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RESEARCH ARTICLE

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Patellofemoral joint geometry and osteoarthritis features 3–10 years after knee injury compared with uninjured knees

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Abstract

In this cross-sectional study, we compared patellofemoral geometry in individuals with a youth-sport-related intra-articular knee injury to uninjured individuals, and the association between patellofemoral geometry and magnetic resonance imaging (MRI)-defined osteoarthritis (OA) features. In the Youth Prevention of Early OA (PrE-OA) cohort, we assessed 10 patellofemoral geometry measures in individuals 3–10 years following injury compared with uninjured individuals of similar age, sex, and sport, using mixed effects linear regression. We also dichotomized geometry to identify extreme (>1.96 standard deviations) features and assessed likelihood of having extreme values using Poisson regression. Finally, we evaluated the associations between patellofemoral geometry with MRI-defined OA features using restricted cubic spline regression. Mean patellofemoral geometry did not differ substantially between groups. However, compared with uninjured individuals, injured individuals were more likely to have extremely large sulcus angle (prevalence ratio [PR] 3.9 [95% confidence interval, CI: 2.3, 6.6]), and shallow lateral trochlear inclination (PR 4.3 (1.1, 17.9)) and trochlear depth (PR 5.3 (1.6, 17.4)). In both groups, high bisect offset (PR 1.7 [1.3, 2.1]) and sulcus angle (PR 4.0 [2.3, 7.0]) were associated with cartilage lesion, and most geometry measures were associated with at least one structural feature, especially cartilage lesions and osteophytes. We observed no interaction between geometry and injury. Certain patellofemoral geometry features are correlated with higher prevalence of structural lesions compared with injury alone, 3–10 years following knee injury. Hypotheses generated in this study, once further evaluated, could contribute to identifying higher-risk individuals who may benefit from targeted treatment aimed at preventing posttraumatic OA.

KEYWORDS

alignment, intra-articular knee injury, morphology, osteoarthritis, patellofemoral joint

1 | INTRODUCTION

Sport-related intra-articular joint injury is a major risk factor for developing structural knee osteoarthritis (OA).[1–3] Structural knee OA commonly begins in the patellofemoral joint and later involves the tibiofemoral joint.[4–7] Patellofemoral joint geometry, which consists of patellofemoral joint alignment and bony morphology, has also been shown to be associated with patellofemoral OA.[8,9] This association has been seen as early as 1 year following anterior cruciate ligament reconstruction (ACLR),[10] and may lead to worsening of OA features within 5 years after ACLR.[11]

While extreme values of joint geometry—such as a patella that is laterally displaced far beyond mean values or an extremely shallow trochlear groove—can be seen in individuals without a history of joint injury,[12] the two can also co-occur. For example, in ACL-deficient knees, the patella may be more laterally tilted or displaced, or more inferiorly displaced, compared with uninjured contralateral knees.[13,14] ACLR may at least partially restore alignment, but a certain amount of "malalignment" may persist.[14,15] Certain patterns of patellofemoral joint geometry may influence the amount of pressure or pressure distribution acting on patellofemoral joint cartilage during daily activities, representing a possible mechanism by which risk of OA is increased.

It is unknown whether the presence of extreme values of patellofemoral joint geometry combined with joint injury accelerates the development of posttraumatic patellofemoral OA. Previous studies investigating the associations between patellofemoral joint geometry and posttraumatic patellofemoral OA have not included an uninjured comparison group, and therefore this was not previously possible to evaluate.[10,11] If our overarching hypothesis is correct, that the combination of extreme patellofemoral geometry values and injury increases risk of posttraumatic patellofemoral OA, then unique interventions aimed at optimizing geometry or associated cartilage pressures may promote secondary OA prevention in these individuals.[16,17]

The purpose of the present study was hypothesis-generating in nature. We evaluated patellofemoral geometry (alignment and morphology) in individuals 3–10 years following a youth-sport-related intra-articular knee injury compared with matched, uninjured individuals. We also evaluated the associations between patellofemoral joint geometry and patellofemoral joint magnetic resonance imaging (MRI) features of OA in these two groups.

2 | METHODS

This was a cross-sectional ancillary analysis of data from the Alberta Youth Prevention of Early OA (PrE-OA) study.[18–20] Injured participants had sustained a youth sport-related knee injury, either during a previous cohort study or by having attended a Sport Medicine Centre for this injury, 3–10 years before study enrollment. Injuries included clinically diagnosed knee ligament, meniscal or other intra-articular tibiofemoral or patellofemoral injury that required medical consultation and disrupted regular participation in their sport. Uninjured participants had no previous time-loss knee injury and were of similar age, sex, and sport as injured individuals at the time of injury. Participants included in the present analyses had magnetic resonance imaging (MRI) studies available. Ethics approval was granted from the University of Calgary. All participants provided informed consent to participate in this study.

2.1 | Image acquisition

Complete MR images for the present study were available in one knee per participant in a 1.5 Tesla clinical scanner at an offsite diagnostic imaging facility. The following sequences were acquired: sagittal proton density (PD) (repetition time [TR] 1500/echo time [TE] 10 ms, slice thickness 3.5 mm, FOV 150 × 140 mm); sagittal and coronal PD fat-saturated (FS) (TR/TE 2660/28 ms, slice thickness 3.5 mm, FOV 150 × 140 mm); and 3D gradient echo FIESTA sequence (TR/TE 10.5/4.2 ms, flip angle 55°, slice thickness 1.0 mm, isotropic voxels, matrix 512 × 512).[21]

2.2 | Patellofemoral geometry

All alignment and morphology variables were measured on FIESTA sequence MR images using an open-source version of OsiriX™ Lite v10.0 (Pixmeo SARL) available through Horos™ (Horos Project). One author (E. M. M.) with approximately 9 years experience of measuring imaging-based patellofemoral joint geometry performed all measurements using previously established methods (Figure 1).[10–12,22–27] Reliability of these measures was previously established: intrarater reliability intraclass correlation coefficients (ICC [1, 3]) ranged from 0.89 to 0.99, and interrater reliability (ICC [1,2]) values ranged from 0.85 to 0.98.[10,12] We selected four MRI slices to perform 10 measurements. In the axial plane, we selected the slice with the largest posterior femoral condyles to measure sulcus angle, lateral trochlear inclination, medial trochlear inclination, trochlear angle, and trochlear depth.[11,12,23,25] On this slice we also identified the posterior condylar line (PCL), a line running across the medial and lateral posterior femoral condyles—when needed, this line was transposed to other axial slices. We then selected the axial slice with the maximum mediolateral patellar width to measure bisect offset, patellar tilt angle and lateral patellar tilt angle.[11,12] We selected the axial slice at the level where the patellar tendon joins the tibial tuberosity to measure the tibial-tuberosity-to-trochlear-groove (TT-TG) distance.[28] We selected the sagittal image slice with the widest oblique distance across the patella to measure Insall-Salvati Ratio.[11,22,29] We normalized distance measures (TT-TG and trochlear depth) relative to knee size by expressing them as a percentage of the femoral trans-epicondylar axis distance, a measure of knee width.[28]

We defined our main alignment measure as bisect offset and our main morphology measure as sulcus angle because these measures

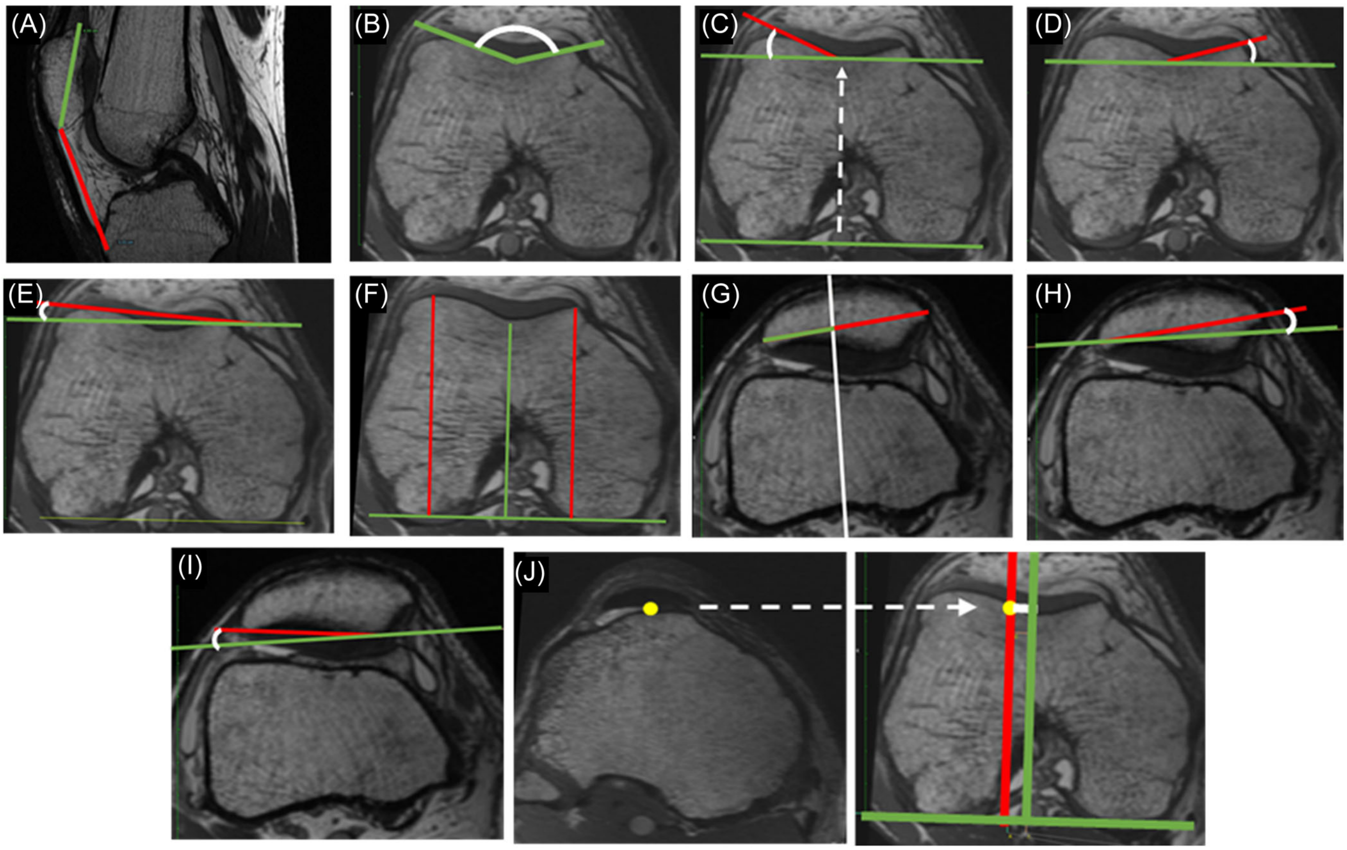

FIGURE 1 Morphology and alignment measures. (A) Insall-Salvati Ratio: patellar tendon length to longest patella length ratio. Larger number = higher patellar position. (B) Sulcus angle: angle formed by lateral and medial trochlear facet margins. Larger number = shallower sulcus. (C) Lateral trochlear inclination: angle formed by posterior lateral condyle (PCL, shown transposed here for illustrative purposes) and lateral trochlear facet margin. Larger angle = deeper sulcus laterally. (D) Medial trochlear inclination: angle formed by PCL and medial trochlear facet margin. Larger angle = deeper sulcus medially. (E) Trochlear angle: angle formed by PCL and anterior condylar line. Larger angle = deeper sulcus laterally. (F) Trochlear depth: Difference in length between line from PCL to deepest part of sulcus, and average length of two lines joining PCL to anterior condyles. Normalized by expressing as percentage of trans-epicondylar axis width. Larger number = deeper trochlea. (G) Bisect offset: percentage of line across patella that is lateral to a line bisecting deepest part of trochlea that runs perpendicular to the PCL. Larger percentage = more laterally displaced patella. (H) Patellar tilt angle: angle formed by PCL and line across patella. Larger angle = more lateral tilt. (I) Lateral patellar tilt angle: angle formed by PCL and the posterior bony margin of the lateral patellar facet. Larger angle = less lateral tilt. (J) TT-TG: Distance between two parallel lines that run perpendicular to PCL: one through point of tibial tuberosity, and one bisecting deepest part of trochlea. Normalized by expressing as percentage of trans-epicondylar axis width. Larger number = greater distance to tibial tuberosity. PCL, posterior condylar line; TT-TG, tibial tuberosity to trochlear groove distance. [Color figure can be viewed at wileyonlinelibrary.com]

have consistently been found to be associated with OA features and pain in individuals with patellofemoral pain, patellofemoral OA, and ACLR.[8,10–12,30]

All patellofemoral geometry measures were evaluated as continuous variables. However, to assist with clinical interpretation, we also created dichotomized patellofemoral geometry variables that define extreme alignment or morphology (Supporting Information: Table 1). To do this, we used previously defined reference values from a large population-based cohort of individuals with no pain and no patellofemoral OA.[12] In four additional measures not previously reported in that cohort, we derived reference values from uninjured individuals in the present study using the same approach: mean plus 1.96 standard deviations in a direction known to be associated with poor clinical outcomes. The four measures were: Insall Salvati Ratio (both high and low values), lateral patellar tilt angle (low values indicating extreme lateral patellar tilt), trochlear depth (low values indicating a shallow sulcus), and TT-TG (large values indicating lateralised tibial tuberosity or medialised trochlear groove). We used this approach because previously published MRI-derived reference values typically involved small sample sizes[17,20,25,31] or reported values substantially different than ours, suggesting possible differences in measurement methodology.[17,28]

2.3 | MRI-defined structural features

MRI-derived OA features were scored according to the MRI OA Knee Score (MOAKS).[32] MOAKS is a semiquantitative scoring system in which the knee is divided into 15 subregions (patella 2, femur 6, tibia 7) and regional scores are assigned for various OA features. Any cartilage loss, our main outcome, is defined by MOAKS as absent (scored 0), or covering less than 10% (scored 1), 10%–75% (scored 2), or more than 75% (scored 3) of regional cartilage surface area. We also evaluated osteophytes (MOAKS scoring between 0 = none and 3 = large), effusion-synovitis (0 = normal to 3 = severe), and Hoffa's synovitis (0 = normal to 3 = severe). We did not evaluate bone marrow lesions (BMLs) due to their low prevalence in this cohort. For the present study, we dichotomized MOAKS scores to define presence or absence of each structural feature based on a cut-off score of at least 1.

Reliability was assessed in the PrE-OA parent study, with cartilage morphology intrarater κ 0.53 and interrater κ, 0.44; and osteophytes 0.73 and 0.72, respectively.[20] Synovitis was not prevalent enough to evaluate reliability in the parent study, but has previously been reported for effusion-synovitis (intrarater weighted κ 0.90, interrater 0.72) and for Hoffa synovitis (0.42 and 0.70, respectively).[32] All images were read and scored by a musculoskeletal radiologist (J. L. J.) with 13 years of experience. Images were read blinded to injury history or surgical intervention.

2.4 | Statistical analyses

To evaluate whether our main alignment outcome, bisect offset, differed between the injured and uninjured groups, we performed mixed-effects linear regression, adjusting for age and body mass index (BMI) and specifying a random intercept for clustering (sport and sex). We then evaluated the likelihood of having high bisect offset in the injured compared with uninjured groups by performing Poisson regression with robust estimates of variance according to cluster, and reported point estimates for prevalence ratios (PR) along with 95% confidence intervals (CI). We repeated these analyses when evaluating our main morphology outcome, sulcus angle, and with all remaining geometry measures.

To evaluate the association between patellofemoral geometry and MRI-derived structural features, and how they differed according to group, we performed restricted cubic spline Poisson regression using three knots and robust estimates of variance, according to cluster, adjusting for age and BMI. We selected this approach because previous work has demonstrated a dose–response pattern in which risk of prevalent MRI-defined structural lesions remains low through a wide range of geometry values but increases toward the extreme ranges of geometry.[12,33] After performing each model, we confirmed goodness of fit of the model and then we used Stata's *lincom* syntax to calculate the predicted PR (95% CI) at the reference threshold defining extreme geometry (the same reference values used to dichotomize geometry variables, described above) in the injured and uninjured groups separately. The reference used for these predicted PRs was the median patellofemoral geometry value of the uninjured group. Finally, we compared the PRs of the injured group to the uninjured group, and reported this as relative risk (RR, 95% CI), which is equivalent to the main effect due to injury only. We then performed two sensitivity analyses with the full sample. First, we added interaction terms of group-by-geometry to all models, and calculated Akaike's Information Criteria (AIC) and variance inflation factors to consider the effect of interaction terms in model performance. Second, we ran models stratified by group, thus models were of smaller sample sizes and did not compare groups or account for matching.

Finally, we repeated all analyses in the subgroup of participants who had undergone ACLR only (i.e., we excluded other types of knee injury), along with uninjured individuals of similar age, sex, and sport.

All statistical analyses were performed using Stata/S.E. 16.0 (StataCorp). Statistical significance was defined as $p \leq 0.05$. We did not adjust for multiplicity because this was an exploratory evaluation of multiple tests involving correlated exposure variables and correlated outcome variables.[34] Sample size calculations for the parent study have been previously reported,[18] but were not performed in the present study because of the ancillary study design.

3 | RESULTS

Of the 200 participants from the PrE-OA parent study, complete MRI data were available for 80 participants with previous knee injuries and 81 uninjured individuals. The full sample mean (SD) age was 23 (3) years, BMI was 24.6 (3.2) kg/m^2, and 66 (41%) were women. The most frequently played sport at the time of injury was soccer (n = 31, 39%), the mean (SD) time since injury was 84.7 (24.9) months, and the most frequent injury was ACL rupture, all of which were reconstructed (*n* = 46, 58%) (Table 1).

3.1 | Between-group differences in patellofemoral geometry

Our main alignment measure, bisect offset, did not differ on average between groups in adjusted models (Table 2). While our main morphology measure, sulcus angle, was on average nearly 3° larger in the injured group, this was not statistically significant (2.73° [95% CI −0.25, 5.70] wider). Among the remaining patellofemoral geometry measures, few differed by group. The injury group had a significantly lower lateral patellar tilt angle (−2.11° [−3.81, −0.41]), indicating greater lateral tilt) and a significantly shallower lateral trochlear inclination (−2.29° [−3.97, −0.61]) compared with the uninjured group.

When dichotomizing geometry into those with and without extreme alignment or morphology values (i.e., according to reference values), injured participants were more likely to have an extremely wide sulcus angle (PR 3.9 [95% CI 2.3, 6.6]). They were also more likely to have extremely shallow lateral trochlear inclination (PR 4.3 [1.1, 17.9]), and extremely shallow trochlear depth (PR 5.3 [1.6, 17.4]). While Insall-Salvati Ratio and lateral patellar tilt angle demonstrated large point estimates, CIs were very wide, and results were not significant.

3.2 | Associations between patellofemoral geometry and MRI-derived structural features according to group

The injured group consistently demonstrated a similar direction of effect (i.e., higher PR values) in comparison to the uninjured group in every model, and these PRs reached statistical significance more frequently in the injured group (Table 3). High bisect offset was significantly associated with cartilage lesions, osteophytes, and effusion-synovitis (Table 3). The PRs only differed statistically between groups with osteophytes, since injury was not associated with the other structural features. In other words, the injured group was 6.3 (2.8, 14.0) times more likely to have prevalent osteophytes with a high bisect offset (>62%) compared with the median bisect offset (54%) of the uninjured group (Figure 2). This breaks down to 1.7 (1.1, 2.6) times due to the main effect of high bisect offset and 3.7 (1.4, 9.4) times due to the main effect of injury. Extremely shallow sulcus angle was associated with cartilage lesions only.

Among the remaining patellofemoral geometry measures, the Insall-Salvati ratio was the only measure showing no association with any structural outcome. Both patellar tilt measures were associated with osteophytes, lateral patellar tilt angle was also associated with cartilage lesions and Hoffa's synovitis. High TT-TG was associated with osteophytes and effusion-synovitis. Lateral

TABLE 1 Participant characteristics.

	Injured (*n* = 80)	Uninjured (*n* = 81)
Age, years mean (SD)	22.6 (2.5)	22.6 (2.6)
Female, *n* (%)	32 (40%)	34 (42%)
Body mass index, kg/m^2 mean (SD)	25.2 (3.4)	24.0 (2.9)
Time since injury, months mean (SD)	84.7 (24.9)	n.a.
Sport, *n*		
Soccer	31	30
Ice hockey	15	14
Basketball	9	9
Volleyball	4	3
Dance/martial arts/gymnastics/wrestling	2	1
Rugby/lacrosse	2	5
Baseball	1	1
Track/running	2	2
Skiing/snowboarding	6	8
American football	5	5
Swimming		
Field hockey	1	1
Biking		
Horseback riding/rodeo	1	1
Figure skating	1	1
KOOS mean (SD)		
Symptoms	83.8 (13.9)	91.7 (9.1)
Pain	90.9 (10.5)	96.9 (5.9)
Activities of Daily Living	95.8 (6.8)	98.9 (2.5)
Sport & Recreation	91.5 (8.9)	97.1 (5.1)
Quality of Life	89.2 (9.1)	98.1 (3.8)
Type of injury, *n*		
ACL rupture	46	n/a
Other knee ligament	13	n/a
Isolated meniscus	11	n/a
Other injury	10	n/a
MRI structural features, *n*		
Any cartilage signal/damage	22	14
Any bone marrow lesions	5	5
Any osteophytes	20	5
Any effusion-synovitis	18	6
Any Hoffa's synovitis	63	59

Abbreviations: ACL, anterior cruciate ligament; KOOS, Knee injury and osteoarthritis outcome score; MRI, magnetic resonance imaging; norm, normalized to knee size as a percentage of femoral trans-epicondylar axis distance; TT-TG, tibial tuberosity to trochlear groove distance.

TABLE 2 Knee geometry measures, between-group comparisons adjusting for age and BMI, clustered by sex and sport.

	Injured (n = 80) Unadjusted mean (SD)	Uninjured (n = 81) Unadjusted mean (SD)	Adjusted difference compared with uninjured Mean (95% CI)	Prevalence ratio for having extreme alignment or morphology versus uninjured PR (95% CI)
Bisect offset (%)	53.60 (8.07)	54.18 (6.63)	−0.80 (−3.08, 1.47)	1.6 (0.7, 3.9)
Patellar tilt angle (°)	11.31 (4.88)	10.32 (5.24)	1.20 (−0.25, 2.66)	1.2 (0.6, 2.5)
Lateral patellar tilt angle (°)	7.56 (5.45)	9.50 (5.52)	**−2.11 (−3.81, −0.41)**	9.2 (0.9, 98.4)
TT-TG normalized (%)	10.61 (4.65)	9.36 (4.72)	1.33 (−0.10, 2.80)	1.3 (0.2, 10.0)
Insall-Salvati Ratio	1.05 (0.16)	1.08 (0.14)	−0.03 (−0.08, 0.02)	4.9 (0.9, 26.4)
Sulcus angle (°)	127.45 (9.84)	124.92 (9.30)	2.73 (−0.25, 5.70)	**3.9 (2.3, 6.6)**
Lateral trochlear inclination (°)	25.84 (5.63)	28.21 (5.20)	**−2.29 (−3.97, −0.61)**	**4.3 (1.1, 17.9)**
Medial trochlear inclination (°)	29.63 (5.63)	29.85 (5.29)	−0.40 (−2.15, 1.35)	1.9 (0.9, 3.7)
Trochlear angle (°)	1.78 (2.81)	2.04 (2.39)	−0.19 (−1.00, 0.62)	1.1 (0.6, 1.9)
Trochlear depth normalized (%)	9.56 (2.02)	10.09 (2.05)	−0.58 (−1.20, 0.05)	**5.3 (1.6, 17.4)**

Note: Bold values show significant between-group difference.

Abbreviation: TT-TG, tibial tuberosity to trochlear groove distance, normalized to knee width.

trochlear inclination was associated with cartilage lesions and effusion-synovitis; medial trochlear inclination was associated with Hoffa's synovitis; trochlear angle was associated with osteophytes and effusion-synovitis; and trochlear depth was associated with cartilage lesions. Large but nonsignificant PRs were noted for both medial trochlear inclination and trochlear depth, which were approximately two and three times more likely to have prevalent effusion-synovitis, respectively.

Adding interaction terms to the models resulted in: higher AICs, very large variance inflation factors (range 10–783), drastic changes to point estimates that did not look physiologically plausible, and exceedingly large CIs (Supporting Information: Table 2). Stratified analyses of our main exposure and outcome variables, bisect offset and sulcus angle with cartilage lesions, did not give different results in significance compared with our main models, though the point estimate increased for sulcus angle from PR 4.0 (2.3, 7.0) to 6.1(1.9, 20.2) in the uninjured group when stratified by group (Supporting Information: Table 3). Among remaining comparisons slightly fewer comparisons achieved statistical significance and point estimates shifted in some models.

3.3 | Subgroup analysis: ACLR

Limiting analyses to individuals with ACLR, lateral patellar tilt angle and lateral trochlear inclination no longer differed significantly, and Insall-Salvati became significantly lower in the ACLR group (−0.06 [−0.11, −0.01]), and was thus the only measure that differed between groups (Supporting Information: Table 4).

When dichotomizing geometry into those with and without extreme alignment or morphology, participants who underwent ACLR remained more likely to have extremely shallow trochlear depth than uninjured participants, though the point estimate was smaller (PR 1.7 [1.1, 2.4], Supporting Information: Table 4). The ACLR group was no longer significantly more likely to have shallow sulcus angle or shallow lateral trochlear inclination, though the magnitude and direction of effect did not change substantially.

Regarding associations between patellofemoral geometry and MRI-derived structural features, high bisect offset (our main alignment measure) remained associated with cartilage lesions, osteophytes, and effusion-synovitis (Supporting Information: Table 5). Extremely shallow sulcus angle (our main morphology measure) remained associated with cartilage lesions but was also more strongly and significantly associated with osteophytes. Insall-Salvati ratio continued to show no association with any structural outcome, though TT-TG was also not associated with any structural outcome. The association between lateral patellar tilt angle and cartilage lesions was slightly smaller and no longer significant; lateral trochlear inclination increased slightly and became significant across all four structural features; and trochlear depth was more strongly and significantly associated with effusion-synovitis. A few remaining changes in significance were related to changes in variance rather than due to substantial changes in point estimates.

4 | DISCUSSION

4.1 | Between-group differences in patellofemoral geometry

A key finding of the present study is that injured participants were moderately more likely to have an extremely shallow trochlear

TABLE 3 Association between patellofemoral geometry and injury with MRI-defined structural features.

	Cartilage PR (95% CI)[a] RR (95% CI)[b]	Osteophytes PR (95% CI) RR (95% CI)	Effusion-synovitis PR (95% CI) RR (95% CI)	Hoffa synovitis PR (95% CI) RR (95% CI)
Bisect offset > 62%				
Injured	**2.4 (1.6, 3.4)**	**6.3 (2.8, 14.0)**	**4.2 (1.2, 14.4)**	1.2 (0.9, 1.6)
Uninjured	**1.6 (1.3, 2.1)**	**1.7 (1.1, 2.6)**	**1.6 (1.0, 2.6)**	1.1 (1.0, 1.3)
Relative risk	1.5 (0.9, 2.3)	**3.7 (1.4, 9.4)**	2.6 (0.9, 7.1)	1.1 (0.9, 1.3)
Patellar tilt angle > 17°				
Injured	1.9 (0.5, 6.8)	**28.4 (9.2, 87.1)**	2.4 (0.4, 13.8)	1.3 (0.8, 2.0)
Uninjured	1.3 (0.5, 3.6)	**6.7 (2.5, 17.6)**	0.8 (0.3, 2.8)	1.1 (0.8, 1.7)
Relative risk	1.5 (0.9, 2.4)	**4.2 (1.7, 10.9)**	2.8 (1.0, 8.1)	1.1 (0.9, 1.3)
Lateral patellar tilt angle < −1°				
Injured	**2.3 (1.2, 4.2)**	**2.3 (1.2, 4.2)**	3.4 (0.9, 12.3)	**1.3 (1.0, 1.7)**
Uninjured	**1.8 (1.1, 2.9)**	**1.8 (1.1, 2.9)**	1.3 (0.6, 2.6)	**1.2 (1.1, 1.4)**
Relative risk	1.3 (0.8, 2.0)	1.3 (0.8, 2.0)	2.7 (1.0, 7.3)	1.1 (0.9, 1.3)
TT-TG normalized > 19 mm				
Injured	1.6 (0.5, 4.9)	**8.4 (2.6, 27.0)**	**4.8 (1.5, 15.0)**	1.3 (0.9, 1.7)
Uninjured	1.2 (0.5, 3.1)	**2.1 (1.2, 3.9)**	**2.0 (1.1, 3.3)**	1.2 (0.9, 1.5)
Relative risk	1.3 (0.8, 2.2)	**3.9 (1.4, 10.6)**	2.5 (0.9, 6.7)	1.1 (0.9, 1.3)
Insall Salvati Ratio				
≥1.35, Injured	2.5 (0.9, 7.4)	2.6 (0.4, 15.4)	1.0 (0.08, 11.0)	1.4 (0.8, 2.4)
Uninjured	1.6 (0.6, 4.1)	0.7 (0.2, 2.5)	0.3 (0.06, 1.8)	1.3 (0.8, 2.2)
Relative risk	1.6 (0.9, 2.8)	**3.9 (1.5, 10.4)**	**2.9 (1.0, 8.2)**	1.1 (0.9, 1.3)
≤0.80, Injured	2.4 (0.9, 6.3)	3.3 (0.7, 15.8)	1.2 (0.2, 6.8)	1.3 (0.8, 2.0)
Uninjured	1.5 (0.5, 4.8)	0.9 (0.3, 2.3)	0.4 (0.1, 1.3)	1.2 (0.7, 1.9)
Relative risk	1.6 (0.9, 2.8)	**3.9 (1.5, 10.4)**	**2.9 (1.0, 8.2)**	1.1 (0.9, 1.3)
Sulcus angle > 142°				
Injured	**4.4 (2.5, 7.7)**	**6.4 (2.4, 17.1)**	3.5 (0.5, 24.9)	1.3 (0.9, 1.8)
Uninjured	**4.0 (2.3, 7.0)**	1.7 (0.7, 4.3)	1.5 (0.3, 6.6)	1.2 (0.9, 1.6)
Relative risk	1.1 (0.7, 1.7)	**3.8 (1.4, 10.8)**	2.4 (0.9, 6.3)	1.1 (0.9, 1.3)
Lateral trochlear inclination < 19°				
Injured	**3.2 (1.7, 6.2)**	**5.8 (2.1, 15.9)**	**4.6 (1.3, 16.9)**	1.2 (0.9, 1.6)
Uninjured	**2.9 (1.8, 4.6)**	1.5 (0.8, 2.9)	**2.0 (1.0, 3.6)**	1.1 (1.0, 1.4)
Relative risk	1.1 (0.7, 1.8)	**3.8 (1.3, 11.5)**	2.4 (0.9, 6.2)	1.1 (0.9, 1.3)
Medial trochlear inclination ≤ 22°				
Injured	**2.2 (1.4, 3.7)**	**6.8 (2.6, 17.5)**	5.4 (0.8, 34.7)	**1.3 (1.0, 1.6)**
Uninjured	1.6 (1.0, 2.8)	1.8 (1.0, 3.1)	2.1 (0.7, 6.6)	**1.2 (1.0, 1.3)**
Relative risk	1.4 (0.8, 2.2)	**3.8 (1.4, 10.6)**	2.5 (0.9, 7.4)	1.1 (0.9, 1.3)
Trochlear angle ≥ 5°				
Injured	1.4 (0.8, 2.5)	**6.0 (2.1, 17.1)**	**4.0 (1.4, 11.8)**	1.1 (0.9, 1.4)

(Continues)

TABLE 3 (Continued)

	Cartilage PR (95% CI)[a] RR (95% CI)[b]	Osteophytes PR (95% CI) RR (95% CI)	Effusion-synovitis PR (95% CI) RR (95% CI)	Hoffa synovitis PR (95% CI) RR (95% CI)
Uninjured	1.0 (0.7, 1.4)	**1.6 (1.4, 1.9)**	**1.7 (1.5, 1.9)**	1.0 (0.9, 1.1)
Relative risk	*1.5 (0.9, 2.4)*	***3.7 (1.3, 10.3)***	*2.4 (0.8, 7.2)*	*1.1 (0.9, 1.3)*
Trochlear depth normalized ≤ 6 mm				
Injured	**3.1 (1.6, 6.2)**	**6.0 (2.4, 14.5)**	**7.1 (1.1, 46.4)**	**1.2 (1.0, 1.5)**
Uninjured	**2.5 (1.4, 4.6)**	1.6 (0.7, 3.3)	3.1 (0.9, 10.5)	1.1 (1.0, 1.3)
Relative risk	*1.2 (0.8, 1.9)*	***3.8 (1.4, 10.5)***	*2.2 (0.9, 5.9)*	*1.1 (0.9, 1.3)*

Note: Bold values show significant association at threshold (compared with reference value of uninjured group) or significant association due to injury in the case of relative risk values *(italicized)*.

Abbreviations: BMI, body mass index; PR, predicted prevalence ratio; RR, relative risk; TT-TG, tibial tuberosity to trochlear groove distance.

[a]PR (95% CI), extracted at the cut-point for extreme geometry compared with the median reference value of the uninjured group.

[b]RR (95% CI), compares between-group differences in PRs, which in these models RR is the main effect due to injury.

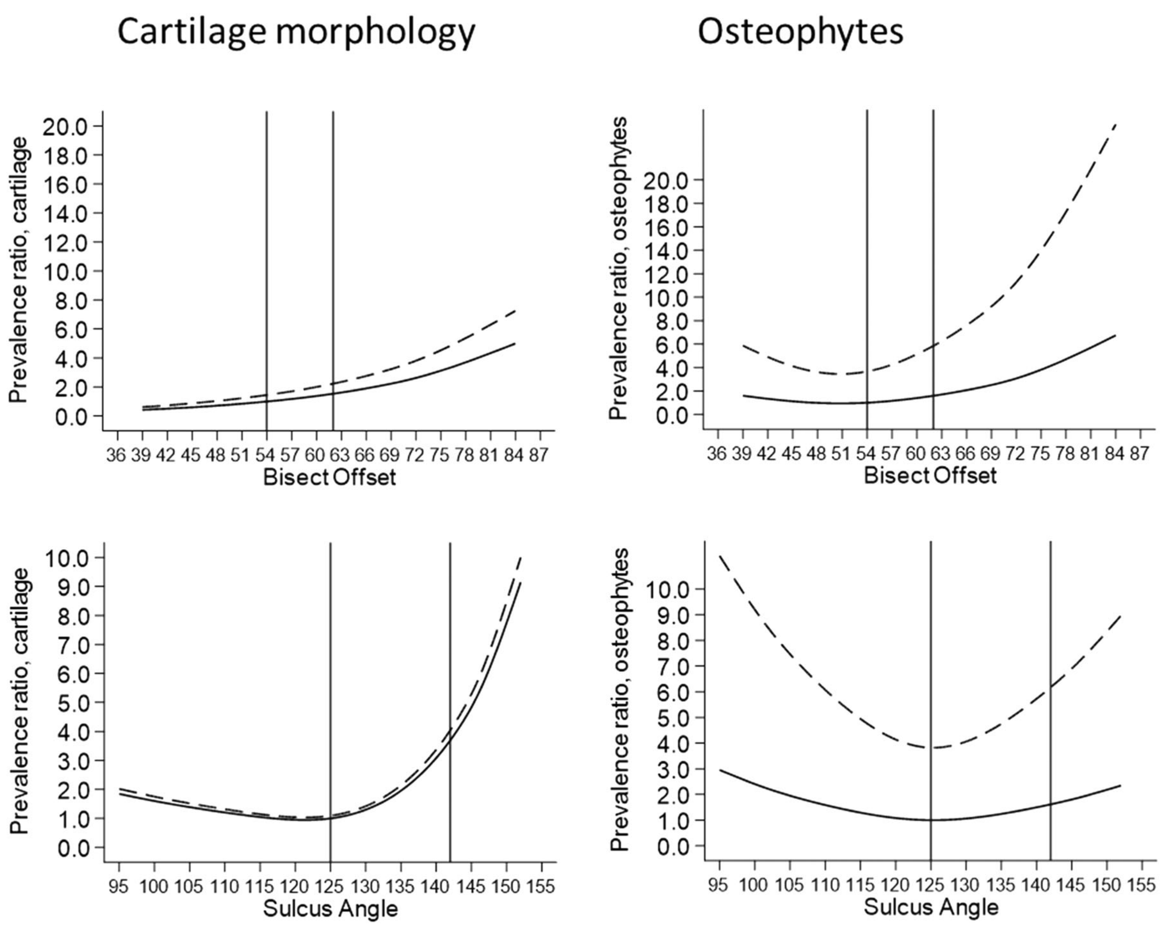

FIGURE 2 Predicted dose–response curves of associations between patellofemoral geometry—bisect offset (top row) and sulcus angle (bottom row)—with cartilage damage (left) and osteophytes (right) along the spectrum of respective geometry values. Prevalence ratios in Table 3 represent the comparison between extreme values (right vertical line: bisect offset 62%; sulcus angle 142°) compared with median values (left vertical line: bisect offset 54%; sulcus angle 125°). Error bars intentionally omitted for figure readability—see Table 3 for confidence intervals at the cut-point defining extreme geometry value. Solid line = uninjured group, dashed line = injured group.

morphology according to three of the five trochlear morphology measures. This was found in spite of the relatively small mean differences between groups—only lateral patellar tilt angle and lateral trochlear inclination differed by more than 2°, and the clinical relevance of these differences is not known. When evaluating only the subgroup with ACLR, the only significant between-group difference in alignment was for Insall-Salvati ratio, with ACLR knees having a lower positioned patella compared with the uninjured group. A lower Insall-Salvati ratio has been previously reported in ACLR knees,[35] though this is not consistent.[10] Moreover, the ACLR group was more likely to have extremely shallow morphology on only one measure, trochlear depth, a finding that is inconsistently supported in other ACL studies.[36,37]

In the case of alignment, these findings could suggest that individuals who sustained injury either: (i) had, on average, alignment values that were like uninjured individuals before injury; (ii) did not undergo a substantial worsening of alignment because of the injury, or (iii) if they did have worse alignment that it was partially or fully reduced following treatment for their injury. For example, ACL injuries may lead to worse patellar alignment, but this may be at least partly corrected with ACLR.[10,13–15]

In the case of morphology, there is no evidence or obvious biological reason to suggest that the trochlear groove would become shallower as a result of knee injury. The fact that individuals in the injured group were more likely to have shallow morphology, therefore, suggests that shallow morphology existed before the injury, and ergo may be a risk factor for traumatic knee injury. To confirm this would require a large prospective cohort study of uninjured athletes followed to injury and through recovery. However, the resources required to perform an adequately powered study to address this question may not be justified given that trochlear morphology is not generally treatable, with the exception of rare salvage procedures such as trochleoplasty in the case of chronic severe patellar instability.[38] Individuals with shallow trochlear morphology may nonetheless benefit from preventive strategies like strengthening and movement re-education to optimize movement patterns during sport, though the efficacy of this remains speculative.

4.2 | Associations between patellofemoral geometry and MRI-derived structural features

A key finding of the present study is that, in the full sample, we found significant associations between most alignment or morphology measures and at least one structural feature, most frequently with cartilage and osteophytes, and rarely with Hoffa synovitis. The only significant between-group differences, that is, due to injury, were seen with osteophytes, where prevalence ratios in the injured group were approximately four times higher than in the uninjured group for having osteophytes with nearly every geometry measure. When evaluating only the ACLR subgroup, the injured group was approximately 6 times more likely to have osteophytes, and they were also approximately 3.5 times more likely to have effusion-synovitis. These findings are consistent with literature demonstrating that knee injury is a risk factor for OA.[1–3]

We were unable to explore whether an interaction exists between geometry and injury, because adding interaction terms to our model produced nonviable results. This is likely because extreme geometry values are relatively rare, even in injured knees, as would be expected. While our findings suggest that the association between geometry and structural features are not different in injured versus uninjured individuals, it does highlight that an injury combined with extreme values of patellofemoral geometry may be associated with a higher risk of developing OA than in an injured person with typical geometry. For example, for both bisect offset and sulcus angle, instead of extreme values being approximately four times more likely to have osteophytes 3–10 years following intra-articular knee injury, these individuals may be more than six times more likely to have osteophytes, and in the ACLR subgroup even more so. While these results are exploratory and hypothesis generating, further confirmatory research could clarify whether these individuals are indeed at higher risk of OA and if they could thus benefit from more intense or more targeted OA-prevention management.

Most previously published studies on this topic focus on ACL injuries, thus our results may differ somewhat because our sample, by design, was more heterogeneous by including not only ACLR but also other injuries like other ligament or meniscus injuries. In a cross-sectional study 1 year after ACLR, higher bisect offset, shallower sulcus angle, and higher trochlear angle were associated with definite patellofemoral radiographic osteophytes, similar to the results of our present study, for both the full sample and the ACLR subgroup.[10] However, where the previous study found no association with lateral patellar tilt and lateral trochlear inclination, we did find associations with osteophytes in the present study. The different study findings could be due to the other study sample only being 1-year post-ACLR, or because of using radiographs instead of MRI to evaluate osteophytes. Alternatively, it could relate to the different analysis methods, since the previous study used logistic regression, which would assume a constant linear relationship along the spectrum of geometry values, whereas we focused on extreme values of geometry known to be associated with higher risk of OA.[12] Like the other study, we also found that Insall-Salvati ratios were not associated with any OA-related structural features among injured individuals. While this is consistent with the previous ACLR study,[10] it is in contrast to another study in a sample 7 years post-ACLR in which Insall-Salvati ratios were lower among those who had patellofemoral OA compared with those without.[35]

Having an uninjured comparison group in our present study extends previous findings that associations exist between geometry and structural lesions within individuals following injury, adding that these associations may also exist in the knees of similar but uninjured individuals. Patellofemoral geometry may not be the primary driver of posttraumatic OA onset, though it may contribute to this process. The injury itself, including the related inflammatory cascade or surgery following the injury, likely remains a key driver of early onset posttraumatic OA, particularly osteophyte formation.

4.3 | Limitations

The PrE-OA study included participants 3–10 years following injury, and therefore exact characteristics of injuries are not known because we were unable to acquire MRI images at the time of injury. Since this was an ancillary analysis of an existing cohort, the study was not powered for this research question. This, in addition to the multiple comparisons performed in this study, may have resulted in spurious findings. A much larger sample would be needed to confirm the hypotheses generated from this exploratory study. To adequately power such a study would require consideration that prevalence of extreme values of patellofemoral geometry are expected to be quite low, even in injured populations, as are signs of structural damage in the initial years following a knee injury.

A related limitation is that only 6% of our participants had BMLs, thus we were unable to evaluate this feature as an outcome. This appears to be lower than in previously published studies, even in those without knee injuries. For example, a 3 Tesla study of uninjured athletes of similar age to our present study in which 51% had patellar BMLs,[39] and pooled estimates of BMLs in uninjured knees in individuals of all ages who play weight-bearing sports is approximately 30%.[40] The difference among studies is not fully understood but could in part relate to participant characteristics, strength of scanners, or sequence parameters used to evaluate BMLs.

We did not evaluate the lateral patellofemoral joint separately in the present study on account of overall low prevalence of structural features. This is relevant since lateral patellofemoral joint OA may be more strongly associated with knee geometry than medial patellofemoral joint OA, and thus evaluating OA of the entire patellofemoral joint could statistically mask true effects.[11,12]

Geometry measures were derived from MRI images in which participants were positioned in supine and nonweightbearing. While this would not influence bony morphology measures, alignment likely differs during upright, weightbearing positions and during daily activities in comparison to supine. It is not known to what extent this would influence our study results.

Finally, this was a cross-sectional study, and a longitudinal study design would make it possible to consider whether these associations represent a causal mechanism for the onset or worsening of posttraumatic OA.

4.4 | Perspective

Sport-related intra-articular joint injury is a major risk factor for developing posttraumatic knee OA.[1–3] Preventing posttraumatic OA is hence an important aspect of rehabilitation efforts in sports medicine and orthopaedics. Although knee OA commonly begins in the patellofemoral joint and later progresses to involve the tibiofemoral joint,[4–7] little is known about what factors might cause OA to develop in this compartment, or whether targeting the patellofemoral joint during rehabilitation could mitigate the overall risk of developing posttraumatic knee OA.

We found that alignment and morphology were associated with one or more MRI-derived structural features, most commonly cartilage and osteophytes but also effusion-synovitis. Because the PrE-OA cohort included uninjured individuals, we were able to contribute a novel finding to the field in this study, namely that the likelihood of having MRI-derived OA features may be highest when extreme values of alignment or morphology are detected in individuals with a history of knee injury. Clinically, these individuals may benefit from targeted interventions[16,17] that might optimize alignment or associated cartilage pressures and prevent posttraumatic OA. We note that these hypotheses derived from our exploratory study require further confirmatory investigation before offering concrete recommendations to clinicians.

AUTHOR CONTRIBUTIONS

This study was conceived of and designed by Carolyn A. Emery, Jackie L. Whittaker, Janet L. Ronsky, Jacob L. Jaremko, and Erin M. Macri. Data were collected by Jackie L. Whittaker, Gregor Kuntze, Clodagh M. Toomey, Jacob L. Jaremko, and Erin M. Macri. Statistical analysis was performed by Erin M. Macri and Jean-Michel Galarneau, and Carolyn A. Emery, Jackie L. Whittaker, Janet L. Ronsky, Jacob L. Jaremko, Gregor Kuntze, Clodagh M. Toomey, Erin M. Macri, and Jean-Michel Galarneau interpreted the results. Erin M. Macri wrote the manuscript with critical input from Carolyn A. Emery, Jackie L. Whittaker, Janet L. Ronsky, Jacob L. Jaremko, Gregor Kuntze, Clodagh M. Toomey, and Jean-Michel Galarneau. All authors approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

Jackie L. Whittaker is Associate Editor for British Journal of Sports Medicine, and Editor for Journal of Orthopaedic & Sports Physical

Therapy. Erin M. Macri is Associate Editor for British Journal of Sports Medicine, and Editor for Arthritis Care & Research. The remaining authors declare no conflict of interest.

ETHICS STATEMENT

Ethics approval was granted from the Conjoint Health Research Ethics Board, University of Calgary, Canada. All participants provided informed consent to participate in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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