress would remain fairly constant from 0° to 60° and increase significantly from 60° to 90°. Furthermore, we hypothesized that the patellofemoral joint reaction force and stress would be significantly higher while squatting with an external load than while squatting without one, and that the increase in joint reaction force and stress would be proportional to the applied load. Knowledge of the magnitude of patellofemoral joint stress during squatting and how external resistance influences stress is important when prescribing rehabilitative exercise for individuals with patellofemoral pain.

METHODS

Subjects

Fifteen healthy adults (6 men, 9 women), averaging 26 ± 5 years of age, participated in this study. The average height and mass of the subjects were 171 ± 9 cm and 72 ± 16 kg, respectively. All subjects were free from orthopaedic injuries that would have limited their ability to perform the squatting techniques described below.

Instrumentation

A 6-camera motion-analysis system (Vicon 370, Oxford Metrics, Oxford, UK) was used to record three-dimensional coordinates of superficial markers placed on bony landmarks of the pelvis, thigh, shank, and foot, at a rate of 60 Hz. Bilateral ground reaction force data were collected from 2 AMTI force platforms (OR 6-6-1, Watertown, MA) at a rate of 600 Hz.

Procedures

Before participation, informed consent was obtained from each subject. The Institutional Review Board of the Health Science Campus at the University of Southern California approved all procedures. After warming up for 5 minutes on a stationary bicycle, reflective markers (1.5-cm spheres) were taped bilaterally to the first and fifth metatarsal heads, lateral malleolus, posterior calcaneus, lateral epicondyles, anterior superior iliac spines, and posterior superior iliac spines. Reflective markers attached to 5-cm wands also were taped to the lateral shank and thigh.

Each subject performed 2 to 4 practice squats. Subjects were instructed to execute the squat from a neutral position (approximately 0° of knee flexion) to a depth of approximately 110° of knee flexion while maintaining heel contact with the floor. Individual squatting maneuvers were constrained to 3 seconds in duration, measured from initiation of knee flexion through the return to full knee extension. Verbal feedback regarding both the depth and duration of the movement was provided after each practice squat. Before data collection, each subject was capable of performing the squatting maneuver within the protocol guidelines.

Testing consisted of 3 unloaded single-repetition squats followed by 3 loaded ones. Subjects placed one foot on each forceplate using a stance width consistent with their practice session (approximately shoulder width). After the comfortable standing posture was achieved, the squatting motion was initiated. In the unloaded trials, the squats were performed with the hands placed behind the head (Figure 1A).

The loaded trials used a 22-kg Olympic barbell and resistance plates positioned posteriorly across the shoulders (Figure 1B). Consistent with previous studies, resistance during the loaded trials was set at 35% of body weight (BW).[15,22]

After each trial, the squatting maneuvers were analyzed to ensure that the squat duration was approximately 3 seconds, with trials between 2.75 and 3.25 seconds considered as acceptable. Trials were repeated if the duration requirements were not met. An average of 7 attempts were required to obtain the 6 acceptable trials.

Data Reduction

The raw coordinate and force data were stored in a data file generated by the Vicon 370 software. Data-processing software (Vicon Workstation, Oxford Metrics, Oxford, UK) was used to calculate the sagittal plane knee joint angles and net knee moments.[12]

A biomechanical model of the patellofemoral joint, as previously described by Salem and Powers,[20] was used to calculate the patellofemoral joint reaction force and stress. In the model, quadriceps force was calculated as the knee extensor moment divided by the effective lever arm. The effective lever arm for the quadriceps was calculated using a nonlinear equation (effective lever arm = $8.0e^{-5}x^3 - 0.013x^2 + 0.28x + 0.046$; where x = tibiofemoral joint angle) fit to the data ($R^2 = 0.98$) of van Eijden et al.[24] Patellofemoral joint reaction force was calculated as the product of the quadriceps force and a constant, defined as the ratio of the patellofemoral joint reaction force to quadriceps tendon force. The constant was determined for each tibiofemoral joint angle by using a nonlinear equation (constant = $[-3.8e^{-5}x^2 + 1.5e^{-3}x + 0.462]/[-7.0e^{-7}x^3 + 1.6e^{-4}x^2 - 0.016x + 1]$)[29] fit to the data ($R^2 = 0.99$) of van Eijden et al.[23] Patellofemoral joint stress was then calculated as the patellofemoral joint reaction force divided by the patellofemoral contact area. Contact area was obtained from the data reported by Powers et al[18] (1.71 cm^2 at 30°; 1.95 cm^2 at 45°; 2.40 cm^2 at 60°; 2.12 cm^2 at 75°; 2.20 cm^2 at 90° of knee flexion). The same contact area was used for both loaded and unloaded conditions as previous work in our laboratory has shown that in healthy individuals, contact area

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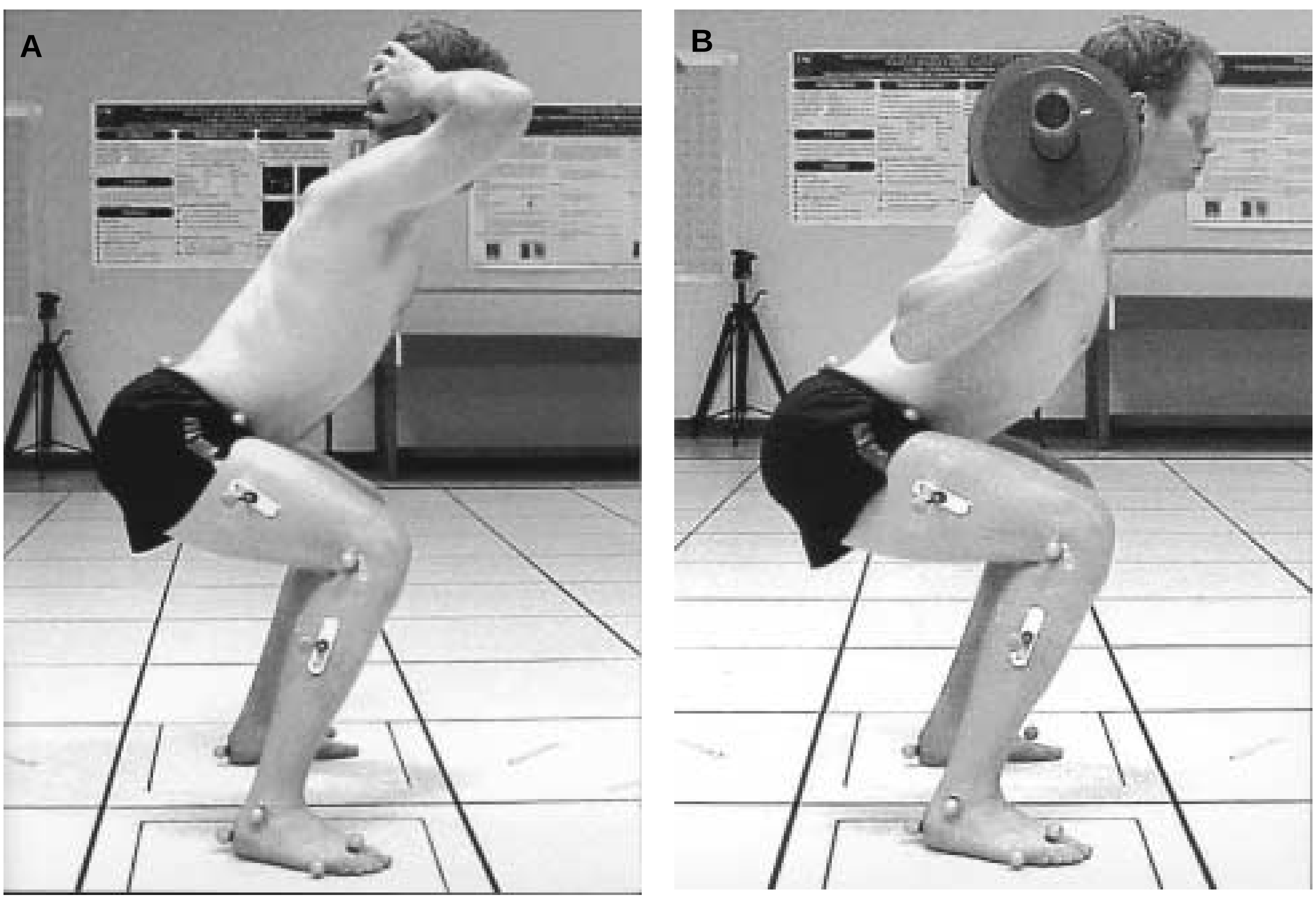

FIGURE 1. Experimental setup used to obtain kinematic and kinetic data during the performance of the squat: (A) unloaded condition and (B) loaded condition.

does not change appreciably between loaded (leg press with 25% BW resistance) and unloaded conditions.[25]

Squatting maneuvers were separated into eccentric (0–90°) and concentric (90–0°) phases. For each loading condition within each phase, kinetic data (knee extensor moment, patellofemoral joint reaction force, and patellofemoral joint stress) were averaged across the 3 trials at 5 knee flexion angles (30°, 45°, 60°, 75°, and 90°).

Statistical Analysis

A 2-way ANOVA with repeated measures was used to compare the mean value of each dependent variable (knee extensor moment, patellofemoral joint reaction force, and patellofemoral joint stress) across the 5 knee flexion angles and the 2 loading conditions. This analysis was repeated for both the eccentric and concentric phases. When significant main effects were identified, a Scheffe post hoc analysis was used to identify statistically significant differences. Though bilateral data were collected, the differences between the left and right sides were not statistically significantly different ($P > 0.05$) and therefore only data from the left side were reported. A 0.05 level of Type I error rate was used to determine statistical significance. All statistical analyses were conducted using SPSS statistical software, Version 10.0 (Chicago, IL).

RESULTS

Data from a total of 14 subjects were suitable for statistical analysis. One participant failed to reach a maximum knee flexion angle of at least 90°, so this subject's data were excluded.

Knee Extensor Moment

For the eccentric and concentric phases, statistically significant differences were evident between each knee angle during both the loaded and unloaded conditions (Figure 2). In general, knee extensor moment increased from 0 to 90° of knee flexion during the eccentric phase (Figure 2A), and decreased from 90–0° during the concentric phase (Figure 2B).

During the eccentric phase, the knee extensor moments were an average of 44% ± 2.2% greater in the loaded trials versus the unloaded trials, with statistically significant differences observed across all knee flexion angles (Figure 2A). The magnitudes of these differences were fairly uniform, ranging from 41% to 49% across all knee angles. During the concentric phase, the knee extensor moments were statistically greater in the loaded trials at 60°, 75°, and 90° of knee flexion. The magnitudes of these differences were 20%, 30%, and 39%, respectively.

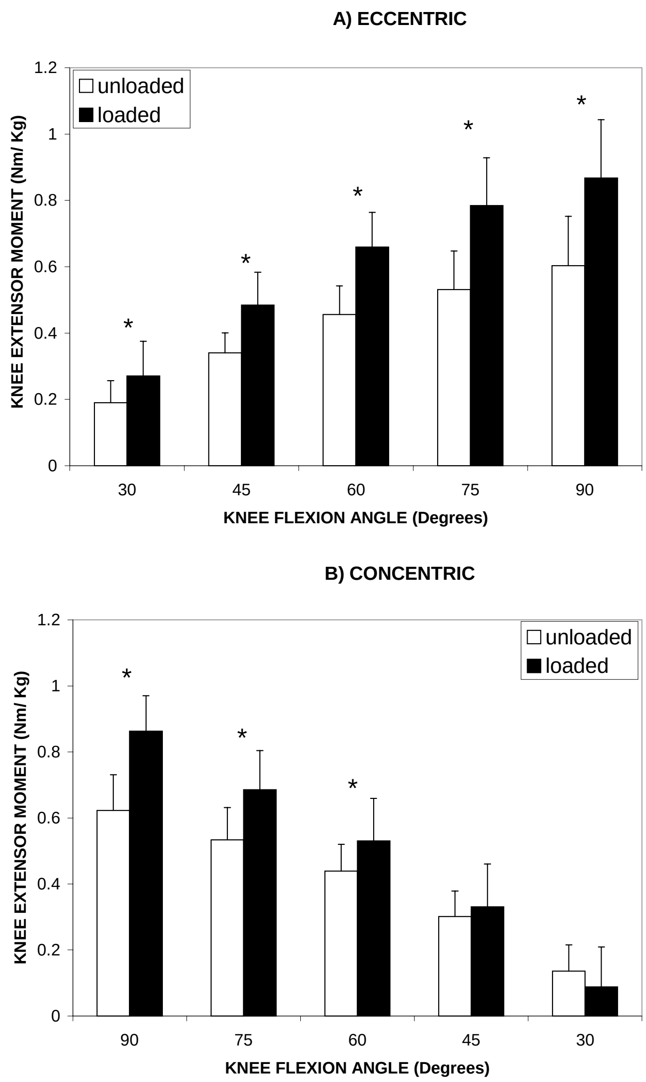

FIGURE 2. Mean loaded and unloaded knee extensor moments versus knee flexion angle during (A) eccentric phase and (B) concentric phase of the squatting maneuver. Error bars represent ± 1 SD. Significant differences were observed between each knee flexion angle for both the loaded and unloaded trials ($P < 0.05$). *Represents significant differences between the loaded versus unloaded trials for a specific knee flexion angle ($P < 0.05$).

Patellofemoral Joint Reaction Force

For the eccentric and concentric phases, statistically significant differences were observed between each knee flexion angle during both the loaded and unloaded conditions (Figure 3). The average joint reaction force during the eccentric phase increased from 30° to 90° of knee flexion, reaching peaks of 34.4 N/kg and 24.0 N/kg for the loaded and unloaded trials, respectively (Figure 3A). The joint reaction force during the concentric phase was also highest at 90° of knee flexion (34.3 N/kg, loaded; 24.7 N/kg, unloaded), and then decreased throughout the remainder of the squatting maneuver (Figure 3B).

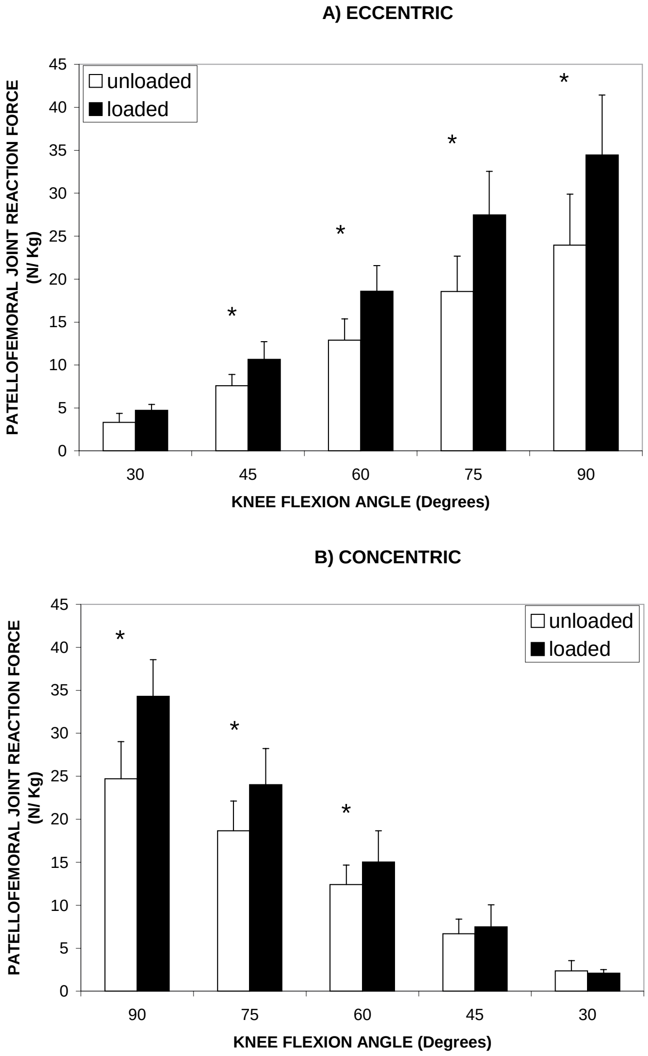

FIGURE 3. Mean loaded and unloaded patellofemoral joint reaction forces versus knee flexion angle during (A) eccentric phase and (B) concentric phase of the squatting maneuver. Error bars represent ± 1 SD. Significant differences were observed between each knee flexion angle in both the loaded and unloaded trials ($P < 0.05$). *Represents significant differences between the loaded and unloaded trials for a specific knee flexion angle ($P < 0.05$).

The patellofemoral joint reaction force during the eccentric phase was statistically greater in the loaded trials versus the unloaded trials at 45°, 60°, 75°, and 90° of knee flexion (Figure 3A). In agreement with the moment data, the average magnitude of these differences was 45% ± 2.2%. During the concentric phase, it was only at higher knee flexion angles (60°, 75°, and 90°) that the patellofemoral joint reaction force in the loaded trials was statistically greater than those observed in the unloaded trials (Figure 3B). The magnitudes of these differences were 21%, 30%, and 39%, respectively.

Patellofemoral Joint Stress

For both the eccentric and concentric phases, statistically significant differences were observed between each knee flexion angle during both loaded and unloaded trials (Figure 4). Increasing linearly from 30° to 90° of knee flexion, the stress during the eccentric phase reached peaks of 13.06 MPa (loaded) and 9.06 MPa (unloaded) (Figure 4A). The stress during the concentric phase was also highest at 90° of knee flexion (13.0 MPa, loaded; 9.3 MPa, unloaded) and then decreased linearly throughout the remainder of the phase (Figure 4B).

During the eccentric phase, the patellofemoral joint stress was statistically greater for the loaded trials versus the unloaded trials at 45°, 60°, 75°, and 90° of knee flexion (Figure 4A). The average magnitude of these differences was 45% ± 2.2%. In contrast, the patellofemoral joint stress during the concentric phase was only statistically greater in the loaded trials versus the unloaded trials at the two highest knee flexion angles, 75° and 90° (differences of 31% and 40%, respectively) (Figure 4B).

DISCUSSION

The primary hypothesis tested in this study was that patellofemoral joint stress during squatting may remain fairly constant from 0° to 60° of knee flexion, and may substantially increase from 60° to 90° of knee flexion. The results, however, indicate that patellofemoral joint stress increases linearly with increasing knee flexion angle and decreases with decreasing knee flexion angle.

The linear rise and decline in joint stress can be attributed to the angle-specific changes in both patellofemoral joint reaction force and the patellofemoral contact area. From 0° to 60° of knee flexion, patellofemoral contact area increases with increasing knee angle,[2,10,18] potentially distributing the joint reaction force over a greater area. In this study, however, patellofemoral joint stress increased linearly from 30° to 60° of knee flexion, suggesting that increases in the patellofemoral contact area were not large enough to offset the increases in the patellofemoral joint reaction force. At the higher knee flexion angles (60–90°), patellofemoral joint stress continued its linear rise. This finding was a result of the continued increase in the joint reaction force while the patellofemoral contact area remained fairly constant as previously reported.[2,10,18]

No published studies were found in our literature review that quantified patellofemoral joint stress during a squatting maneuver throughout a full arc of motion (0–90° of knee flexion). However, using a similar biomechanical model of the patellofemoral joint, Steinkamp et al[21] reported a steady increase in patellofemoral joint stress during a static leg press exercise through a comparable range of motion. Although the peak values reported by Steinkamp et al[21] (at 90° of knee flexion, 29.1 MPa for men and

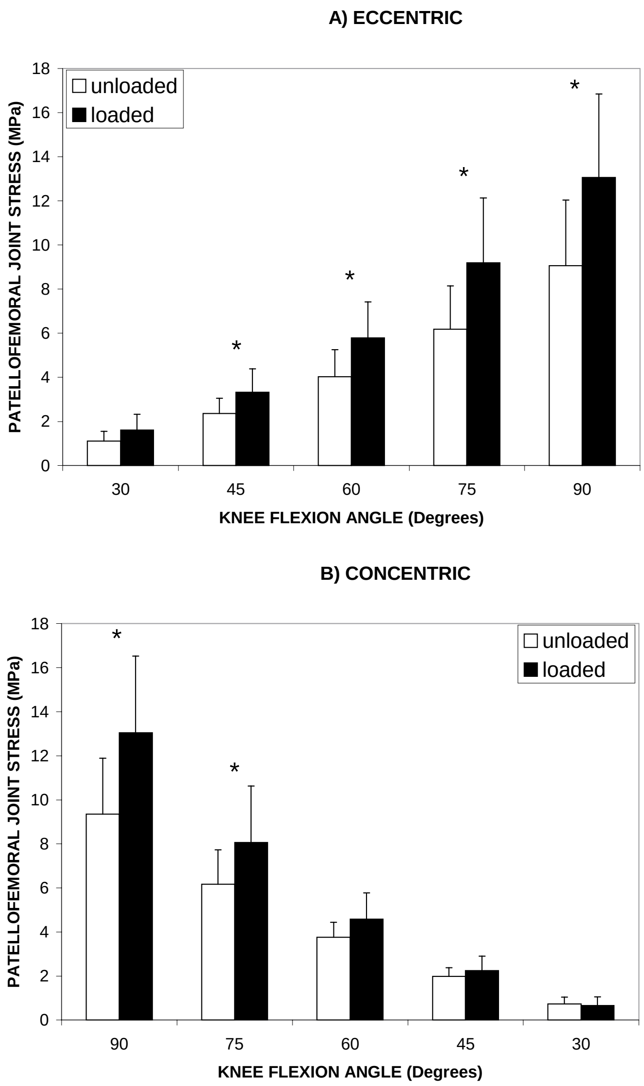

FIGURE 4. Mean loaded and unloaded patellofemoral joint stresses versus knee flexion angle during (A) eccentric phase and (B) concentric phase of the squatting maneuver. Error bars represent ± 1 SD. Significant differences were observed between each knee flexion angle in both the loaded and unloaded trials ($P < 0.05$). *Represents significant differences between the loaded and unloaded trials for a specific knee flexion angle ($P < 0.05$).

17.1 MPa for women) were much greater than those reported in the current study, the overall trend was similar, showing a linear increase of patellofemoral joint stress from 0° to 90° of knee flexion. The greater absolute values reported by Steinkamp et al[21] can be explained by the use of higher loads than those used in the present study and by the fact that the leg press exercise used in the former study has been shown to place a greater demand on the knee extensors than the squatting exercises used in the present study.[26] The results of Steinkamp et al[21] and those of the current study taken together indicate that during weight-bearing activity, patellofemoral joint stress increases with greater knee flexion angles.

As expected, the patellofemoral joint reaction force increased with increasing knee flexion angle. The increase in the joint reaction force was largely driven by the knee extensor moment, which also increased from 0° to 90° of knee flexion. Previous studies quantifying the effects of squatting on patellofemoral joint reaction forces have reported comparable results.[3,5] Although the absolute values between studies tend to vary as a result of the external loading, they show a similar trend in an increase of joint reaction force during the eccentric phase and a decrease during the concentric phase.

The second hypothesis tested in the current investigation was that squatting with an external load would result in significantly greater patellofemoral joint reaction force and stress compared to an unloaded squat, and that the increase would be proportional to the applied load. Our findings demonstrated that the application of an external resistance resulted in significantly greater patellofemoral joint reaction force and stress; however, the magnitude of the difference varied between eccentric and concentric maneuvers.

During the eccentric phase of the squat, a 35%-BW external load resulted in an average increase in patellofemoral joint stress of 44% across all knee flexion angles. The stress during the concentric phase was an average of 19% greater; however, only at the deeper knee flexion angles (75° and 90°) were significant differences observed (35.5% greater). The lack of statistical differences in patellofemoral stress at 30° and 45° during the concentric phase can be attributed to the fact that the knee extensor moment did not increase significantly at these knee flexion angles, despite the application of the external load. One explanation for this finding may be related to trunk position, as it was observed that subjects assumed a more anterior trunk posture during the concentric phase. An anterior trunk position would move the center of pressure closer to the knee joint axis, thereby decreasing the knee extensor moment. The percentage increase in patellofemoral joint stress was higher than the applied external load during the eccentric phase and somewhat lower than the applied load during the concentric phase. These findings suggest that care should be taken in solely using the external load to estimate increases in patellofemoral joint stress during this activity.

Though it has been hypothesized that elevated patellofemoral joint stress contributes to various pathologies (eg, osteoarthritis, chondromalacia),[6,7] the amount of stress necessary to constitute an injurious load to the patellofemoral joint is not known. However, in persons with patellofemoral pain, stair climbing often reproduces symptoms. To better understand this problem, researchers have characterized patellofemoral joint mechanics during stair climbing using both static biomechanical models and dynamic ones.[14,19,9] Reilly and Martens,[19] as well as Heino Brechter and Powers,[9] reported that average peak patellofemoral joint reaction forces were approximately 3.3–3.7 × BW during stair climbing. In cadaver-based estimates[14] and subject-specific measurements of contact area using MRI,[9] it has been reported that average peak patellofemoral joint stresses during stair ascent were approximately 5 to 8 MPa. This range of joint stress corresponds to the stresses observed in this study for angles above 60° of knee flexion for loaded and unloaded conditions. Therefore, when attempting to minimize patellofemoral symptom exacerbation, clinicians may consider limiting squatting depth to less than 60°. It should be recognized, however, that this recommendation is based on data obtained from healthy adults. It is possible that individuals with patellofemoral pain may experience symptoms at lesser knee flexion angles.

Though the present study provides important insights into the patellofemoral joint stress during squatting with and without loads, caution should be exercised in extrapolating these data to individuals with patellofemoral pain. It is likely that persons with pain may employ different compensatory strategies to complete squatting maneuvers when overcoming significant loads, thereby altering patellofemoral joint reaction forces and stress. For example, it has been documented that during functional tasks, persons with patellofemoral pain often decrease their knee extensor moment to minimize patellofemoral joint reaction force.[4]

One limitation of this study was the use of a model that did not compensate for the potential effects of cocontraction at the knee (ie, simultaneous hamstring or gastrocnemius activity with quadriceps activity). As a result, the absolute values for the quadriceps force and patellofemoral joint kinetics were most likely underestimated. To more closely approximate actual knee extensor forces, future studies should characterize the influence of hamstring and gastrocnemius muscle forces on patellofemoral joint force and stress.

CONCLUSION

During squatting, patellofemoral joint stress steadily increases with increasing knee flexion angle. Overall, the addition of a 35% external resistance increased the patellofemoral joint stress 44% during the eccentric phase, and 19% during the concentric phase. To limit the patellofemoral joint stress during squatting activities, clinicians should consider limiting terminal joint flexion angles and resistance loads.

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