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Knee biomechanics during a jump-cut maneuver: Effects of gender & ACL surgery

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Abstract

Purpose—The purpose of this study was to compare kinetic and knee kinematic measurements from male and female ACL-intact (ACL_{INT}) and ACL-reconstructed (ACL_{REC}) subjects during a jump-cut maneuver using biplanar videoradiography.

Methods—Twenty subjects were recruited; 10 ACL_{INT} (5 males, 5 females) and 10 ACL_{REC} (4 males, 6 females; five years post surgery). Each subject performed a jump-cut maneuver by landing on a single leg and performing a 45° side-step cut. Ground reaction force 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—ACL_{INT} female subjects landed with a larger peak vertical GRF ($p<0.001$) compared to ACL_{INT} male subjects. ACL_{INT} subjects landed with a larger peak vertical GRF ($p \leq 0.036$) compared to ACL_{REC} 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±0.01%/millisecond; $p=0.037$) after contact compared to male subjects. Furthermore, ACL_{REC} subjects had a lower rate of anterior tibial translation compared to ACL_{INT} subjects (0.05±0.01%/millisecond; $p=0.035$). 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, ACL_{REC} subjects also perform the jump cut maneuver with lower GRF than ACL_{INT} subjects five years post surgery. 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.

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CONFLICT OF INTEREST

None.

Keywords

kinematics; kinetics; landing stiffness; ground reaction force; anterior tibial translation; biplanar videoradiography

INTRODUCTION

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 prior to a rapid direction change (17). Approximately 70% of ACL injuries occur during deceleration maneuvers without contact from another athlete (23). Although males suffer non-contact deceleration injury, females are reported to be up to ten times more prone when participating in the same high-risk activities (19). Although many theories exist, the ACL failure mechanism and the associated gender bias remain unclear.

During normal function, the ACL restrains excessive anterior tibial translation and stabilizes secondary knee rotations (i.e., internal/external 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 re-injury (40), 45% fail to return to their pre-injury sport level (5), and 80% to 90% will develop radiographic evidence of osteoarthritis even as early as seven years post surgery (20).

Given the unexplained greater risk of non-contact deceleration ACL injury in female subjects, any differences between gender and ACL reconstruction status in the kinematic and kinetic factors during associated sport activities may point to root causes for injury, re-injury, and avenues for prevention and rehabilitation. Unfortunately, the biomechanics of male and female ACL-intact (ACL_{INT}) and ACL-reconstructed (ACL_{REC}) knees during high risk non-contact deceleration activities, such as a jump-cut maneuver, are not well understood. These data have previously been difficult to obtain, in part, because non-invasive 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 following 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). While 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 non-contact deceleration ACL injury, has not been investigated (15,17). Additionally, the biomechanics of ACL_{REC} subjects during these other dynamic tasks were investigated between 4 and 12 months after surgery (14,33,34). While these time points are crucial for quantifying the immediate effects of ACL reconstruction, understanding the biomechanics of the knee more than five years 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 differences would point to plausible risk factors for injury.

Knee kinematic measurements were primarily obtained from biplanar videoradiography; however, knee flexion/extension outside the field of view of the biplanar videoradiography system was obtained from traditional optical motion capture. The specific aims were to determine differences due to both gender and ACL reconstruction status between $\mathrm{ACL}_{\mathrm{REC}}$ patients who were at least five years post-surgery, and $\mathrm{ACL}_{\mathrm{INT}}$ control subjects. More specifically, it was anticipated that $\mathrm{ACL}_{\mathrm{INT}}$ women would tend to perform the jump-cut maneuver more upright with more landing stiffness than $\mathrm{ACL}_{\mathrm{INT}}$ 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 $\mathrm{ACL}_{\mathrm{REC}}$ females and males five years post reconstruction 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 gender 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 $\mathrm{ACL}_{\mathrm{INT}}$ (5 males, 5 females) and 10 were $\mathrm{ACL}_{\mathrm{REC}}$ (4 males, 6 females; 7 bone-patellar tendon-bone autografts, 3 hamstring tendon autografts). Age, weight, and height for all subjects are displayed in Table 1. The inclusion criteria for the $\mathrm{ACL}_{\mathrm{INT}}$ subjects were: 1, no history of lower extremity injury; 2, no neurological disease(s); 3, no pregnancy; and 4, a Tegner activity score of five of greater (35). It should be noted that the $\mathrm{ACL}_{\mathrm{INT}}$ 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 $\mathrm{ACL}_{\mathrm{REC}}$ patients were: 1, unilateral ACL reconstruction using bone-patellar tendon-bone or four-stranded hamstring tendon autograft (looped semitendinosus and gracilis); 2, at least five years post ACL reconstruction; 3, no systemic infection; 4, no neurological disease(s); 5, no pregnancy; and 6, a Tegner activity score of five or greater. The ACL reconstruction surgery type was confirmed from patient records. After granting their informed consent, each subject was outfitted with 23 retro-reflective 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 $\mathrm{ACL}_{\mathrm{INT}}$ subjects (6L and 4R). For the $\mathrm{ACL}_{\mathrm{REC}}$ subjects, the ACL reconstructed leg was outfitted (7L and 3R).

Jump-Cut Maneuver

Each subject performed a jump-cut maneuver that was adapted from Ford et al (15), and previously described in detail (24). Briefly, three targets were placed on the floor within the testing environment (Figure 1A). The first target was located in the center of a force plate (Kistler model 9281B, Amherst, NY, USA). 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 one meter 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 as 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 ten correctly executed trials were performed, and the subject was unaware of the directional prompt prior to 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, USA; http://www.xromm.org). A four camera OMC system (Qualisys Oqus 5, Gothenburg, Sweden) was used to track the retro-reflective 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, Amherst, NY, USA) was used to measure the GRF at 5,000 Hz. The biplanar videoradiography system was engaged for a maximum of six trials and measured motion at 250 Hz within a restricted field of view (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 de-distortion and 3-D space calibration followed established protocols using custom MATLAB software (XrayProject, Brown University, Providence, RI, USA; http://www.xromm.org) (9).

Additionally, 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 mm^3. 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, USA).

Custom markerless tracking software (Autoscoper, Brown University, Providence, RI, 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 (DRRs) were generated from the CT volumes, and the kinematic transforms from CT space to each radiograph frame were determined after optimally matching the DRRs with the two views from the biplanar videoradiography system (Figure 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 (Figure 2A) was observed in the vertical GRF within the first 25 milliseconds. 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

(ACSs). These ACSs were determined from the 3-D CT models of the femur and tibia using previously described methods (25). In order to use the same ACSs for both OMC and biplanar videoradiography, their global coordinate spaces were co-registered using a rigid lattice containing spherical markers that were radio-opaque and retro-reflective (24). The mean and standard deviation for the root mean square fit error of the co-registration transforms was 0.31±0.09 mm.

Knee joint rotations in flexion/extension (FL/EX), adduction/abduction (AD/AB), and internal/external (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 percent ME/LA or AN/PO tibial plateau width. Normalization was performed in order to make kinematic evaluations on individuals of different sizes.

Due to the limited field of view (FOV) of the biplanar videoradiography system, the joint rotations and translations were time normalized from 16 milliseconds prior to contact to 60 milliseconds after contact. This window was selected since 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. Additionally, 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 time period containing the biplanar videoradiography data. Despite the soft tissue artifact observed in secondary rotations (AB/AD, IN/EX rotation) and translations (ME/LA, AN/PO) obtained from OMC, FL/EX remains relatively unaffected (24). Using the OMC data, the minimum flexion angle after contact was determined. Additionally, 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 gender (M and F) and ACL reconstruction status (ACL_{INT} and ACL_{REC}) were made for all kinematic and kinetic variables using two way analyses of variance. 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 gender 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 gender and ACL reconstruction status was observed for the peak vertical GRF (Figure 2). Within the ACL_{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_{REC} male and female subjects had nearly equal peak vertical GRFs. The ACL_{REC} male subjects' peak vertical GRF was 0.22 body weights larger than the female ACL_{REC} subjects but was not statistically significant (p=0.522). When comparing within ACL reconstruction status, both the male and female ACL_{INT} subjects had a larger peak vertical GRF than the male and female ACL_{REC} subjects, respectively. The male ACL_{INT} subjects' peak vertical GRF were 0.80 body weights larger than the male ACL_{REC} subjects (p=0.036), and the female ACL_{INT} subjects' peak vertical GRF were 2.46 body weights larger than the female ACL_{REC} subjects (p<0.001).

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

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

The AD/AB rotational excursion (Figure 3) was relatively constant after contact, changing less than 2 degrees for both male and female ACL_{REC} and ACL_{INT} subjects. Despite the minimal rotational change after contact, the female subjects were abducting (valgus) slightly after contact while the male subjects were adducting (varus) slightly after contact (average female abduction excursion equal to 1.02 degrees, average male adduction excursion equal to 1.07 degrees; p=0.033). The IN/EX rotational excursion (Figure 3) for all subjects followed a consistent pattern. Specifically, the male and female ACL_{INT} and ACL_{REC} subjects all began internally rotating after contact. While no statistically significant differences were observed in any group, the ACL_{INT} male and female subjects had a 76 larger AUC than the ACL_{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 following ground contact. Following 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) (Figure 4). These FL/EX kinematic data were determined from the OMC system.

We have included the following data as supplemental digital content in order 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); 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); and 3, the AN/PO and ME/LA knee translation excursions in millimeters (see Table C, Supplemental Digital Content 3).

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 non-contact 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 five years or more after their reconstruction. This may be a result of differences in strength, confidence, habit, and/or training following 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_{INT} subjects compared to their male ACL_{INT} counterparts (Figure 2). Notably, peak anterior tibial translation for the ACL_{INT} female subjects occurred within 60 milliseconds. A similar peak is not observed in the male ACL_{INT} subjects or the male and female ACL_{REC} subjects. Interestingly, the time to peak vertical GRF was significantly less in female subjects as compared to male subjects. Also, the time to peak vertical GRF appears to be smaller in ACL_{INT} subjects as compared to ACL_{REC} subjects. The increased rate of anterior tibial translation observed in female ACL_{INT} 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_{INT} subjects and male and female ACL_{REC} 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 milliseconds after contact) and increased at a lower rate after contact for the male ACL_{INT} and male and female ACL_{REC} 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_{INT} females during four functional tasks, Myers et al observed that anterior tibial translation was increased in activities of increasing external loading (29). Specifically, they observed a 2.4 mm increase in anterior tibial translation during landing maneuvers as compared to walking. Moreover, their results show the same characteristic peak vertical GRF immediately following ground contact during the landing tasks. This peak is absent in the vertical GRF walking trace. Conversely, another study by Myers et al showed no differences in anterior tibial translation between soft and stiff drop landings (28). 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. While no excessive rotational or translation motion was observed in our study, the increased rate of anterior translation in female ACL_{INT} 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_{REC} subjects immediately following contact may be influenced by the lower peak vertical GRF.

This low peak vertical GRF observed in both male and female ACL_{REC} subjects matches results from Paterno et al (30,31) and Vairo et al (38). In two separate studies, Paterno et al showed ACL_{REC} male and female subjects decreased peak vertical GRF when performing landing activities two years after reconstruction. Vairo et al reported decreased vertical peak GRF upon landing from a vertical drop among ACL_{REC} subjects approximately two years post surgery. These results are consistent with those reported in our study for ACL_{REC} men and women who are at least five years post-reconstruction. Additionally, no gender differences were observed in the peak GRF within ACL_{REC} subjects. Even after five years of strengthening activities, including formal rehabilitation, functional exercise and return to sports, the ACL_{REC} subjects performed the jump-cut maneuver with less energy compared to the ACL_{INT} subjects. While the exact mechanisms for this are unknown, it is possible that both behavioral and neuromechanical deficiencies are present in the ACL_{REC} 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_{REC} subjects' rehabilitation. Additional research investigating neuromuscular activity and contrallateral biomechanics may provide additional insight into the reduced vertical GRF observed in both male and female ACL_{REC} subjects.

In addition to the larger peak vertical GRF and rate of anterior tibial translation, the female subjects were generally abducting after contact (Figure 3A–B). This is an interesting finding because videographic studies have suggested that a valgus (abduction) collapse is involved in the non-contact deceleration ACL injury mechanism (21). Furthermore, the results presented herein are consistent with previous reports suggesting that females land with more knee abduction compared to males (15). While the female subjects in our study were abducting after contact compared to the male subjects, the total amount of abduction (< 2 degrees) 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 gender 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 gender difference observed in AD/AB angle, the similar kinematic outcomes observed between gender and ACL reconstruction status after contact does not support our hypothesis. Deneweth et al showed that, as compared to the ACL_{INT} contralateral knees, ACL_{REC} knees were more externally rotated and less laterally translated during a single-leg hopped landing (14). 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 five degrees 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 gender 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 the initiation and progression of osteoarthritis in ACL_{REC} 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 ACL_{INT} and ACL_{REC} subjects while they performed an activity in a controlled laboratory setting that has been associated with non-contact 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 employ biplanar 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 gender and ACL reconstruction status. While we did ensure that all subjects were recreational athletes, we were not able to control for surgeon or rehabilitation protocol for the ACL_{REC} subjects. Additionally, 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 recognize this as a study limitation.

Limitations associated with biplanar videoradiography should be noted. Specifically, the field of view restricted our ability to capture kinematic data for all subjects from 16 milliseconds before contact to 60 milliseconds after contact. Previous research has shown that peak anterior tibial translation occurs between 40 milliseconds to 50 milliseconds after contact (37), within the temporal range studied. Finally, each subject received up to 22 millirem of radiation exposure as a result of the biplanar videoradiography system and CT scan. While this falls well below the guidelines instituted by the NIH 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 gender and ACL reconstruction status during a jump-cut maneuver. Specifically, we found that female ACL_{INT} subjects landed and cut with a smaller amount of knee flexion angle excursion and larger peak vertical GRF than the male ACL_{INT} subjects. Furthermore, we observed that the ACL_{REC} subjects had a significantly lower peak vertical GRF just after impact as compared to the ACL_{INT} subjects. We also noted that female ACL_{INT} 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 to the male subjects; albeit, the amount of abduction does not appear to correspond to a valgus collapse position. Finally, no significant interactions were found between gender and ACL reconstruction status for IN/EX rotation or ME/LA translation after contact.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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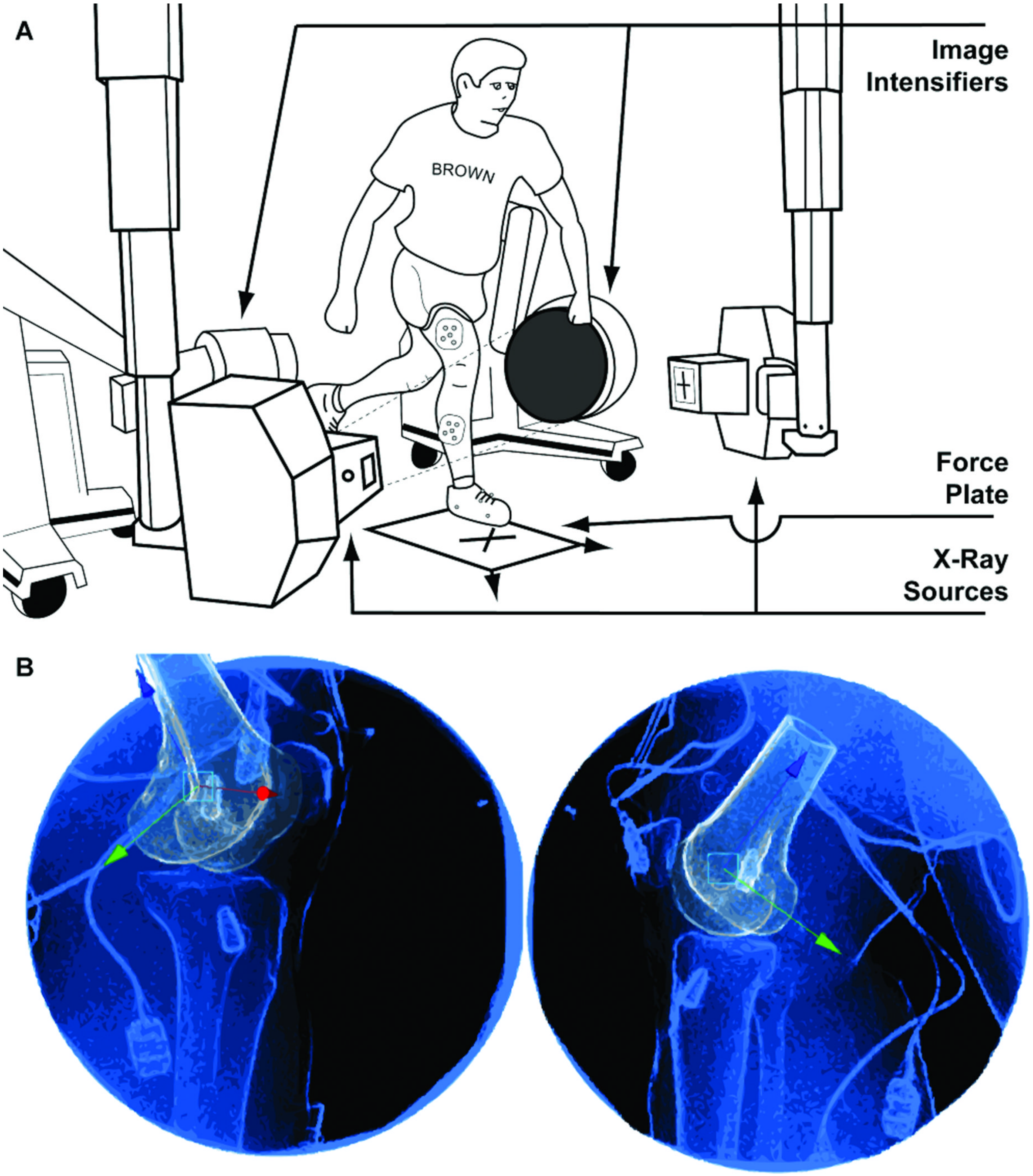

Figure 1.

A, illustration depicting the experimental set-up used to capture both biplanar videoradiography and OMC data during a jump-cut maneuver. A screen directly in front of the subject prompted them with the directional arrow. The subject would land and cut in the direction they were prompted using the opposite leg. For example, if prompted with the left arrow, the subject would land and cut to the left using their right leg. The four OMC cameras are not displayed in this figure; however, they were positioned to capture the retro-reflective markers shown on the subject's right leg. *B*, example frame from the Autoscoper markerless tracking software. Each view represents one frame from each of the two videoradiographs generated from the two image intensifiers (Figure 1A). The blue and black portions of the images represent the actual radiographs. The orange femur represents the DRR. Both the DRR and videoradiographs have been enhanced with a sobel edge detection filter and a contact filter. This was done to create a strong visual match between the DRR and actual radiograph. The translational manipulator is shown. This manipulator allowed the user to translate the DRR within the 3-D environment. A rotational manipulator was also available to the user. The DRR is shown here after performing markerless registration. The knee shown in this image is from one of the ACL_{REC} subjects. Both interference screws are visible in the femur and tibia.

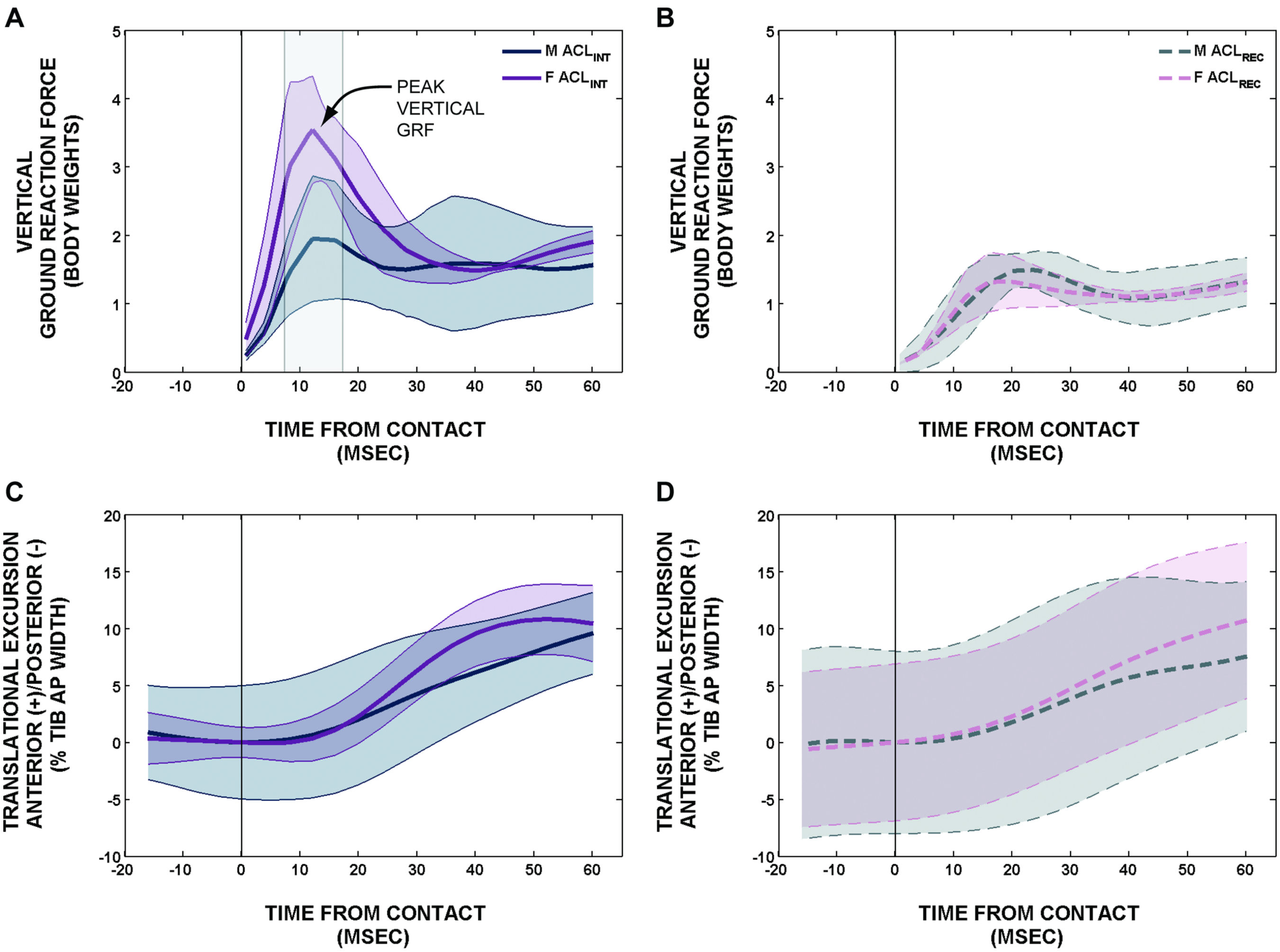

Figure 2.

A, ACL$_{INT}$ vertical GRF. *B*, ACL$_{REC}$ 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$_{INT}$ vertical GRF graph. All curves are displayed as mean ± 1 SD. The vertical line on each graph represents the time at contact. *C*, ACL$_{INT}$ AN/PO translational excursion. *D*, ACL$_{REC}$ 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 percent 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.

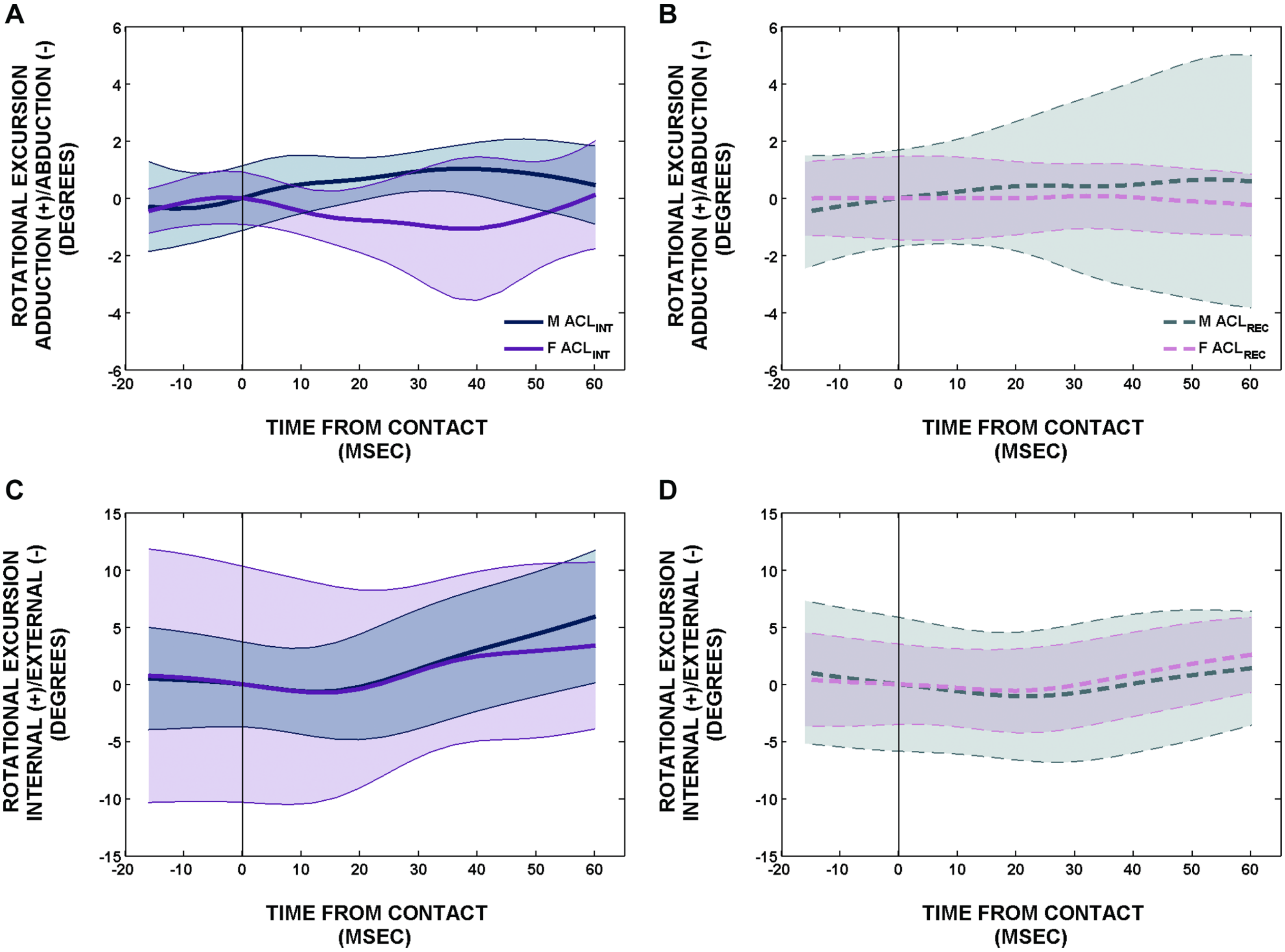

Figure 3.

A, ACL_{INT} AD/AB rotational excursion. *B*, ACL_{REC} AD/AB rotational excursion. Adduction is positive and abduction is negative. *C*, ACL_{INT} IN/EX rotational excursion. *D*, ACL_{REC} IN/EX rotational excursion. All rotational excursion units are in degrees. All curves are displayed as mean ± 1 SD. The vertical line on each graph represents the time at contact. It should be noted that these data were obtained from the biplanar videoradiography system.

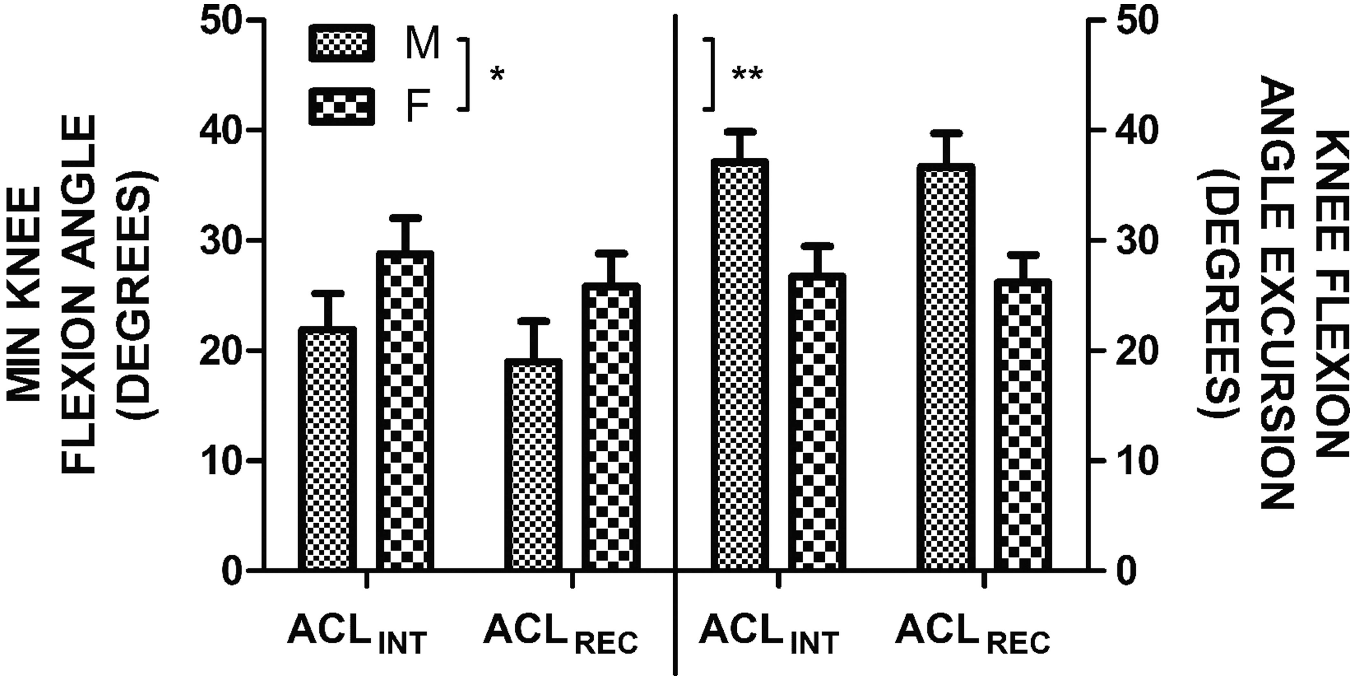

Figure 4.

Left y-axis, minimum knee flexion angle for ACL_{INT} and ACL_{REC} male and female subjects. Minimum flexion occurred at or immediately following ground contact. No statistically significant differences between gender and condition were observed for minimum knee flexion angle values; however, the * represents a p-value of 0.054 denoting an apparent gender difference. *Right y-axis*, knee flexion angle excursion for ACL_{INT} and ACL_{REC} male and female subjects. Knee flexion angle excursion was defined as the change in knee flexion angle from minimum flexion to maximum flexion. A statistically significant difference was observed between male and female subjects. This is highlighted by the **, which represents a p-value of 0.002. The minimum knee flexion angle and knee flexion angle excursion units are in degrees. It should be noted that these data were obtained from the OMC system.

Table 1

ACL_{INT} and ACL_{REC} male and female age, mass, and height demographics. Ages are in years, mass is in kilograms, and height is in centimeters. A two-way analysis of variance was performed on each set of demographics data, and no statistically significant differences ($p \leq 0.05$) were found between gender and condition. Statistically significant differences ($p \leq 0.05$) are highlighted using a dark gray background fill.

PARAMETER	ACL STATUS	MEAN	SEM		GENDER	MEAN	SEM		INTERACTION	MEAN	SEM	
AGE (YEARS)	ACL_{INT}	25.20	1.64	p=0.464	M	27.53	1.74	p=0.235	INT × M	25.80	2.32	p=0.481
									INT × F	24.60	2.32	
	ACL_{REC}	26.96	1.67		F	24.63	1.57		REC × M	29.25	2.59	
									REC × F	24.67	2.12	
MASS (KG)	ACL_{INT}	73.16	2.93	p=0.242	M	84.88	3.11	**p<0.001**	INT × M	81.53	4.15	p=0.617
									INT × F	65.07	4.15	
	ACL_{REC}	78.26	2.99		F	66.55	2.81		REC × M	88.49	4.64	
									REC × F	68.03	3.79	
HEIGHT (CM)	ACL_{INT}	172.85	2.09	p=0.736	M	178.70	2.21	**p=0.003**	INT × M	177.40	2.95	p=0.605
									INT × F	168.30	2.95	
	ACL_{REC}	173.88	2.13		F	168.03	2.00		REC × M	180.00	3.30	
									REC × F	167.75	2.70	

Table 2

ACL_{INT} and ACL_{REC} male and female kinematic AUC, rate, and peak vertical GRF results. A two-way analysis of variance was performed on each set of data. Statistically significant differences ($p \le 0.05$) are highlighted using a dark gray background fill. Near statistical significance ($p \le 0.10$) is highlighted using a light gray background fill. Pair-wise comparisons were made using the Holm-Sidak method when a significant (or near significant) gender and ACL reconstruction status interaction was determined. These results, denoted by the * or **, are shown in the bottom row of the table. The data presented in the parentheses (ME/LA and AN/PO AUC, AN/PO rates) are the raw translational values in millimeters. Finally, it should be noted that the kinematic data presented in Table 2 were obtained from the biplanar videoradiography system. Supplemental Digital Content 1 *.pdf

OUTCOME	ACL STATUS	MEAN	SEM		GENDER	MEAN	SEM		INTERACTION	MEAN	SEM	
AD\AB EXCURSION AUC DEG·MSEC	ACL_{INT}	−5.18	13.74	p=0.406	M	26.03	14.58	**p=0.033**	INT × M	25.88	19.43	p=0.415
									INT × F	−36.24	19.43	
	ACL_{REC}	11.57	14.03		F	−19.65	13.16		REC × M	26.19	21.73	
									REC × F	−3.05	17.74	
IN\EX EXCURSION AUC DEG·MSEC	ACL_{INT}	76.59	32.91	p=0.171	M	38.06	34.21	p=0.815	INT × M	86.81	45.61	p=0.505
									INT × F	66.37	45.61	
	ACL_{REC}	10.59	32.25		F	49.04	30.88		REC × M	−10.63	50.99	
									REC × F	31.71	41.63	
ME\LA EXCURSION AUC %·MSEC (MM·MSEC)	ACL_{INT}	6.56 (4.06)	12.65 (9.31)	p=0.153	M	−17.35 (−14.25)	13.41 (9.87)	p=0.269	INT × M	−6.85 (−5.72)	17.89 (13.16)	p=0.739
									INT × F	19.97 (13.83)	17.89 (13.16)	
	ACL_{REC}	−20.57 (−15.92)	12.91 (9.50)		F	3.34 (2.319)	12.11 (8.91)		REC × M	−27.84 (22.79)	20.00 (14.72)	
									REC × F	−13.292 (−9.20)	16.33 (12.02)	
AN\PO EXCURSION AUC %·MSEC (MM·MSEC)	ACL_{INT}	303.85 (162.80)	27.417 (15.08)	p=0.180	M	244.38 (139.89)	29.08 (15.99)	p=0.122	INT × M	270.85 (150.74)	38.77 (21.33)	p=0.961
									INT × F	336.84 (174.85)	38.77 (21.33)	
	ACL_{REC}	248.96 (138.56)	27.98 (15.39)		F	308.42 (161.47)	26.25 (14.44)		REC × M	217.91 (129.04)	43.35 (23.84)	
									REC × F	280.01 (148.08)	35.40 (19.47)	
AN\PO AVERAGE RATE %/MSEC (MM/MSEC)	ACL_{INT}	0.22 (0.12)	0.02 (0.01)	**p=0.035**	M	0.17 (0.10)	0.02 (0.01)	**p=0.037**	INT × M	0.18 (0.10)	0.02 (0.01)	p=0.213
									INT × F	0.26 (0.13)	0.02 (0.01)	
	ACL_{REC}	0.17 (0.10)	0.02 (0.01)		F	0.22 (0.12)	0.01 (0.01)		REC × M	0.16 (0.10)	0.02 (0.01)	
									REC × F	0.18 (0.10)	0.02 (0.01)	

OUTCOME	ACL STATUS	MEAN	SEM		GENDER	MEAN	SEM		INTERACTION	MEAN	SEM	
AN\PO MAXIMUM RATE %/MSEC[*] (MM/MSEC)	ACL_{INT}	0.39	0.03	**p=0.035**	M	0.31	0.03	p=0.135	INT × M	0.32 (0.18)	0.04 (0.02)	*p=0.087*
		(0.21)	(0.01)			(0.18)	(0.02)		INT × F	0.45 (0.23)	0.04 (0.02)	
	ACL_{REC}	0.30	0.03		F	0.37	0.03		REC × M	0.30 (0.18)	0.04 (0.02)	
		(0.17)	(0.02)			(0.19)	(0.01)		REC × F	0.29 (0.16)	0.03 (0.02)	
PEAK VIRT GRF MAG BW[**]	ACL_{INT}	1.53	0.17	NA	M	2.04	0.17	NA	INT × M	2.44	0.23	**p=0.003**
									INT × F	3.88	0.23	
	ACL_{REC}	3.16	0.16		F	2.65	0.16		REC × M	1.64	0.26	
									REC × F	1.42	0.21	
PEAK VIRT GRF TIME MSEC	ACL_{INT}	16.73	1.70	*p=0.066*	M	22.25	1.80	**p=0.021**	INT × M	21.87	2.40	p=0.117
									INT × F	11.60	2.40	
	ACL_{REC}	21.53	1.74		F	16.01	1.63		REC × M	22.63	2.69	
									REC × F	20.42	2.19	

[*] MvF in I: *p=0.027*; MvF in R: p=0.863; IvR in M: p=0.751; IvR in F: *p=0.007*

[**] MvF in I: **p<0.001**; MvF in R: p=0.522; IvR in M: **p=0.036**; IvR in F: **p<0.001**