■ KNEE

# Tibiofemoral contact and alignment in patients with anterior cruciate ligament rupture treated nonoperatively versus reconstruction

AN UPRIGHT, OPEN MRI STUDY

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## Aims

**Anterior cruciate ligament (ACL) rupture commonly leads to post-traumatic osteoarthritis, regardless of surgical reconstruction. This study uses standing MRI to investigate changes in contact area, contact centroid location, and tibiofemoral alignment between ACL-injured knees and healthy controls, to examine the effect of ACL reconstruction on these parameters.**

## Methods

**An upright, open MRI was used to directly measure tibiofemoral contact area, centroid location, and alignment in 18 individuals with unilateral ACL rupture within the last five years. Eight participants had been treated nonoperatively and ten had ACL reconstruction performed within one year of injury. All participants were high-functioning and had returned to sport or recreational activities. Healthy contralateral knees served as controls. Participants were imaged in a standing posture with knees fully extended.**

## Results

**Participants' mean age was 28.4 years (SD 7.3), the mean time since injury was 2.7 years (SD 1.6), and the mean International Knee Documentation Subjective Knee Form score was 84.4 (SD 13.5). ACL injury was associated with a 10% increase (p = 0.001) in contact area, controlling for compartment, sex, posture, age, body mass, and time since injury. ACL injury was associated with a 5.2% more posteriorly translated medial centroid (p = 0.001), equivalent to a 2.6 mm posterior translation on a representative tibia with mean posteroanterior width of 49.4 mm. Relative to the femur, the tibiae of ACL ruptured knees were 2.3 mm more anteriorly translated (p = 0.003) and 2.6° less externally rotated (p = 0.010) than healthy controls. ACL reconstruction was not associated with an improvement in any measure.**

## Conclusion

**ACL rupture was associated with an increased contact area, posteriorly translated medial centroid, anterior tibial translation, and reduced tibial external rotation in full extension. These changes were present 2.7 years post-injury regardless of ACL reconstruction status.**

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## Introduction

In patients who rupture their anterior cruciate ligament (ACL), 41% to 51% will subsequently develop osteoarthritis ten to 20 years after their injury.[1,2] ACL reconstruction reliably improves dynamic instability resulting from ACL rupture, however long-term outcome studies indicate that surgery may not protect the knee from osteoarthritis (OA).[3,4]

ACL rupture results in the loss of an important knee stabilizer whose primary function is to resist anterior tibial translation and whose secondary role is to protect against excess internal rotation.[5] Anteroposterior laxity occurs primarily in the lateral compartment in the ACL ruptured knee,[6,7] and ACL reconstruction has proven effective at reducing this;[8] however, the degree to which this

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**Table I.** T2 double echo steady state sequence parameters in the upright, open MRI.

| Parameter | Value |
|---|---|
| Repetition time, ms | 16 |
| Echo time, ms | 6 |
| Field of view, cm | 22 × 22 x 16 |
| Acquisition matrix size | 256 × 256 x 38 |
| Slice thickness, mm | 2.5 |
| Slice gap, mm | 0 |
| Voxel dimensions, mm | 0.859 × 0.859 x 2.5 |
| Flip angle, ° | 30 |
| Bandwidth, Hz/pixel | 146.9 |
| Total scan time, mins | 3.5 |

**Table II.** Descriptive data for participants.

| Variable | Total | ACL-R | ACL-nR | p-value* |
|---|---|---|---|---|
| Total, n | 18 | 10 | 8 | |
| Mean age, yrs (SD) | 28.4 (7.3) | 25.5 (4.6) | 32.1 (8.7) | 0.081 |
| Female, n (%) | 11 (61.1) | 6 (60.0) | 5 (62.5) | > 0.999 |
| Mean BMI, kg/m$^2$ (SD) | 24.6 (3.7) | 24.3 (3.2) | 25.0 (4.6) | 0.710 |
| Mean time to surgery, yrs (SD) | N/A | 0.53 (0.36) | N/A | N/A |
| Mean time since injury, yrs (SD) | 2.7 (1.6) | 2.6 (1.3) | 2.8 (1.9) | 0.826 |
| Mean IKDC (SD) | 84.4 (13.5) | 89.4 (9.0) | 77.3 (16.2) | 0.108 |
| Mean KOOS (SD) | 87.9 (14.4) | 92.3 (8.4) | 81.6 (19.3) | 0.210 |

*ACL-R vs ACL-nR; paired *t*-test.
ACL-nR, anterior cruciate ligament ruptured, nonreconstructed; ACL-R, anterior cruciate ligament ruptured, reconstructed; IKDC, International Knee Documentation Committee questionnaire; KOOS, Knee Injury and Osteoarthritis Outcome Score; N/A, not applicable; SD, standard deviation.

mitigates future arthritis is the subject of ongoing debate.[3,9] The potential failure of ACL reconstruction to protect the knee from OA may result from the procedure being unable to completely restore normal joint mechanics. Reviews of gait kinematics report changes in sagittal and frontal plane kinematics which persist for years after ACL reconstruction.[10,11] Joint alignment, represented by the six degrees-of-freedom position of the tibia relative to the femur, remains abnormal.[12] Cartilage contact behaviour is also not restored by ACL reconstruction, with medial contact centroids that are posteriorly translated and contact areas observed to be smaller than in normal knees.[13,14]

The post-reconstruction rehabilitation process, evidence of persistent mechanical changes, and no guarantee of a reduced arthritis risk, can make the decision to undergo ACL reconstruction surgery difficult for patients. Some are able to resume pre-injury levels of activity without dynamic instability and have been termed ACL “copers”.[15] It has been suggested that ACL copers may have equivalent functional outcomes to patients who undergo ACL reconstruction.[16]

There is no description of the contact mechanics of patients that were successfully treated nonoperatively. All participants in previously reported in vivo studies on the contact mechanics of ACL-deficient knees subsequently went on to undergo surgery.[13,17-20] This knowledge would aid understanding of any changes in mechanics that may influence the eventual development of OA, where no difference between patients treated operatively and nonoperatively has been identified.[21-23]

Our research questions were: in a standing, weightbearing posture, are there differences in tibiofemoral contact area, centroid location, and alignment between knees with ACL rupture versus healthy contralateral knees; and in a standing, weightbearing posture, are there differences in tibiofemoral contact area, centroid location, and alignment between patients with ACL rupture treated nonoperatively versus those treated with ACL reconstruction?

## Methods

This was an observational cohort study approved by the University of British Columbia Clinical Research Ethics Board (H18-01459). All participants provided informed, written consent.

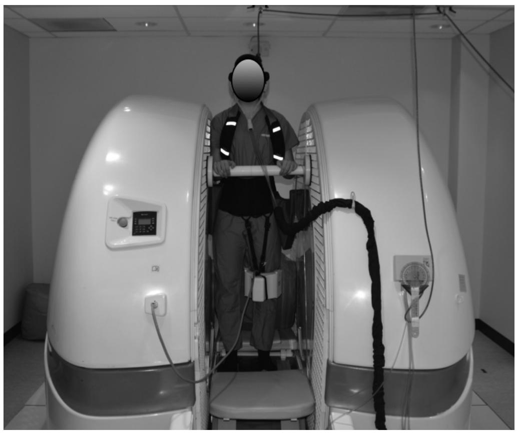
**Participants.** A convenience sample of 18 patients with prior ACL rupture was recruited through posted notifications and targeted emails. Inclusion criteria for the study were: adult participants aged between 18 and 50 years; reported unilateral, isolated ACL rupture diagnosed by a physician within the last five years; if reconstructed, done within one year of injury; intact cartilage (i.e. no evidence of arthritis) and confirmation of complete ACL rupture on MRI; and self-reported graduated rehabilitation programme culminating with return to sport or recreational activities.

Exclusion criteria were: associated ligament rupture other than the ACL, with the exception of incomplete medial collateral ligament (MCL) ruptures; incompletely rehabilitated injury, defined as range of motion less than 0° to 130°, quadriceps atrophy, or persistent dynamic instability; individuals prohibited from undergoing MRI; prior or subsequent knee surgery other than diagnostic arthroscopy to the affected knee, or any surgical intervention to the healthy knee; and history of corticosteroid injection to either knee.

**Outcomes.** Demographic data were obtained from participants and they completed two validated outcome questionnaires.[24,25]

All MR scanning was performed in a 0.5 T upright, open MRI (UO-MRI) scanner (ParaMed MROpen, Italy). Participants sat for 30 minutes prior to scanning, during which time they completed questionnaires. Supine scans were initially acquired with the knees in full extension and the toes taped together to ensure the patellae were pointing directly anterior (Figure 1a). Hip and ankle scans were used, noting the distance between them and the knee, to define 3D coordinate systems in the tibia and femur. Both knees were imaged while supine to confirm that the ACL of the affected knees was ruptured or reconstructed depending on the participant, and that the ACL and other soft-tissue structures in the healthy knee were intact. Participants then stood for 15 minutes prior to acquiring standing scans to ensure that a cartilage deformation equilibrium had been reached.[26,27] Participants were instructed to stand comfortably with their legs fully extended, distributing their weight equally between legs. The MRI technician suspended a two-channel commercial knee coil (ParaMed) around the knee and placed three horizontal support bars that helped the participant remain still during scanning. Each participant wore a chest harness suspended from an aluminium ceiling track as a precautionary measure in case the participant fainted during

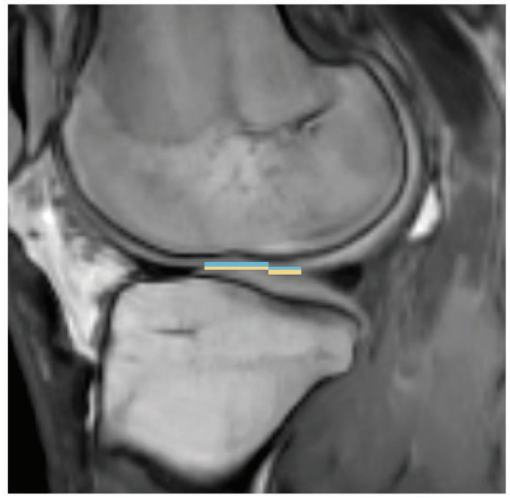
a



b

Fig. 1

a) Supine participant scan setup and b) standing participant scan setup.



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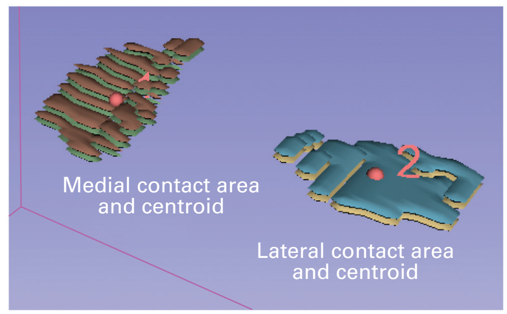


b

Fig. 2

a) Mid-lateral tibiofemoral compartment sagittal 0.5T MRI T2 DESS slice showing tibial (yellow) and femoral (blue) cartilage in contact and b) representation of medial and lateral cartilage contact areas with corresponding contact centroids (red dots).

upright scanning. No weight was borne through the bars or the harness (Figure 1b).

**MRI sequence.** Sagittal images were obtained with a double echo steady state (DESS) T2 sequence (Table I) using a commercial two-channel knee coil (ParaMed). The sequence was chosen because it provides excellent cartilage signal and can be acquired quickly enough to minimize the effects of patient movement and fatigue while standing.

The free induction decay (FID) image of the DESS sequence was used for contact area definition and joint coordinate system determination.

**Contact area.** Contact area was defined as the regions of tibiofemoral cartilage in direct contact on cross-sectional imaging (Figure 2a). Cartilage contact areas were manually segmented using the Editor module in 3D Slicer[28] to manually trace contact in a slice-by-slice manner, similar to the method previously validated by McWalter et al.[29] Multiplying the number of voxels within each contact region by the known voxel dimensions yielded contact areas for the medial and lateral compartments. To account for differences in size between subjects, this measure was normalized by taking the ratio (%) of the contact area over the maximum axial cross-sectional area of the tibial plateau. The centroid location was the geometrical centre generated from the contact area segmentation in the medial and lateral compartments (Figure 2b).

We previously established inter-rater, test-retest, and intra-rater reliability for tibiofemoral contact area using this scanning protocol in the UO-MRI.[30] Five participants from the present study participated in the analysis. Intraclass correlation coefficients (ICCs) for reliability measures ranged from 0.95 to 0.99 in the medial compartment and 0.83 to 0.91 in the lateral compartment. The smallest detectable change with 95% confidence ($SDC_{95}$) was 1.28% in the medial compartment and 0.95% in the lateral. An accuracy assessment was carried out in which four bovine osteochondral blocks were axially loaded and contact areas acquired in 0.5 T UO-MRI were compared to high-resolution 7 T scans. Our method was accurate to within 11 mm.[30]

**Alignment and centroid location.** The knee joint coordinate system proposed by Grood and Suntay[31] was used to describe tibiofemoral alignment using images acquired in the UO-MRI. Right-handed Cartesian coordinate systems local to the tibia and femur were established based on bony landmarks, allowing for description of the position and orientation of the tibia relative to the femur in three dimensions.[32] In this system, the

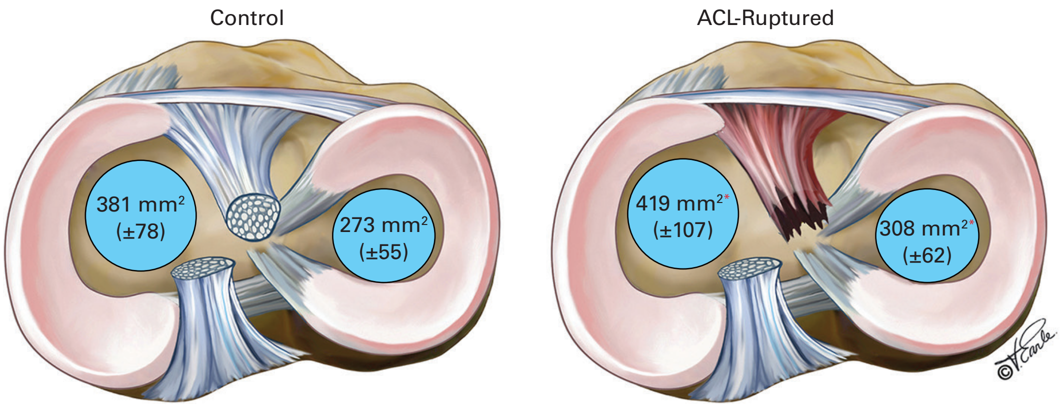


Fig. 3

Contact area differences between knees with anterior cruciate ligament (ACL) rupture and healthy matched controls.*Significant at p = 0.001.

origin of the tibial segment is located between the intercondylar eminences. Reference bony landmarks were established from supine scans of the hip, knee, and ankle, with the scan position relative to each other noted from the difference in UO-MRI scan table position. Positions and orientations of the coordinate systems in the upright posture were determined by registering supine images of the tibia and femur to corresponding upright images using Analyze 10.0 (AnalyzeDirect, USA). Three rotations and three translations describing the orientation and position of the tibia segment relative to the femur segment for the standing positions were calculated using a custom MATLAB program. This allowed comparison of joint position changes between ACL-reconstructed and non-reconstructed knees, and between participants' ACL-ruptured knees and their healthy knees.

We implemented a normalized reference frame for centroid location translation by segmenting the tibial plateau and creating bounds mediolaterally and posteroanteriorly based on the minimum and maximum coordinates of the corresponding axes. The result was a 2D reference frame with the origin at the most posterior and medial point on the tibial plateau. Centroid location translations were calculated in the posteroanterior and mediolateral direction. In a previous assessment of the reliability of the six degrees-of-freedom alignment analysis using the same Grood and Suntay method in the UO-MRI, test-retest ICC ranged from 0.95 to 0.99 for the tibiofemoral joint.[33]

**Sample size.** The sample size was calculated based on data from a supine MRI study[34] that examined in vivo, loaded tibiofemoral contact area. Sample size calculations were based on the planned cohort analysis comparing ACL-non-reconstructed knees to reconstructed knees to ensure the study was powered for both the cohort analysis and the case-control analyses. From the study's observed contact area standard deviation of 13.6 $mm^2$, we calculated that eight or more knees per group were needed to detect a minimum contact area change of 20 $mm^2$ with 80% power and an $\alpha$ of 0.05.

**Statistical analysis.** A linear mixed-effects model was employed to test the null hypothesis that there was no effect of ACL rupture on tibiofemoral contact area, controlling for cartilage region, sex, posture, age, BMI, and time from injury, allowing for random intercepts for inter-subject variability. Similar model parameters were used for the cohort analysis, testing the null hypothesis that there was no effect of ACL reconstruction status on contact area. Meniscal injury was not included as a confounder due to heterogeneity in the location, size, and type that would lead to excessively small cell sizes in the regression models. For the secondary analysis examining joint alignment and contact centroids, we used a paired *t*-test to test the null hypothesis that there was no difference between ACL-ruptured knees versus control knees, and the independent-samples *t*-test between ACL reconstruction versus no reconstruction. Tests were two-sided, the level of significance was set at $p < 0.05$, and Bonferroni correction was used to account for multiple comparisons. All analyses were performed using R Version 3.5.1 (R Core Team, Austria).

## Results

Eight participants with non-reconstructed ACL rupture and ten participants with reconstructed ACL rupture met the inclusion criteria and were recruited. Each participant's healthy contralateral knee was included in the control group. The case-control analysis therefore included 18 ACL-ruptured knees and 18 healthy matched control knees; the cohort analysis included eight ACL-ruptured, non-reconstructed knees (i.e. ACL copers) and ten ACL-ruptured, reconstructed knees (Table II). Hamstrings autograft was used in all reconstructed ACLs, except one where patellar tendon autograft was used. A single-bundle technique was universally used in the ACL-reconstructed cohort, with tunnels drilled through the standard anatomical ACL insertion sites. A total of 13 participants had meniscal pathology: seven had tears in the posterior portion of the lateral meniscus, three in the posterior portion of the medial meniscus, and three in both the medial and lateral menisci. Five occurred in the non-reconstructed group and eight in the reconstructed group. Nine were in the white-white zone (in the operative group, these were treated with partial meniscectomy), two in the red-white zone (both in the operative group, both repaired), and two in the red-red zone (both noted on MRI in the nonoperative group). *t*-tests showed no significant difference in medial contact area (p = 0.577) or lateral contact area (p = 0.925) based on the

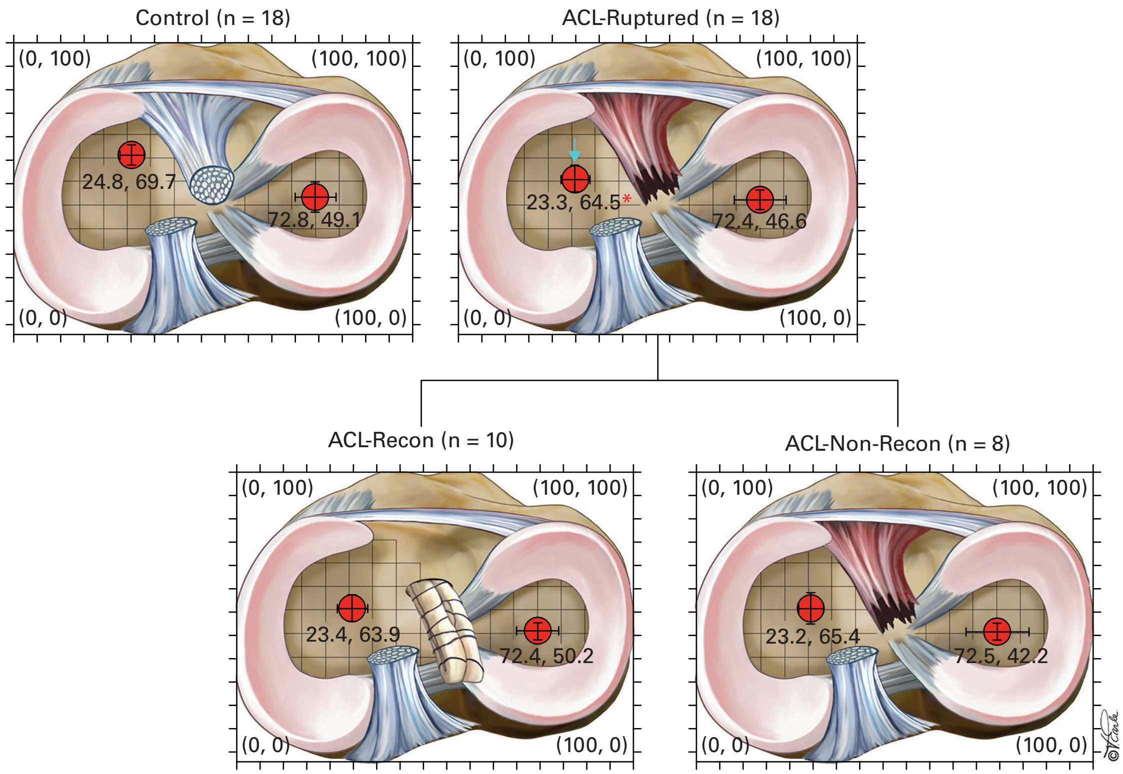


Fig. 4

Contact centroid locations comparing anterior cruciate ligament (ACL)-ruptured knees versus healthy contralateral control knees, and ACL-reconstructed knees versus non-reconstructed knees. *Significant at p = 0.001.

presence of any meniscal tear, nor any significant difference in medial contact area (p = 0.419) or lateral contact area (p = 0.455) based on the presence of a medial meniscal tear.

Knees with ACL rupture had 10.4% higher mean contact area (p = 0.001) than healthy knees after adjusting for region, posture, sex, age, BMI, and time since injury (Figure 3, Supplementary Table i). There was no difference (p = 0.710) in contact area between knees with and without ACL reconstruction (Supplementary Table ii).

In ACL-ruptured knees in the standing position, the medial centroid was located 5.2% more posterior (95% confidence interval (CI) 2.4 to 8.0; p = 0.001) than in healthy matched control knees (as indicated by the blue arrow in Figure 4 and in Supplementary Table iii). This is equivalent to a 2.6 mm posterior translation on a representative tibia from our population which had a mean posteroanterior width of 49.4 mm. For the change in medial centroid location, post hoc power analysis gave a 96% chance of correctly observing the difference (given a pooled standard deviation of 4.2%, 18 participants in each group, and an $\alpha$ of 0.05). There were no differences in centroid location in the mediolateral direction for the medial centroid, nor in either mediolateral or posteroanterior directions for the lateral centroid. No differences were found in the location of contact centroids between ACL-ruptured knees with and without reconstruction (Figure 4; Supplementary Table iv).

The tibiae of knees with ACL rupture were 2.3 mm more anterior (95% CI 0.9 to 3.6; p = 0.003) than controls (as indicated by the red arrow in Figure 5 and in Supplementary Table v). No significant differences in medial/lateral position or inferior/superior position between knees with ACL rupture versus controls were identified. The position of the tibia relative to the femur between ACL-ruptured knees with and without ACL reconstruction showed no significant difference (Figure 5; Supplementary Table vi).

Knees with ACL rupture were significantly less externally rotated by 2.6° (95% CI 0.7 to 4.5; p = 0.010) than controls (as indicated by the red arrow in Figure 5 and in Supplementary Table vii). There were no differences in flexion/extension or abduction/adduction between knees with ACL rupture versus controls. Tibiofemoral alignment between knees with and without reconstruction were not significantly different (Supplementary Table viii).

## Discussion

Results from this study suggest that ACL injury results in changes to tibiofemoral contact area, contact centroid location, and knee alignment that ACL reconstruction does not restore.

The finding of larger contact area, by a mean 38 mm$^2$ in the medial compartment and 35 mm$^2$ in the lateral compartment, in knees with ACL rupture at a mean 2.7 years after injury, is not consistent with studies done sooner after injury. Chen et al[13] reported a smaller contact area by 14.3 mm$^2$ in the medial compartment with non-significant changes in the lateral compartment of ACL-deficient knees,[13] and Van de Velde et

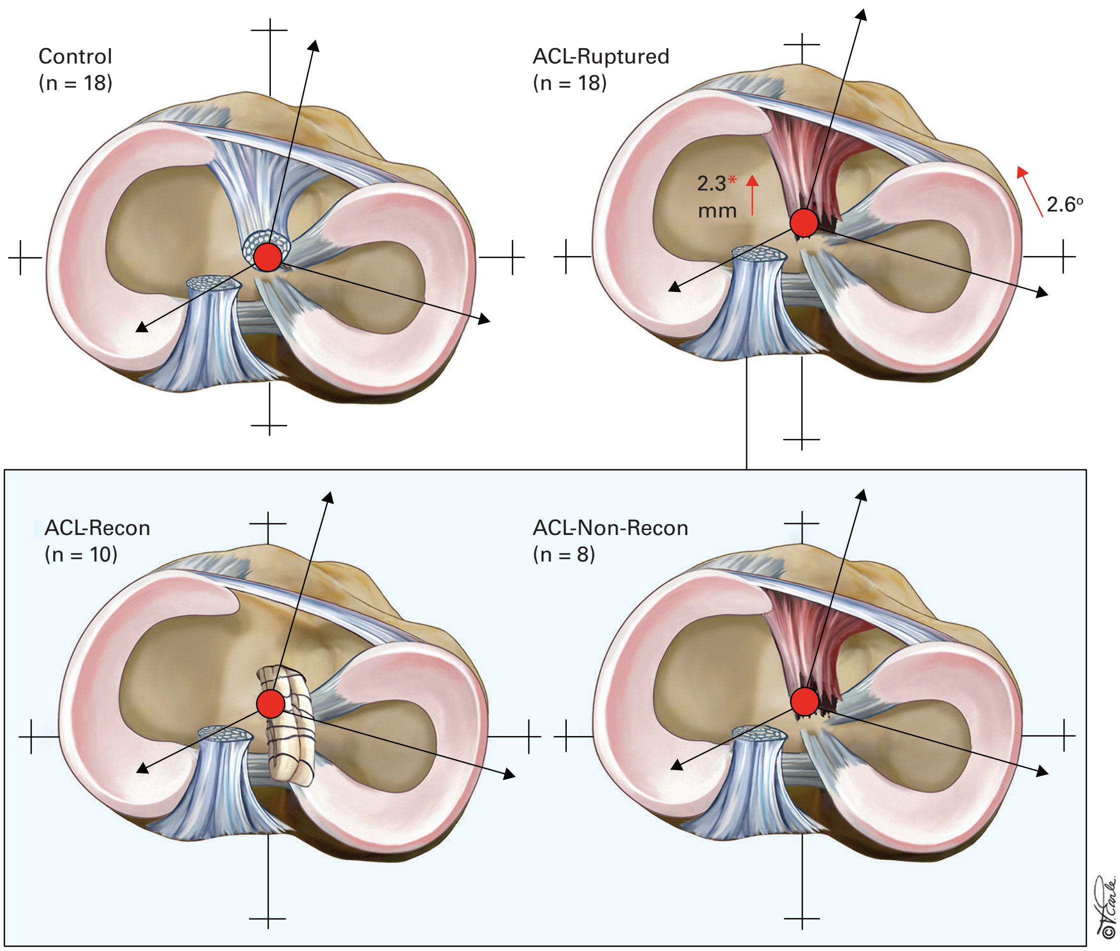


Fig. 5

Alignment mean differences comparing anterior cruciate ligament (ACL)-ruptured knees versus healthy contralateral control knees, and ACL-reconstructed knees versus non-reconstructed knees. *Significant at p = 0.003.

al[20] reported a smaller contact area by 94.8 mm$^2$ medially and 56.3 mm$^2$ laterally. The former study then re-imaged participants at the two-year postoperative mark finding that contact areas had increased from the immediate postoperative measurement, suggesting that longitudinal changes to contact area may occur.[13] Moderate arthritis has been associated with a significant increase in contact area in the medial compartment by 93.1 mm$^2$.[34] Our cohorts were scanned at a mean of 2.7 years from injury while other investigators scanned much closer to the time of injury, which suggests our findings may represent the natural course of injury if participants developed pre-clinical, post-traumatic arthritis. Another contributing factor may be the method of contact area determination. A commonly used method of weightbearing contact area determination matches weightbearing biplanar radiological models to high-resolution MRI images and inferring contact area via projected areas of cartilage overlap. The measurement error for this technique is reportedly 14%,[35] whereas the measurement error for the direct method of contact area determination used in this study was 4.8%.[30]

In this study, ACL rupture was associated with a posterior translation of the medial centroid by 5.2% which was consistent with a prior study. A study of 20 participants in supine MRI found that the medial contact centroid in healthy control knees was positioned a mean 66.4% of the posteroanterior distance versus a mean 64.4% in ACL-ruptured knees (p = 0.012).[36] Our results were consistent with a previous study showing ACL-deficient knees that go on to total knee arthroplasty have more posteriorly located wear patterns.[37] Other studies report contact location in ACL-deficient knees that eventually underwent reconstruction, however this is the first study to demonstrate similar findings in a group of ACL-deficient participants following successful nonoperative treatment.

In the cohort of ACL copers there was no evidence of significant anterolateral laxity which has been described,[7] however, previous findings were in individuals who ultimately received an ACL reconstruction so they likely were dynamically unstable. Early studies, also using an open bore 0.5 T MRI, measured the displacement of the femoral flexion facet centres relative to the posterior tibia, on mid-medial and mid-lateral compartment slices, in weightbearing participants during a wall-slide squat from 0° to 90°.[6-8] After ACL reconstruction sagittal laxity was observed to improve although anterior tibial translation persisted. We noted similar findings that anterior translation persisted but the absence of significant lateral compartment changes was unexpected. This is important with the slight internal rotation that was noticed in both the ACL reconstruction and the ACL coper group. One important difference between these studies done in open MRI was the measures used to deduce alignment. The relationship between a change in alignment and a change in contact centroid may not be proportional given the interaction between the shape and congruity of articulating surfaces. Both have been implicated as important variables in knee kinematics after ACL rupture and reconstruction.[38,39]

The key strength of this study is the recruitment of an ACL coper cohort enabling a comparison of contact and alignment measures directly between a high-functioning, ACL-reconstructed cohort and a similarly high-functioning, non-reconstructed cohort. We did not observe a significant change in the lateral contact centroid in the ACL copers. This suggests that not all ACL ruptures result in significant anterolateral instability and those patients may be predisposed to successful nonoperative management. Another advantage is that our measures were well-validated, with a clear specification of the minimum detectable difference. Finally this study assessed knee joint contact in a weightbearing, standing posture using a single modality. Conventional MRI studies require simulation of physiological weightbearing, and biplanar radiography studies require assessments with two or more scanners followed by substantial analysis.

One limitation of the study is that we did not evaluate kinematic changes through the range of knee flexion, and focused on the static, terminally extended position. This was not a complete representation of physiological activity, however this knee position is where differences were most notable in previous studies,[12,18,40] and is the position of the knee in mid-stance of gait during which the ipsilateral leg bears the majority of body weight. Previous open MRI studies on patients with ACL rupture were able to perform dynamic assessment throughout greater ranges of motion because the scan was optimized for bone, with only two MRI slices used to determine the outcome measurements.[6-8] The multislice scans in this study were optimized for cartilage detection and as a result were necessarily longer and precluded dynamic analysis. Second, it was not possible to ensure complete homogeneity of the ACL-reconstructed group, and there may have been some differences in placement of graft that may have affected the findings in the ACL-reconstructed cohort.[41] Owing to the heterogeneity of meniscal lesions in the recruited patinets, we were unable to control for them in our analysis. Meniscal lesions undoubtedly play a role in tibiofemoral contact mechanics,[42–45] and to accurately control for their presence would require a sample size beyond that of this study. There was no significant difference in the number of meniscal lesions between the ACL-reconstructed and non-reconstructed groups, and no partial meniscectomies were performed beyond the white-white zone. Finally, while there were no statistically significant differences between cohorts, the ACL-non-reconstructed group tended to be older with slightly worse functional outcome scores. This may represent a potential bias towards ACL reconstruction in the younger patient. It is possible that ACL 'copers' may not reach quite the level of physical function as individuals who undergo a reconstruction. In the present study, this observation may have contributed to Type II error in the comparison between the ACL reconstructed and non-reconstructed group.

This is the first study to quantify the mechanical changes present in a cohort of ACL 'copers' that have returned to activity after injury. In joint contact area, centroid location, and alignment, our findings support the recommendation to trial nonoperative management in individuals without dynamic instability. Secondly, we describe an in vivo method to directly measure these mechanical outcomes in standing, weightbearing postures. Longer-term follow-up and investigation of associated patient, injury,[46] and surgical factors is required.[47–49]

This study supports the hypothesis that persistently abnormal mechanics may predispose to cartilage degeneration after ACL rupture. Patients and clinicians can be reassured that nonoperative management of this injury, in certain individuals, results in no detectable differences in the measures used in this study compared to ACL reconstruction.

## Take home message

- Using standing MRI, we found evidence of abnormal tibiofemoral cartilage contact area, contact centroid location, and knee alignment after anterior cruciate ligament (ACL) rupture.
- These changes were present in active individuals, regardless of whether or not their ACLs were reconstructed.
- Our findings support the theory that persistently abnormal knee mechanics may predispose to osteoarthritis after ACL rupture.

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## Supplementary material

Tables i and ii describe the results of the linear mixed-effect models examining the adjusted effects of anterior cruciate ligament (ACL) rupture and ACL reconstruction on contact area. Tables iii through viii describe the data used to construct Figures 3 to 5.

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