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Brief report

Loading response following anterior cruciate ligament reconstruction during the parallel squat exercise

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Abstract

Objective. To determine if individuals 1.5–15 months post-anterior cruciate ligament reconstruction demonstrated an equal loading response on their involved and uninvolved lower extremity during a parallel squat exercise versus a control group.

Design. Four-group repeated measures design with one between-subject factor (time post-anterior cruciate ligament reconstruction) and two within-subject factors (knee angle and added weight).

Background. It has been a clinical observation that post-anterior cruciate ligament reconstruction, individuals do not place equal amounts of weight upon each lower extremity during double-leg exercises.

Methods. Twenty-four subjects were in each of the experimental groups, 1.5–4 months, 6–7 months, and 12–15 months post-anterior cruciate ligament reconstruction, while 24 subjects without history of lower extremity pathology/injury served as the control group. Pedar™ in-shoe sensors were placed inside the subjects' shoes to record loading response patterns during the exercises. All performed 3 sets of 9 randomized squats to each of the three knee flexion angles (30°, 60°, and 90°) with the three different weights (20.45 kg bar only, 35%, and 50% body mass) using a Smith squat rack ™. A three-way repeated measures ANOVA ($P < 0.050$) was used to compare the differences between groups in loading response statically between the uninvolved and involved lower extremity for each of the different weights at each knee flexion angle during the squat exercise.

Results. The three-way repeated measures ANOVA revealed that there was a significant group effect ($P < 0.001$). Thus, the amount of time post-anterior cruciate ligament reconstruction affected the difference in the subjects' loading response for the uninvolved and involved lower extremities. There was also a three-way interaction, indicating that the difference in loading response was dependent on the group, amount of knee flexion, and amount of added weight ($P = 0.010$).

Conclusion. These data suggest that subjects significantly load their uninvolved lower extremity until 12–15 months post-anterior cruciate ligament reconstruction.

Relevance

Based on the results of this study, caution may be warranted when adding resistance during the parallel squat for an individual's first year post-anterior cruciate ligament reconstruction, particularly with less knee flexion to avoid compensation and injury.

Keywords: Anterior cruciate ligament; Weight bearing; Rehabilitation; Knee surgery; Plantar loading

1. Introduction

Strength, balance, proprioception, and range of motion are all reduced in the involved lower extremity (LE) post-anterior cruciate ligament (ACL) reconstruction, and all are factors that play a role in equivalent loading patterns during rehabilitation exercises. It has been a clinical observation that post-ACL reconstruction individuals do not place equal amounts of weight upon each LE during double-leg exercises. Therefore, the purpose of this study was to determine if three groups of subjects between 1.5 and 15 months post-ACL reconstruction demonstrate unequal loading responses on their involved and uninvolved LE during the parallel squat exercise compared to a healthy control group. The squat was chosen since it is a safe and functional exercise [1,2].

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It was assumed that equivalent loading responses were needed for full, safe return to activities of daily living and functional activities. To date, no reports have described loading responses during the parallel squat at different time intervals post-ACL reconstruction.

2. Methods

2.1. Subjects

Three experimental groups plus a control group were established; each group consisted of 24 participants. The three groups were comprised of current or previous patients and were placed into the following groups based on the time post-ACL reconstruction: 1.5–4 months (7 females, 17 males, mean age 28.75 years (SD, 9.12 years), mean mass 79.18 kg (SD, 5.91 kg)), 6–7 months (11 females, 13 males, mean age 24.67 years (SD, 9.41 years), mean mass 84.27 kg (SD, 6.09 kg)), and 12–15 months (11 females, 13 males, mean age 27.46 years (SD, 9.42 years), mean mass 77.50 kg (SD, 6.27 kg)). The control group was without known significant history of LE injury (i.e., knee ligamentous injury, fracture, dislocation) or pathology (10 females, 14 males, mean age 24.38 years (SD, 3.84 years), mean mass 81.15kg (SD, 6.11 kg).

The subjects in each group who had patellar tendon autografts were as follows: 1.5–4 months ($n = 13$), 6–7 months ($n = 12$), and 12–15 months ($n = 16$). The remaining subjects in each group had quadruple-strand hamstring/gracilis autografts. The subjects had no previous history of LE surgery or fracture, nor had suffered a significant injury (other than ACL reconstruction) during the past 2 years. All subjects had full active and passive knee range-of-motion equivalent to their uninjured knee.

2.2. Testing procedure

Prior to data collection, each subject's body mass (BM) was measured. Subjects were then asked to warm-up, prior to testing, for 10 min at a self-selected level on a FITRON™ stationary exercise bicycle (Cybex Inc., Owatanna, MN, USA). Before the testing session, subjects were provided with standardized verbal instructions and a demonstration of the parallel squat. Pedar™ in-shoe sensors were placed inside the subjects' shoes to record their loading forces. The Novel Pedar system™ (Novel Electronics Inc., St. Paul, MN, USA) consists of sensor insoles sized to either men's or women's shoes. Each sensor insole was 2 mm in thickness and contained a matrix of 99 capacitive sensors that directly measured the pressure at the foot-to-shoe interface. Each sensor had an effective area of approximately 1 cm^2 and sensor data were collected at a rate of 50 Hz. Two hundred samples were collected, and the means for bilateral peak force measurements were analyzed during weight bearing at each static testing position. The Novel Pedar in-shoe sensor system was used since it is portable, is a reliable plantar pressure measurement device, and can be externally calibrated in a pressure chamber throughout the measurement range [3–6].

Subjects were instructed to take a "comfortable" shoulder-width stance under the Smith squat rack™ (CYBEX International Inc., Medway, MA, USA), assuming a position that, when squatting, kept their knees posterior to the position of their toes. Subjects were advised to place their feet "in a position of comfort" since it has been recommended by Anderson et al. [7] that an assumption of a comfortable foot placement provides the greatest stability and safety for execution of the squat exercise. Placing tape on the floor medial and posterior to each foot ensured consistent foot placement for each subject. Before testing, a zero measurement was obtained with the Novel Pedar system by having each subject unload one LE at a time. The subject then performed a partial parallel squat, with the bar on their shoulders, from 0° to 90° of knee flexion. An examiner positioned a goniometer to the subject's knee and when 30°, 60°, and 90° of knee flexion was reached, the examiner marked the side of the Smith squat rack™ with tape. The subjects then performed a randomized set of three parallel squats, each at the knee flexion angles of 30°, 60°, and 90° and each with three different weights. The three added weights that subjects lifted were a 20.45 kg bar, 35% and 50% of their BM. An average of three plantar loading measurements were obtained statically at each knee flexion angle (30°, 60°, 90°) and weight lifted (20.45 kg bar, 35%, 50% of their BM).

The desired weight (±1.36 kg) was added to the 20.45 kg bar using iron plates. The squat exercise was repeated three times at each of the added weights before the bar was placed back on the rack. To avoid fatigue, subjects were provided a 6 s rest between each parallel squat and a 1 min rest between each set. Data were gathered from subjects during a single testing session.

2.3. Data analysis

Statistical analysis was performed using SPSS 8.0. A three-way repeated measures ANOVA with an alpha-level of 0.05 was used to compare differences in loading response between the uninvolved and involved LE for each of the different added weights at the various knee flexion angles. Bonferoni post-hoc tests were then performed.

3. Results

The three-way repeated measures ANOVA revealed that there was a significant group effect ($P < 0.001$) (Table 1). This indicated that the amount of time post-

Table 1
Three-way ANOVA with repeated measures analysis of differences in loading response for knee flexion angle and added weight between groups[a]

Source of variation	Sum of squares	Df	Mean square	F	P
Group	102737.06	3	34245.68	22.91	0.00 (S)
Error (Group)	137497.83		1494.54		
Added weight	1952.03	2	976.01	2.21	0.11 (NS)
Error (Added weight)	81337.71	184	442.05		
Knee flexion angle	84.74	2	42.37	0.06	0.94 (NS)
Group*Knee flexion angle	3548.83	6	591.47	0.84	0.54 (NS)
Error (Knee flexion angle)	129588.63	184	704.28		
Added weight*Knee flexion angle	1288.72	4	322.18	1.26	0.28 (NS)
Group*Added weight*Knee flexion angle	6757.73	12	563.14	2.20	0.01 (S)
Error (Added weight*Knee flexion angle)	94109.22	368	255.73		

S denotes significant difference; NS denotes non-significant difference.
[a] control, 1.5–4, 6–7, and 12–15 months post-ACL reconstruction.

ACL reconstruction significantly affected the difference in the subjects' loading response. The difference in loading response for the subjects in the control group ranged from 5% to 6% BM across all knee flexion angles and added weights. The difference in loading response as a percentage of BM for the uninvolved and involved LEs ranged from 33% to 48% for the 1.5–4 months and from 21% to 28% for the 6–7 months post-ACL reconstruction groups across all knee flexion angles and added weights. The injured–uninjured difference in loading response for the 12–15 months group ranged from 7% to 9% across all knee flexion angles and added weights.

Subjects 1.5–4 months post-ACL reconstruction showed significantly greater loading response differences with parallel squat exercises across all knee flexion angles and added weights compared to the 12–15 months post-ACL reconstruction ($P < 0.001$) and control groups ($P < 0.001$). Subjects 6–7 months post-ACL reconstruction showed significantly greater loading response differences with parallel squat exercises across all knee flexion angles and added weights compared to the 12–15 months post-ACL reconstruction ($P = 0.001$) and control group ($P < 0.001$). Subjects 12–15 months post-ACL reconstruction did not significantly differ in the loading response during the parallel squat exercise for all knee flexion angles and added weights compared to the control group ($P = 1.000$). A trend of greater differences in loading response were found with the most recent post-ACL reconstruction groups.

4. Discussion

This study clearly demonstrates a difference in loading patterns between lower extremities during the parallel squat exercise post-ACL reconstruction until one-year post surgery. If loading response patters are altered in subjects up to 12 months post-ACL reconstruction, the benefits of accelerated rehabilitation programs should also be questioned. Accelerated rehabilitation programs are designed to return the patient to full sports participation 4–6 months post-ACL reconstruction [8,9]. If patients are not demonstrating equal LE loading (secondary to strength, balance and/or proprioception deficits or lack of autograft maturity), but have returned to full-sports participation, they may be predisposed to re-injury.

The greatest loading differences between the uninvolved and involved LE were found in the 1.5–4 months post-ACL reconstruction group at 30° of knee flexion with the added weight of 50% BM. It is interesting that this position of 30° of knee flexion also happens to be a position of increased shear on the ACL during the parallel squat exercise as reported by several authors [1,10,11]. In the present study, the greatest loading difference between lower extremities was found with the greater added weight. This finding relates to the findings of Markolf et al. [12]. Markolf et al. [12] examined the shear forces in ACL-deficient cadaver knees and reported that greater amount of anterior tibial shear occurred with higher levels of applied force. Based on results of the present study, caution may be warranted when adding resistance during the parallel squat for patient's post-ACL reconstruction, particularly with less knee flexion to avoid compensation and injury.

There were several limitations of this study. First, the same subjects were not used for all of the testing dates due to time constraints. Instead, a cross-sectional research design was used to examine loading differences at various time post-ACL reconstruction. A second limitation was that the loading response was measured at a static position (specific joint angle) during the parallel squat rather than dynamically throughout the range of motion. Another limitation of this study was that two different grafts were used for the subjects' ACL reconstruction, patellar tendon autografts and quadruple-strand hamstring/gracilis autografts. Despite the fact that several biomechanical and outcome studies have confirmed comparable strength characteristics and surgical results between these two different grafts [13–15]. These factors may have caused variability within each subject group.

The analysis of loading response during functional activities such as the parallel squat may be of benefit to include as part of re-evaluation and discharge testing criteria and biofeedback training. This analysis and feedback may be performed with the assistance of two force plates, in-shoe sensors, or even a simpler means such as a bathroom scale under each foot. These testing devices need to be further researched to determine their reliability, validity, and merit in rehabilitation protocols. Therapists may consider the use of biofeedback training with mirrors and single-leg exercises as an attempt to stimulate knee joint mechanoreceptors for improving balance, proprioception, and strength. Minimizing loading differences of the LEs during rehabilitation exercises may carry over to decreased differences in loading response during functional activities and prevent re-injury. However, prevention of injury by minimizing differences in loading response has not been demonstrated. Subsequent research is also needed to determine if indeed differences in loading responses correlate with functional ability. If a correlation is found, further research addressing the changes in the location of the center of pressure on the foot as one moves into deeper squatting positions may be appropriate. This could provide an alternate explanation for the differences in loading observed at 30° of knee flexion and the potential strain on the ACL. Further research regarding the differences in strength of the involved and uninvolved LE during various exercises compared to the differences in loading response may also be beneficial. If there is a strong relationship, strength assessment may be an easier means of evaluating differences in loading response.

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