Knee Biomechanics during a Jump-Cut Maneuver: Effects of Sex and ACL Surgery

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1Department of Orthopaedics, The Warren Alpert Medical School, Brown University and Rhode Island Hospital, Providence, RI; 2Center for Biomedical Engineering, Brown University, Providence, RI; 3Department of Surgery, The Warren Alpert Medical School, Brown University, Providence, RI; 4Biostatistics, Rhode Island Hospital, Providence, RI; and 5School of Engineering, Brown University, Providence, RI

ABSTRACT

MIRANDA, D. L., P. D. FADALE, M. J. HULSTYN, R. M. SHALVOY, J. T. MACHAN, and B. C. FLEMING. Knee Biomechanics during a Jump-Cut Maneuver: Effects of Sex and ACL Surgery. Med. Sci. Sports Exerc., Vol. 45, No. 5, pp. 942–951, 2013. Purpose: The purpose of this study was to compare kinetic and knee kinematic measurements from male and female anterior cruciate ligament (ACL)–intact (ACLINT) and ACL-reconstructed (ACLREC) subjects during a jump-cut maneuver using biplanar videoradiography. Methods: Twenty subjects were recruited; 10 ACLINT (5 men and 5 women) and 10 ACLREC (4 men and 6 women, 5 yr postsurgery). Each subject performed a jump-cut maneuver by landing on a single leg and performing a 45° side-step cut. Ground reaction force (GRF) was measured by a force plate and expressed relative to body weight. Six-degree-of-freedom knee kinematics were determined from a biplanar videoradiography system and an optical motion capture system. Results: ACLINT female subjects landed with a larger peak vertical GRF (P < 0.001) compared with ACLINT male subjects. ACLINT subjects landed with a larger peak vertical GRF (P ≤ 0.036) compared with ACLREC subjects. Regardless of ACL reconstruction status, female subjects underwent less knee flexion angle excursion (P = 0.002) and had an increased average rate of anterior tibial translation (0.05%ms−1 ± 0.01%ms−1, P = 0.037) after contact compared with male subjects. Furthermore, ACLREC subjects had a lower rate of anterior tibial translation compared with ACLINT subjects (0.05%ms−1 ± 0.01%ms−1, P = 0.035). Finally, no striking differences were observed in other knee motion parameters. Conclusion: Women permit a smaller amount of knee flexion angle excursion during a jump-cut maneuver, resulting in a larger peak vertical GRF and increased rate of anterior tibial translation. Notably, ACLREC subjects also perform the jump cut maneuver with lower GRF than ACLINT subjects 5 yr postsurgery. This study proposes a causal sequence whereby increased landing stiffness (larger peak vertical GRF combined with less knee flexion angle excursion) leads to an increased rate of anterior tibial translation while performing a jump-cut maneuver. Key Words: KINEMATICS, KINETICS, LANDING STIFFNESS, GROUND REACTION FORCE, ANTERIOR TIBIAL TRANSLATION, BIPLANAR VIDEORADIOGRAPHY

Injuries to the anterior cruciate ligament (ACL) are commonly associated with sport maneuvers involving jumping, landing, and cutting (16). These maneuvers result in a sudden loading of the ACL due to the deceleration of the tibia that occurs after landing but just before a rapid direction change (17). Approximately 70% of ACL injuries occur during deceleration maneuvers without contact from another athlete (23). Although men experience noncontact deceleration injury, women are reported to be up to 10 times more prone when participating in the same high-risk activities (19). Although many theories exist, the ACL failure mechanism and the associated sex bias remain unclear.

During normal function, the ACL restrains excessive anterior tibial translation and stabilizes secondary knee rotations (i.e., internal/external (IN/EX) and abduction/adduction) (22). ACL reconstruction has become the gold standard of treatment for athletes with an ACL tear in an attempt to restore joint stability and to return patients to a high functional level (13). Unfortunately, of the 400,000 patients that undergo ACL reconstruction in the United States each year, up to 5% are at risk for reinjury (40), 45% fail to return to their preinjury sport level (5), and 80% to 90% will develop radiographic evidence of osteoarthritis even as early as 7 yr postsurgery (20).

Given the unexplained greater risk of noncontact deceleration ACL injury in female subjects, any differences between sex and ACL reconstruction status in the kinematic and kinetic factors during associated sport activities may point to root causes for injury, reinjury, and avenues for prevention and rehabilitation. Unfortunately, the biomechanics of male and female ACL-intact (ACLINT) and ACL-reconstructed...
(ACL$_{REC}$) knees during high-risk noncontact deceleration activities, such as a jump-cut maneuver, are not well understood. These data have previously been difficult to obtain, in part, because noninvasive measurement of kinematics has been limited to optical motion capture (OMC), which depend on surface markers that are prone to artifact from soft tissue oscillation immediately after landing (24).

Biplanar videoradiography, however, allows for direct measurement of in vivo bone motion, circumventing the effect of soft tissue artifact (14,28,29,33,34,36,37). Biplanar videoradiography has recently been used to study dynamic ACL$_{INT}$ and ACL$_{REC}$ knee motion during running (33,34), two-legged drop landings (28,29,36,37), and single-leg hopping (14). Although these studies have made significant contributions to our understanding of both ACL$_{INT}$ and ACL$_{REC}$ knee function during running, drop landing, and hopping, the combined jump-cut maneuver, which is more commonly associated with noncontact deceleration ACL injury, has not been investigated (15,17). In addition, the biomechanics of ACL$_{REC}$ subjects during these other dynamic tasks were investigated between 4 and 12 months after surgery (14,33,34). Although these time points are crucial for quantifying the immediate effects of ACL reconstruction, understanding the biomechanics of the knee more than 5 yr after surgery may provide further insight into the long-term recovery process.

The purpose of this study was to compare force plate kinetic data and knee kinematic measurements from male and female ACL$_{INT}$ and ACL$_{REC}$ recreational athletes during a jump-cut maneuver in hopes that the differences would point to plausible risk factors for injury. Knee kinematic measurements were primarily obtained from biplanar videoradiography; however, knee flexion/extension (FL/EX) outside the field of view (FOV) of the biplanar videoradiography system was obtained from traditional OMC. The specific aims were to determine differences due to both sex and ACL reconstruction status between ACL$_{REC}$ patients, who were at least 5 yr postsurgery, and ACL$_{INT}$ control subjects. More specifically, it was anticipated that ACL$_{INT}$ women would tend to perform the jump-cut maneuver more upright with more landing stiffness than ACL$_{INT}$ men. This would be evident as decreased knee flexion angle excursion and increased peak ground reaction force (GRF), relative to their body weight, resulting in greater tibial translation (particularly anterior). In contrast, it was not known whether or not ACL$_{REC}$ females and males 5 yr postreconstruction would follow a similar pattern or if their injury and subsequent repair and rehabilitation would have resulted in altered kinetic and kinematic parameters (tested as an interaction between sex and ACL reconstruction status).

**METHODS**

**Subjects.** All experimental procedures were approved by the institutional review board. Twenty recreational athletes were enrolled in this study. Of these subjects, 10 were ACL$_{INT}$ (5 males and 5 females) and 10 were ACL$_{REC}$ (4 males and 6 females; seven bone-patellar tendon-bone autografts and three hamstring tendon autografts). Age, weight, and height for all subjects are displayed in Table 1. The inclusion criteria for the ACL$_{INT}$ subjects were as follows: 1) no history of lower extremity injury, 2) no neurological disease(s), 3) no pregnancy, and 4) a Tegner activity score of 5 or greater (35). It should be noted that the ACL$_{INT}$ subjects were part of a separate study investigating the effects of soft tissue artifact on kinematic outcomes during a combined jump-cut maneuver (24). The inclusion criteria for the ACL$_{REC}$ patients were as follows: 1) unilateral ACL reconstruction using bone-patellar tendon-bone or four-stranded hamstring tendon autograft (looped semitendinosus and gracilis), 2) at least 5 yr of post-ACL reconstruction, 3) no systemic infection, 4) no neurological disease(s), 5) no pregnancy, and 6) a Tegner activity score of 5 or greater. The ACL reconstruction surgery type was confirmed from patient records. After granting their informed consent, each subject was outfitted with 23 retroreflective surface markers on a single leg to permit measurement of foot, shank, and thigh motion using OMC (10). The outfitted leg was chosen at random for the ACL$_{INT}$ subjects (6L and 4R). For the ACL$_{REC}$ subjects, the ACL reconstructed leg was outfitted (7L and 3R).

**Jump-cut maneuver.** Each subject performed a jump-cut maneuver that was adapted from the study of Ford et al. (15) and previously described in detail (24). Briefly, three targets were placed on the floor within the testing environment (Fig. 1A). The first target was in the center of a force plate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ACL Status</th>
<th>Mean</th>
<th>SEM</th>
<th>P</th>
<th>Sex</th>
<th>Mean</th>
<th>SEM</th>
<th>P</th>
<th>Interaction</th>
<th>Mean</th>
<th>SEM</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>ACL$_{INT}$</td>
<td>25.20</td>
<td>1.64</td>
<td>0.464</td>
<td>M</td>
<td>27.53</td>
<td>1.74</td>
<td>0.235</td>
<td>INT × M</td>
<td>25.80</td>
<td>2.32</td>
<td>0.481</td>
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<tr>
<td>ACL$_{REC}$</td>
<td>26.96</td>
<td>1.87</td>
<td>F</td>
<td>24.63</td>
<td>1.57</td>
<td>REC × M</td>
<td>29.25</td>
<td>2.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>ACL$_{INT}$</td>
<td>73.16</td>
<td>2.93</td>
<td>0.242</td>
<td>M</td>
<td>84.88</td>
<td>3.11</td>
<td>-0.001</td>
<td>INT × M</td>
<td>81.53</td>
<td>4.15</td>
<td>0.617</td>
</tr>
<tr>
<td>ACL$_{REC}$</td>
<td>78.26</td>
<td>2.99</td>
<td>M</td>
<td>66.55</td>
<td>2.81</td>
<td>REC × M</td>
<td>88.49</td>
<td>4.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>ACL$_{INT}$</td>
<td>172.85</td>
<td>2.09</td>
<td>0.736</td>
<td>M</td>
<td>178.70</td>
<td>2.21</td>
<td>0.003</td>
<td>INT × M</td>
<td>177.40</td>
<td>2.95</td>
<td>0.605</td>
</tr>
<tr>
<td>ACL$_{REC}$</td>
<td>173.88</td>
<td>2.13</td>
<td>F</td>
<td>168.03</td>
<td>2.00</td>
<td>REC × M</td>
<td>180.00</td>
<td>3.30</td>
<td></td>
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</tr>
</tbody>
</table>

A two-way ANOVA was performed on each set of demographics data, and no statistically significant differences ($P \leq 0.05$) were found between sex and condition. Statistically significant differences ($P \leq 0.05$) are in boldface.
(Kistler model 9281B, Amherst, NY). The other two targets were placed toward the left and right of the landing target at an angle of 45°. Before beginning the maneuver, the subject was asked to stand approximately 1 m from the force plate with their knees bent approximately 45°. Upon hearing a verbal “GO” prompt, the subject jumped upward and forward toward the first landing target. At the same time as the verbal “GO” prompt, a visual directional prompt, left (L) or right (R), cued the subject to which direction to cut after landing on the target with one leg. Upon landing, the subject performed a sidestep cut and then jogged past the respective angled targets. For example, if a subject was prompted to cut to the left, they would land, cut, and push off with their right leg. A trial was excluded if the subject incorrectly performed the jump-cut maneuver (landing outside the target area, incorrect cut direction, crossover cut, etc.). A total of 10 correctly executed trials were performed, and the subject was unaware of the directional prompt before a given trial.

Data collection and processing. The jump-cut maneuvers were carried out, and kinetic and kinematic data were gathered in the W.M. Keck Foundation XROMM Facility at Brown University (Providence, RI; http://www.xromm.org). A four-camera OMC system (Qualisys Oqus 5, Gothenburg, Sweden) was used to track the retroreflective surface markers (10-mm diameter) on each subject’s outfitted leg during the entire jump-cut maneuver at a capture rate of 250 Hz. A force plate (Kistler model 9281B) was used to measure the GRF at 5000 Hz. The biplanar videoradiography system was engaged for a maximum of six trials and measured motion at 250 Hz within a restricted FOV above the force plate (26). This was done to reduce radiation exposure and maximize the likelihood that the jump-cut maneuver occurred within the FOV of the biplanar videoradiography system. All devices were time synchronized. Image dedistortion and 3-D space calibration followed established protocols using custom MATLAB software (XrayProject, Brown University; http://www.xromm.org) (9).

In addition, a single static clinical computed tomography (CT) scan was collected for each subject’s outfitted knee. Image volumes were captured in the axial plane at 80 kVp while using GE’s SMART mA and Bone Plus reconstruction algorithms. The voxel resolution (slice thickness and in-plane resolution) for each scan was less than 0.625 × 0.465 × 0.465 mm³. The voxels corresponding to the femur and tibia were isolated from each CT volume using previously described methods (25) implemented in commercially available image segmentation software (Mimics v14; Materialise, Ann Arbor, MI).

Custom markerless tracking software (Autoscooper, Brown University; http://www.xromm.org) was used to process the biplanar videoradiography data (26). Briefly, isolated CT volumes for the femur and tibia were input into a virtual 3-D environment containing the biplanar videoradiography sequences and their calibration information. Digitally reconstructed radiographs (DRR) were generated from the CT volumes, and the kinematic transforms from CT space to each radiograph frame were determined after optimally matching the DRR with the two views from the biplanar videoradiography system (Fig. 1B). It has previously been shown that in vivo bone motion can be determined within 0.25 mm and 0.25° using these methods (7,26). Furthermore, the rotational and translational tracking precision for this study was estimated at 0.08° and 0.45 mm, respectively.

The retroreflective marker data from the OMC system were filtered using a digital low-pass Butterworth filter with a cutoff frequency of 25 Hz. The kinematic transforms of the femur and tibia obtained from the biplanar videoradiography system were converted into quaternions. A quaternion is represented by four parameters that can be filtered (12). A digital Butterworth filter with a 25-Hz cutoff frequency was applied to the three kinematic translation...
parameters and the four quaternion parameters. The filtered quaternion parameters were converted back to rotation matrices and recombined with the filtered kinematic translations. The GRF data was filtered using a digital Butterworth filter with a 100-Hz cutoff frequency.

**Data analysis.** For comparison between subjects, the vertical GRF was normalized by body weight. A characteristic peak (Fig. 2A) was observed in the vertical GRF within the first 25 ms. This peak vertical GRF was quantified by its time after contact (peak vertical GRF time) and its magnitude (peak vertical GRF magnitude).

The kinematics of the tibia with respect to the femur were described for both OMC and biplanar videoradiography data sets using two independent anatomical coordinate systems (ACS). These ACSs were determined from the 3-D CT models of the femur and tibia using previously described methods (25). To use the same ACS for both OMC and biplanar videoradiography, their global coordinate spaces were coregistered using a rigid lattice containing spherical markers that were radioopaque and retroreflective (24). The mean and SD for the root mean square fit error of the coregistration transform was $0.31 \pm 0.09 \text{ mm}$.

Knee joint rotations in FL/EX, adduction/abduction (AD/AB), and IN/EX rotations of the tibia relative to the femur were interpreted using the method described by Grood and Suntay (18). Joint translations in medial/lateral (ME/LA) and anterior/posterior (AN/PO) displacements of the tibia relative to the femur were determined by a vector originating at the origin of femoral ACS and terminating at the origin of the tibial ACS (14). The ME/LA and AN/PO translations were normalized for each subject according to the ME/LA or AN/PO width of their tibial plateau, similar to the method reported by Tanifuji et al. (32). These translations are interpreted as percentage ME/LA or AN/PO tibial plateau length. Normalization was performed to make kinematic evaluations on individuals of different sizes.

Because of the limited FOV of the biplanar videoradiography system, the joint rotations and translations were time normalized from 16 ms before contact to 60 ms after contact. This window was selected because it was common to all subjects for at least one trial. For comparison, all joint rotations and translations were zeroed at contact and interpreted as excursion. The average rate and maximum rate of AN/PO excursion was determined for each subject. Average rate was calculated as the total range divided by the change in time, and the maximum rate was calculated as the maximum time derivative. In addition, the area under the curve (AUC), which simplifies time-series curve comparisons, was calculated for each time-series kinematic excursion trace by integrating the signal with respect to time.

The FOV of the OMC system is significantly larger than that of the biplanar videoradiography system, permitting the measurement of knee FL/EX angle outside the period containing the biplanar videoradiography data. Despite the

![Graphs](https://example.com/graphs)

**Figure 2**—A, ACL\textsubscript{INT} vertical GRF. B, ACL\textsubscript{REC} vertical GRF. Each subject's GRF was normalized by their respective weight. Thus, vertical GRF units are in body weights. Notice the highlighted peak in the ACL\textsubscript{INT} vertical GRF graph. All curves are displayed as mean $\pm$ 1 SD. The vertical line on each graph represents the time at contact. C, ACL\textsubscript{INT} AN/PO translational excursion. D, ACL\textsubscript{REC} AN/PO translational excursion. Anterior is positive and posterior is negative. All AN/PO translations were normalized for each subject by their respective tibial plateau width. Thus, translational units are defined as a percentage of the total tibial width in the anterior–posterior direction. It should be noted that the AN/PO translational excursion data were obtained from the biplanar videoradiography system.
soft tissue artifact observed in secondary rotations (AD/AB and IN/EX rotation) and translations (ME/LA and AN/PO) obtained from OMC, FL/EX remains relatively unaffected (24). Using the OMC data, the minimum flexion angle after contact was determined. In addition, the change from minimum flexion angle to maximum flexion angle after contact was calculated and interpreted as excursion. The OMC data were presented for only knee joint FL/EX. The biplanar videoradiography data are presented for all other kinematic parameters (AD/AB and IN/EX rotations, ME/LA and AN/PO translations).

The described kinematic and GRF outcomes were determined for each applicable subject trial, and then all trials were ensemble averaged for each subject. Comparisons between sex (M and F) and ACL reconstruction status (ACL_\text{INT} and ACL_\text{REC}) were made for all kinematic and kinetic variables using two-way ANOVA. These tests were performed with a significance level (alpha) of 0.05. Pairwise multiple comparisons were made using the Holm–Sidak method when a significant sex and ACL reconstruction status interaction was determined. The Holm–Sidak method maintains alpha at 0.05 across a set of hypothesis tests and adjusts \( P \) values differently depending on their values ranked against each other. This is effective at maintaining alpha and avoiding beta inflation.

**RESULTS**

A statistically significant interaction (\( P = 0.003 \)) between sex and ACL reconstruction status was observed for the peak vertical GRF (Fig. 2). Within the ACL_\text{INT} subjects, the females had a peak vertical GRF that was 1.45 body weights larger than the male subjects (\( P < 0.001 \)). In contrast, the ACL_\text{REC} male and female subjects had nearly equal peak vertical GRF. The ACL_\text{REC} male subjects’ peak vertical GRF was 0.22 body weights larger than the female ACL_\text{REC} subjects but was not statistically significant (\( P = 0.522 \)). When comparing within ACL reconstruction status, both the male and female ACL_\text{INT} subjects had a larger peak vertical GRF than the male and female ACL_\text{REC} subjects, respectively. The male ACL_\text{INT} subjects’ peak vertical GRF were 0.80 body weights larger than the male ACL_\text{REC} subjects (\( P = 0.036 \)), and the female ACL_\text{INT} subjects’ peak vertical GRF were 2.46 body weights larger than the female ACL_\text{REC} subjects (\( P < 0.001 \)).

The peak vertical GRF for the female subjects occurred 6.24 ms earlier than the male subjects (\( P = 0.021 \)). The interaction between sex and ACL reconstruction status approached but was not statistically significant (\( P = 0.117 \)); the peak vertical GRF for the female ACL_\text{REC} subjects occurred only 2.21 ms before the male ACL_\text{REC} subjects. Conversely, the peak vertical GRF for the female ACL_\text{INT} subjects occurred 10.27 ms before the male ACL_\text{INT} subjects. Moreover, the peak vertical GRF appears to occur earlier in ACL_\text{INT} subjects than ACL_\text{REC} subjects (4.80 ms, \( P = 0.066 \)).

The average rate of AN/PO translational excursion (Fig. 2) was 0.05%ms\(^{-1}\) larger for ACL_\text{INT} subjects compared with ACL_\text{REC} subjects (\( P = 0.035 \)) and 0.05%ms\(^{-1}\) larger for female subjects compared with male subjects (\( P = 0.037 \)). The maximum rate of AN/PO translational excursion was 0.13%ms\(^{-1}\) larger in female ACL_\text{REC} subjects as compared with male ACL_\text{INT} subjects; however, the difference between sexes in ACL_\text{REC} subjects was only 0.01%ms\(^{-1}\). Pairwise multiple comparisons revealed that maximum AN/PO translational excursion rate differences were significant for males versus females within ACL_\text{INT} subjects (\( P = 0.027 \)) and for ACL_\text{INT} versus ACL_\text{REC} within female (\( P = 0.007 \)). In addition, the AUC of the AN/PO translational excursion was observed to be 55%ms larger for ACL_\text{INT} subjects than ACL_\text{REC} subjects (\( P = 0.180 \)). The AUC for the female subjects was also larger than the AUC for the male subjects (64%ms, \( P = 0.122 \)). No significant interaction between sex and ACL reconstruction status was observed (\( P = 0.961 \)). However, the AUC of the AN/PO translational excursion was observed to be 66%ms larger for female ACL_\text{INT} subjects than for male ACL_\text{INT} subjects, and the AUC for the female ACL_\text{REC} subjects was also larger than the AUC for the male ACL_\text{REC} subjects (62.1%ms). These AN/PO translational kinematic data were determined from the biplanar videoradiography system.

The AD/AB rotational excursion (Fig. 3) was relatively constant after contact, changing less than 2° for both male and female ACL_\text{REC} and ACL_\text{INT} subjects. Despite the minimal rotational change after contact, the female subjects were abducting (valgus) slightly after contact, whereas the male subjects were adducting (varus) slightly after contact (the average female abduction excursion was equal to 1.02° and the average male adduction excursion was equal to 1.07°, \( P = 0.033 \)). The IN/EX rotational excursion (Fig. 3) for all subjects followed a consistent pattern. Specifically, the male and female ACL_\text{INT} and ACL_\text{REC} subjects all began internally rotating after contact. Although no statistically significant differences were observed in any group, the ACL_\text{INT} male and female subjects had a 76°ms larger AUC than the ACL_\text{REC} male and female subjects (\( P = 0.171 \)). These AD/AB and IN/EX rotational kinematic data were determined from the biplanar videoradiography system.

The minimum flexion angle occurred at or immediately after ground contact. After this, all of the subjects absorbed the landing and continued the cut by flexing through stance phase to a maximum flexion angle. Using the OMC data to quantify the minimum flexion angle, maximum flexion angle, and the flexion angle excursion (change from minimum to maximum flexion angle), we observed that females tended to be more flexed at contact (\( P = 0.054 \)), but their total excursion was significantly less (\( P = 0.002 \)) (Fig. 4). These FL/EX kinematic data were determined from the OMC system.

We have included the following data as supplemental digital content to provide contextual reference for the above results: 1) the knee angles (in degrees) at contact and peak vertical GRF for knee FL/EX, AD/AB, and IN/EX obtained...
from OMC and biplanar videoradiography (see Table A, Supplemental Digital Content 1, http://links.lww.com/MSS/A242); 2) the peak AN/PO and ME/LA knee translations in millimeters and their respective time points in milliseconds (see Table B, Supplemental Digital Content 2, http://links.lww.com/MSS/A243); and 3) the AN/PO and ME/LA knee translation excursions in millimeters (see Table C, Supplemental Digital Content 3, http://links.lww.com/MSS/A244).

**DISCUSSION**

We have compared knee kinematic and kinetic measurements from male and female ACL\_INT and ACL\_REC recreational athletes during a jump-cut maneuver associated with noncontact deceleration ACL injury. Two major findings were observed in our study. First, female subjects who have never had an ACL reconstruction appeared to perform the jump-cut maneuver with greater landing stiffness (smaller amount of knee flexion angle excursion combined with larger peak vertical GRF [28]) than males with or without a history of ACL reconstruction and other females with a history of ACL reconstruction. This was evidenced by the differences observed in the knee flexion angle excursion, which translated to qualitatively comparable differences in peak vertical GRF. Second, the male and female ACL\_REC subjects appear to perform the jump-cut maneuver with less energy than the ACL\_INT subjects, resulting in a lower peak vertical GRF even 5 yr or more after their reconstruction. This may be a result of differences in strength, confidence, habit, and/or training after their injury.

These kinetic differences likely influence the differences observed in the rate of anterior tibial translation after contact, which is a common instigator of ACL injury. Specifically, we observed that anterior tibial translation increased at a faster...
rate in female ACL
subjects compared with their male ACL
counterparts (Fig. 2). Notably, peak anterior tibial translation for the ACL
female subjects occurred within 60 ms. A similar peak was not observed in the male ACL
subjects or the male and female ACL
subjects. Interestingly, the time-to-peak vertical GRF was significantly less in female subjects as compared with male subjects. Also, the time-to-peak vertical GRF appears to be smaller in ACL
subjects as compared with ACL
subjects. The increased rate of anterior tibial translation observed in female ACL
subjects is likely a result of the larger and more rapid peak vertical GRF observed immediately after ground contact. This rapid and large peak vertical GRF appears to produce a “snapping” motion that differs from the more gradual increase in peak vertical GRF and anterior tibial translation observed in male ACL
subjects and male and female ACL
subjects. It may be that there is a reliable tendency for females to absorb less energy upon landing, which, through greater peak vertical GRF, resultant forces, and/or abnormal kinematics, may increase the risk for ACL injury.

Previous research has suggested that increased landing stiffness, as characterized by a smaller amount of knee flexion angle excursion combined with a high vertical GRF during landing and cutting activities, place individuals at increased risk of ACL injury (6,8,11). Attempts have been made to correlate increased landing stiffness with increased anterior tibial translation with the goal of developing knee injury prevention training and rehabilitation programs (28). During the jump-cut maneuver in our study, the female subjects landed and cut with less knee flexion angle excursion after contact. This result, when interpreted in the context of the faster and larger peak vertical GRF, confirms that the females are performing the jump-cut maneuver with more landing stiffness. This finding is in contrast to the observations made for the male subjects, who appear to be absorbing the energy they are applying at ground contact by flexing through the landing and subsequent cut. Moreover, the AN/PO translation never reached a maximum (within 60 ms after contact) and increased at a lower rate after contact for the male ACL
subjects and male and female ACL
subjects. This combination of increased knee flexion angle excursion and/or reduced peak vertical GRF (decreased landing stiffness) may contribute to the slower time-to-peak anterior tibial translation after contact for these subjects.

In a similar study investigating the knee kinematics of ACL
females during four functional tasks, Myers et al. (29) observed that anterior tibial translation was increased in activities of increasing external loading. Specifically, they observed a 2.4-mm increase in anterior tibial translation during landing maneuvers as compared with walking. Moreover, their results show the same characteristic peak vertical GRF immediately after ground contact during the landing tasks. This peak is absent in the vertical GRF walking trace. Conversely, another study by Myers et al. (28) showed no differences in anterior tibial translation between soft and stiff drop landings. The authors attributed these findings to the ability of the ligaments and musculature about the knee to keep joint translations within a safe envelope of motion during controlled activities where external loading conditions are anticipated. Although no excessive rotational or translation motion was observed in our study, the increased rate of anterior translation in female ACL
subjects suggests that stiffer landings under more unanticipated cutting activities may affect kinematic translations more than controlled, anticipated activities. Furthermore, the lower rate of anterior tibial translation seen in the ACL
subjects immediately after contact may be influenced by the lower peak vertical GRF.

This low peak vertical GRF observed in both male and female ACL
subjects matches results from Paterno et al. (30,31) and Vairo et al. (38). In two separate studies, Paterno et al. showed ACL
male and female subjects decreased peak vertical GRF when performing landing activities 2 yr after reconstruction. Vairo et al. reported decreased vertical peak GRF upon landing from a vertical drop among ACL
subjects approximately 2 yr postsurgery. These results are consistent with those reported in our study for ACL
men and women who are at least 5 yr postreconstruction. In addition, no sex differences were observed in the peak GRF within ACL
subjects. Even after 5 yr of strengthening activities, including formal rehabilitation, functional exercise, and return to sports, the ACL
subjects performed the jump-cut maneuver with less energy compared with the ACL
subjects. Although the exact mechanisms for this are unknown, it is possible that both behavioral and neuromechanical deficiencies are present in the ACL
subjects when performing jump-cut maneuvers on their previously injured limb. Alternatively, it is possible that the altered mechanics are a result of protective habits obtained during the ACL
subjects’ rehabilitation. Additional research investigating neuromuscular activity and contralateral biomechanics may provide additional insight into the reduced vertical GRF observed in both male and female ACL
subjects.

In addition to the larger peak vertical GRF and rate of anterior tibial translation, the female subjects were generally abducting after contact (Figs. 3A–B). This is an interesting finding because videographic studies have suggested that a valgus (abduction) collapse is involved in the noncontact deceleration ACL injury mechanism (21). Furthermore, the results presented herein are consistent with previous reports suggesting that females land with more knee abduction compared with males (15). Although the female subjects in our study were abducting after contact compared with the male subjects, the total amount of abduction (<2°) does not seem to correspond to a valgus collapse position. This may be a result of the subjects’ ability to safely perform the jump-cut maneuver, which was implemented in our study to challenge the ACL. A valgus collapse position was not observed, neither were any adverse events (injury).

No significant differences were observed between sex and ACL reconstruction status for both IN/EX rotation or ME/LA translation after contact (Table 2). In general, all
subjects began internally rotating after contact and remained stable in the ME/LA direction. With exception to the sex difference observed in AD/AB angle, the similar kinematic outcomes observed between sex and ACL reconstruction status after contact do not support our hypothesis. Deneweth et al. (14) showed that, as compared with the ACL\_INT contralateral knees, ACL\_REC knees were more externally rotated and less laterally translated during a single-leg hopped landing. Unfortunately, obtaining contralateral limb kinematics was not feasible for our study. This makes direct comparisons difficult; however, Deneweth et al. does report total IN/EX excursion to be approximately 5° and total ME/LA translation to be less than 1 mm for both reconstructed and contralateral knees. These excursion values align with the results presented in our study.

Despite the kinematic similarities, additional research investigating surface interactions between the medial and lateral compartments of the knee may provide more specific insight into subtle kinematic differences between both sex and ACL reconstruction status. Specifically, methods have been developed to identify distance-weighted proximity centroids, regions of closest proximity (1), and point-based surface velocities (2,3). These techniques take advantage of the accuracy associated with biplanar videoradiography to make inferences about biomechanical changes at the articulating surfaces of the femur and tibia with the hope of better understanding.

**TABLE 2.** ACL\_INT and ACL\_REC male and female kinematic AUC, rate, and peak vertical GRF results.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>ACL_INT</th>
<th>ACL_REC</th>
<th>Sex</th>
<th>Mean</th>
<th>SEM</th>
<th>P</th>
<th>Interaction</th>
<th>Mean</th>
<th>SEM</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADAB excursion AUC (°/ms)</td>
<td>−5.18</td>
<td>11.57</td>
<td>F</td>
<td>19.65</td>
<td>13.16</td>
<td>0.033</td>
<td>INT × M</td>
<td>25.88</td>
<td>9.43</td>
<td>0.415</td>
</tr>
<tr>
<td>INEX excursion AUC (°/ms)</td>
<td>76.59</td>
<td>10.59</td>
<td>F</td>
<td>49.04</td>
<td>30.88</td>
<td></td>
<td>REC × F</td>
<td>6.86</td>
<td>45.61</td>
<td>0.505</td>
</tr>
<tr>
<td>MELA excursion AUC (mm/ms)</td>
<td>6.56</td>
<td>−20.57</td>
<td>F</td>
<td>3.34</td>
<td>12.11</td>
<td></td>
<td>REC × F</td>
<td>19.97</td>
<td>17.92</td>
<td>0.739</td>
</tr>
<tr>
<td>ANPO excursion AUC (mm/ms)</td>
<td>303.85</td>
<td>248.96</td>
<td>F</td>
<td>308.42</td>
<td>26.25</td>
<td></td>
<td>REC × F</td>
<td>270.85</td>
<td>38.77</td>
<td>0.961</td>
</tr>
<tr>
<td>ANPO average rate (%/ms)</td>
<td>0.22</td>
<td>0.22</td>
<td>F</td>
<td>0.22</td>
<td>0.01</td>
<td></td>
<td>REC × M</td>
<td>0.18</td>
<td>0.02</td>
<td>0.213</td>
</tr>
<tr>
<td>ANPO maximum rate (%/ms)</td>
<td>0.39</td>
<td>0.30</td>
<td>F</td>
<td>0.37</td>
<td>0.03</td>
<td></td>
<td>REC × M</td>
<td>0.30</td>
<td>0.04</td>
<td>0.887</td>
</tr>
<tr>
<td>Peak vertical GRF**</td>
<td>1.53</td>
<td>3.16</td>
<td>F</td>
<td>2.65</td>
<td>0.16</td>
<td></td>
<td>REC × M</td>
<td>1.64</td>
<td>0.26</td>
<td>0.003</td>
</tr>
</tbody>
</table>

A two-way ANOVA was performed on each set of data. Statistically significant differences (P ≤ 0.05) are in boldface Roman. Near statistical significance (P < 0.10) is in boldface italics. Pairwise comparisons were made using the Holm–Sidak method when a significant (or near significant) sex and ACL reconstruction status interaction was determined. These results, denoted by the * or **, are given as footnotes. The data presented in the parentheses (ME/LA and ANPO AUC, ANPO rates) are the raw translational values in millimeters. Finally, it should be noted that the kinetic data presented in this table were obtained from the biplanar videoradiography system.

**MvF in I: P < 0.027; MvF in R: P = 0.863; lVf in M: P = 0.751; lVf in F: P = 0.007.
**MvF in I: P < 0.001; MvF in R: P = 0.522; lVf in M: P = 0.036; lVf in F: P < 0.001
understanding the initiation and progression of osteoarthritis in ACLREC individuals (4).

As investigators, we are limited to studying potential injury mechanisms in a laboratory testing environment without many of the situations presented in a sporting environment. Our study investigated male and female ACLINT and ACLREC subjects while they performed an activity in a controlled laboratory setting that has been associated with noncontact deceleration ACL injury. The incorporation of the “unanticipated” element to the jump-cut maneuver mimicked the deceleration and cutting action associated with many sporting events. Despite the design, studies that use bipolaran videoradiography will be hindered by the inability to capture subjects performing sports activities in their native environments.

We acknowledge the small sample size for investigating kinematic and kinetic interactions between sex and ACL reconstruction status. Although we did ensure that all subjects were recreational athletes, we were not able to control for surgeon or rehabilitation protocol for the ACLREC subjects. In addition, we recognize the limitation of using two different graft types in our study. Based on biomechanical studies (34,39) and randomized clinical trials (27), we assumed that both bone-patellar tendon-bone and four-stranded hamstring tendon grafts would respond similarly during the jump-cut maneuver studied herein but recognized this as a study limitation.

Limitations associated with bipolaran videoradiography should be noted. Specifically, the FOV restricted our ability to capture kinematic data for all subjects from 16 ms before contact to 60 ms after contact. Previous research has shown that peak anterior tibial translation occurs between 40 and 50 ms after contact (37), within the temporal range studied. Finally, each subject received up to 22 mrem of radiation exposure as a result of the bipolaran videoradiography system and CT scan. Although this falls well below the guidelines instituted by the National Institutes of Health Radiation Safety Committee for acceptable radiation exposure to research subjects within a year (5 rem), it does limit the number of data collection trials. All subjects were aware of and gave informed consent to radiation exposure.

In conclusion, the results presented in our study support our hypothesis that kinematic and kinetic differences would be observed between both sex and ACL reconstruction status during a jump-cut maneuver. Specifically, we found that female ACLINT subjects landed and cut with a smaller amount of knee flexion angle excursion and larger peak vertical GRF than the male ACLINT subjects. Furthermore, we observed that the ACLREC subjects had a significantly lower peak vertical GRF just after impact as compared with the ACLINT subjects. We also noted that female ACLINT subjects appear to have an increased rate of anterior tibial translation just after contact. Our study associates the increased rate of anterior tibial translation to increased landing stiffness (larger peak vertical GRF combined with smaller knee flexion angle excursion) while performing the jump-cut maneuver. With respect to AD/AB, IN/EX rotation, and ME/LA translation, differences were only observed AD/AB angle. The female subjects in our study were abducting after contact compared with the male subjects; however, the amount of abduction does not appear to correspond to a valgus collapse position. Finally, no significant interactions were found between sex and ACL reconstruction status for IN/EX rotation or ME/LA translation after contact.

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The authors declare no conflict of interest.

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REFERENCES

KNEE BIOMECHANICS DURING A JUMP-CUT MANEUVER


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