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Asymmetric ground reaction forces and knee kinematics during squat after anterior cruciate ligament (ACL) reconstruction

Brooke A. Sanford [a,*], John L. Williams [b], Audrey Zucker-Levin [c], William M. Mihalko [a]

[a] Campbell Clinic Department of Orthopaedics and Biomedical Engineering, University of Tennessee Health Science Center, Memphis, TN 38163, USA
[b] Department of Biomedical Engineering, University of Memphis, Memphis, TN 38152, USA
[c] Physical Therapy Department, University of Tennessee Health Science Center, Memphis, TN 38163, USA

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ABSTRACT

Background: This bilateral squat study tests whether people with anterior cruciate ligament (ACL) reconstruction have symmetric three-dimensional ground reaction forces (GRFs) and symmetric anterior–posterior (AP) translation rates of the femur with respect to the tibia when compared with healthy control subjects. We hypothesized that there would be no long-term asymmetry in knee kinematics and kinetics in ACL reconstructed subjects following surgery and rehabilitation.
Methods: Position and GRF data were collected on eight ACL reconstructed and eight control subjects during bilateral squat. The rate of relative AP translation was determined for each subject. Principal component models were developed for each of the three GRF waveforms. Principal component scores were used to assess symmetry within the ACL reconstructed group and within the control group.
Results: ACL reconstructed knees analyzed in early flexion during squat descent displayed a four-fold greater rate of change in anterior translation in the reconstructed knee relative to the contralateral side than did a similar comparison of normal knees. Differences were found between the ACL reconstructed subjects' injured and uninjured limbs for all GRFs.
Conclusions: Subjects following ACL reconstruction had asymmetric GRFs and relative rates of AP translation at an average of seven years after ACL reconstructive surgery when compared with control subjects.
Clinical Relevance: These alterations in loading may lead to altered load distributions across the knee joint and may put some subjects at risk for future complications such as osteoarthritis.

1. Introduction

The bilateral squat is a multiple-joint exercise commonly performed during post-operative anterior cruciate ligament (ACL) rehabilitation programs for gaining lower extremity strength and control [1,2]. Proper execution of a squat requires control of the body's center of mass by coordinating the extensor moments at the hip, knee, and ankle joints. During bilateral activities, such as the squat, patients may utilize intra-limb substitution patterns in order to shift effort from a targeted muscle group (such as the knee extensors) to a different muscle group (such as the hip extensors) or exhibit inter-limb substitution patterns by shifting the effort from the injured limb to the uninjured limb [2].

The bilateral squat has been used to assess knee kinematics and kinetics in subjects after ACL reconstruction [2,3]. Salem et al. reported the ratio of peak hip extensor moment to peak knee extensor moment to be different for the ACL reconstructed limb compared with the contralateral limb [2]. Castanharo et al. found that ACL reconstructed males had a hip–knee joint power ratio on the operated side that was greater than that of the contralateral side [3]. The ACL group had a deficit in the operated knee that had its joint power partially substituted by the hip joint power of the same side. These studies have focused on intra-limb substitution patterns by analyzing sagittal plane peak joint moments and powers at the knee and hip.

Image-based methods have been used to study asymmetry in tibiofemoral kinematics in subjects following ACL reconstruction surgery during a quasi-static bilateral squat [4]. Asymmetry following ACL reconstruction has also been investigated in jumping and landing [5–7]. These studies describe differences in lower limb movement patterns between ACL reconstructed and non-injured limbs, but do not utilize a symmetry index. Also, these are high-demand activities, more appropriate for young otherwise healthy and athletic subjects, which could potentially put older less athletic subjects at risk for injury. A review of commonly used outcome measures for ACL surgery and post-operative rehabilitation listed walking, running, jumping and hopping as activities that can be objectively assessed to develop a knee rating score, whereas squatting was considered as a subjective outcome measure, along with cutting, pivoting, and ability to decelerate

* Corresponding author.
E-mail addresses: bsanford@uthsc.edu (B.A. Sanford), john.williams@memphis.edu (J.L. Williams), azuckerl@uthsc.edu (A. Zucker-Levin), wmihalko@campbellclinic.com (W.M. Mihalko).

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[8]. Informative and objective measures of a bilateral squat could be useful additions to the functional outcome assessment tests, especially if these can help distinguish specific abnormalities and underlying causes of asymmetry which could impair performance in sports or work.

The bilateral squat (without a resistance weight) is a low-demand activity that allows assessment of lower limb symmetry, as the legs are expected to move and support the body in unison, as opposed to gait where a cyclic symmetry is expected. Three-dimensional motion capture technology allows measurement of both tibiofemoral kinematics and forces. In addition, a bilateral squat allows the relative rate of antero-posterior (AP) translation to be measured since the knees are flexing in unison. Assessing the relative AP translation of the femur with respect to the tibia is of interest since the native ACL provides primary anterior stability necessary for normal knee function. The ACL also provides stability in both the frontal and transverse planes, but motion of the femur in these directions is not analyzed since these are secondary functions of the ACL.

In this study we use principal component analysis (PCA) as a dimension reduction method to explore differences between ACL reconstructed subjects' and control subjects' ground reaction forces during squatting. PCA is a multivariate statistical method of data analysis that transforms a set of chosen variables that may be correlated with one another into a set of uncorrelated variables called principal components. PCA enables the comparison of entire waveforms rather than just discrete values at specific time points or events. PCA has been used previously to analyze the vertical ground reaction force (GRF) in order to discriminate between normal and abnormal gait [9].

Our null hypothesis was that there would be no long-term asymmetry in knee anterior–posterior translation or the GRF in the vertical, medial–lateral, or anterior–posterior direction in ACL reconstructed subjects following surgery and rehabilitation. We designed a bilateral squat study to test whether ACL reconstructed subjects have symmetric three-dimensional ground reaction forces as assessed using PCA and symmetric AP translation rates of the femur with respect to the tibia when compared with healthy control subjects.

2. Methods

Sixteen subjects participated in this investigation. Eight (three males and five females) ACL reconstructed individuals were compared with eight (three males and five females) healthy uninjured height- and weight-matched control subjects. The mean body weight, height, and age of the ACL reconstructed subjects were 73.3 kg (SD 16.0 kg), 1.71 m (SD 0.08 m), and 28 years (SD 7 years). The ACL reconstructed subjects had sustained an isolated unilateral ACL tear during sports activity and were surgically reconstructed with bone-patellar tendon–bone graft more than seven months prior to testing (mean 7.2 years, SD 6.3 years). These subjects had a normal contralateral knee and were cleared by their orthopedist to participate in unrestricted activity by the time of testing. The mean body weight, height, and age of control subjects were 66.9 kg (SD 14.5 kg), 1.73 m (SD 0.09 m), and 25 years (SD 4 years). Control subjects had no history of lower extremity infirmity or pathology that may have affected the ability to perform the activity.

Institutional review board approval of this study was granted, and informed consent was obtained prior to testing. The testing protocol was the same for both groups. Prior to testing, retro-reflective markers were placed over bony landmarks of the pelvis and lower extremities, and rigid arrays of four markers were attached to the thighs and shanks using elastic wrap (Fig. 1). The subjects were tested performing a bilateral squat. Each subject stood barefoot with feet shoulder width apart with each foot on different force plates (AMTI, Watertown, MA, USA). Subjects were asked to keep the torso as upright as possible and to perform continuous bilateral squats to a comfortable level of knee flexion with arms held straight out in front of the chest. Each subject was allowed to squat at a self-selected pace for an interval of 25 s for two trials of data collection.

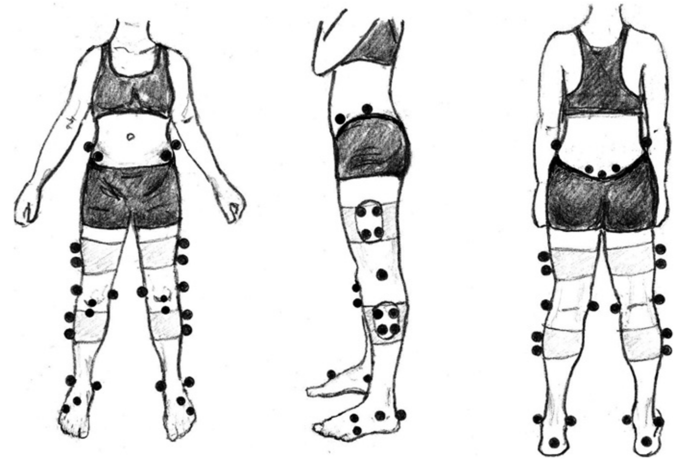

Figure 1. Marker placement. Marker setup showing markers on the pelvis and lower extremities.

A nine camera video-based opto-electronic system (Qualisys AB, Gothenburg, Sweden) was used for 3D motion capture as subjects performed squats. All movement data were collected at 100 Hz, interpolated over a maximum of 10 frames, and low-pass filtered at seven hertz using a fourth-order Butterworth digital filter. The ground reaction force data were collected at 1000 Hz and no filtering was applied.

Relative rate of AP translation at the knee was measured using an approach based on a previously described method [10] for the squat. Similar measurements using bone landmarks and sagittal plane fluoroscopy rather than motion capture of skin mounted targets confirmed the results of the earlier motion capture study lending some support to the marker based approach for measuring AP translation [11]. Markers placed over the inferior pole of the patella, tibial tubercle, and lateral malleolus allowed calculation of AP translation (femur with respect to tibia) in the sagittal plane relative to the uninjured knee. In the control subjects, relative AP translation was chosen as right relative to left or left relative to right based on which measure more closely paralleled the ACL reconstructed subjects. The AP translation data were averaged over multiple cycles for each subject and re-sampled to 101 values corresponding to 0–100% of the squat cycle. The relative AP translation was measured at 10 degree increments of knee flexion starting at 10 degrees up to 50 degrees flexion. Finally, data were normalized so that relative AP translation was zero for each subject at 10 degrees knee flexion. The rate of change of relative translation of the femur on the tibia over each 10 degree increment of knee flexion was calculated for each subject. The rate with the maximum magnitude, retaining sign, was determined for each subject and averaged for the two groups, ACL reconstructed and controls.

Results were compared using Student's paired t-tests assuming unequal variance. The knee flexion angle range of 10–50° was chosen due to subject variability of the maximum and minimum knee flexion angles achieved during squatting. Subjects were asked to perform the squat to a comfortable level of knee flexion. Therefore, both the maximum and minimum values of knee flexion differed between subjects.

The three-dimensional GRFs were averaged over multiple squat trials (range of 6 to 9 squats) for each subject and resampled to 101 values corresponding to 0–100% of the squat cycle. Separate principal component (PC) models were developed for the AP GRF, medial–lateral (ML) GRF, and the vertical GRF waveforms. The posterior, medial, and upward GRFs were defined as positive values. PC scores were generated for each averaged GRF waveform from each limb segment of all subjects and used to assess symmetry within the ACL reconstructed group and within the control group. In short, PC scores measure the contribution of the principal components to each individual waveform and