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Patella malalignment, pain and patellofemoral progression: the Health ABC Study[1]

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Summary

Objective: Patellofemoral (PF) joint osteoarthritis (OA) is strongly correlated with lower extremity disability and knee pain. Risk factors for pain and structural progression in PF OA are poorly understood. Our objective was to determine the association between patella malalignment and its relation to pain severity, and PF OA disease progression.

Methods: We conducted an analysis of data from the Health ABC knee OA study. Health ABC is a community based, multi-center cohort study of 3075 Caucasian and Black men and women aged 70–79 at enrollment. Weight bearing skyline knee X-rays were obtained in a subset (595) of subjects, with and without knee pain, at year 2 and year 5 (mean follow-up 36 months). Films were read paired, and PF osteophytes (OST) and joint space narrowing (JSN) were scored on a 0–3 scale using the Osteoarthritis Research Society International atlas. We defined progression of PF OA as any increase in JSN score. Three measures of *patella malalignment* were made: sulcus angle; patella tilt angle; and patella subluxation medially or laterally (bisect offset). Knee symptoms were assessed using a knee specific Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) knee pain subscale. We assessed the relationship between baseline patella malalignment and pain severity (linear regression for WOMAC) and compartment specific PF OA progression (logistic regression for dichotomous outcomes). We classified continuous measures of patella alignment into quartile groups. We performed multivariable adjusted logistic regression models, including age, gender and body mass index (BMI) to assess the relation of baseline patella alignment to the occurrence of PF JSN progression using generalized estimating equations (GEE).

Results: The subjects had a mean age 73.6 (SD 2.9), BMI 28.8 (SD 4.9), 40.3% male, and 46% were Black. Medial displacement of the patella predisposed to medial JSN progression; odds for each quartile 1, 1.2, 1.2, 2.2 (P for trend = 0.03), whilst protecting from lateral JSN progression; odds for each quartile 1, 0.7, 0.6, 0.4 (P for trend = 0.0004). Increasing patella tilt protected from medial JSN progression; odds for each quartile 1, 0.8, 0.5, 0.2 ($P < 0.0001$) and trended to increasing pain severity ($P = 0.09$).

Conclusion: Patella malalignment is associated with PF disease progression. Medial displacement and tilt of the patella predisposes to medial JSN progression, whilst lateral displacement is predictive of lateral JSN progression. The influence of patella malalignment has important implications since it is potentially modifiable through footwear, taping and/or knee bracing.

Key words: Patellofemoral osteoarthritis, Patella alignment.

Introduction

Our current understanding of the sources of pain and hence disability in knee osteoarthritis (OA) is limited[1]. Previous research has concentrated primarily on the tibiofemoral (TF) joint and has shown a weak correlation between radiographic structural change and both pain and disability[2]. Relatively little attention has been paid to the patellofemoral (PF) joint, despite suggestions that disease there may be strongly correlated with lower extremity disability[3], and that assessment of the PF joint may provide a clearer explanation for knee pain in OA[4]. Whilst good epidemiological information is available for TF OA[5–7], accurate data for risk factors for PF disease are unknown. Epidemiology studies suggest that the risk factors associated with disease are different for PF OA and TF OA[8,9], and the contribution of risk factors unique to PF OA and its progression are relatively unknown[10].

The studies that have been conducted have considered risk factors for TF OA with little regard to the unique

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biomechanics of the PF joint[9,11,12]. OA progression in the PF compartment may be influenced by a profile of factors different from those in either medial or lateral TF disease. Both biomechanical and clinical studies provide support for this theory. First, the designs of the PF and TF compartments each reflect unique functions and mechanics[13]. Second, subjects with knee OA may have disease isolated to the PF compartment, isolated to one TF compartment, or concomitant disease in the PF compartment and one TF compartment[8]. In individuals with PF OA and TF OA in the same knee, no correlation has been found between OA severity in the PF and TF compartments[14].

Patellar malalignment may cause an aberrant dispersion of PF joint reaction (PFJR) force and through this mechanism potentially predispose to pain and/or structural progression[15–17]. Although the kinematics of the knee involve motion patterns composed of axial internal and external rotation and slight varus–valgus movement during flexion and extension, the predominant motion at the knee is flexion–extension. Furthermore, this flexion–extension or hinge type of motion occurs about centers of rotation located above the joint line on the femoral side, proximate to the PF joint. Patellar malalignment is a translational or rotational deviation of the patella relative to any axis that may lead to an aberrant dispersion of the forces transmitted through the PF joint[17]. The main force of concern is lateral in the coronal and especially axial planes[18]. Uncontrolled data suggest that patellae that are located centrally in the trochlear groove, and not malaligned may be less likely to develop OA[14,19,20].

Our objective was to investigate the association between patella malalignment and its relation to pain severity and PF OA disease progression.

Materials and methods

STUDY SAMPLE

Health ABC is a community based, multi-center, cohort study of 3075 non-institutionalized White and Black men and women aged 70–79 (mean age 73) at enrollment. Subjects were recruited primarily from a random sample of Medicare-eligible adults from a list provided by the Health Care Financing Administration; 33% of men and 46% of women are Black. The primary objective of the study is to examine the incidence of physical disability in relation to body composition and weight-related health conditions in healthy older persons. At baseline (1997–1998), all participants reported themselves free of disability in activities of daily living and free of functional limitations (defined as difficulty walking a quarter of a mile or up 10 steps). The study was approved by the Institutional Review Boards at The University of Tennessee and The University of Pittsburgh; the two clinical sites for the study.

ASSESSMENT AND DEFINITION OF KNEE SYMPTOMS

Study interviewers assessed knee symptoms at each visit by asking participants if they had "pain, aching or stiffness on most days for at least 1 month" at some time during the past year, and interviewers also administered a modified Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) pain scale[21]. The modified WOMAC pain subscale uses a five-point Likert scale and asks subjects to rate any knee pain during each of six activities (total score range 0–24): walking on a flat surface, going up or down stairs, at night while in bed, standing upright, getting in or out of a chair, and getting in or out of a car. A knee was defined as having symptoms if the participant reported pain, aching, or stiffness in that knee on most days for at least 1 month in the past 12 months or if they reported moderate or worse knee pain during the last 30 days in association with $\geq$1 activity listed in the WOMAC pain scale.

At the year 2 clinic visit, a subset of participants underwent imaging of the knee to assess OA[22]. At this visit, all participants with frequent knee pain (pain on most days of a month in the past year) and those with moderate or worse knee pain during any activity on the WOMAC knee pain scale were recruited to have a bilateral knee radiograph. Of subjects with at least one symptomatic knee, 861 (94%) completed the X-ray exam. In addition, in Health ABC a random sample of 276 participants without knee symptoms had a knee X-ray exam.

RADIOGRAPHIC ASSESSMENT

Bilateral views of the TF compartment of the knee joint were obtained using the Fixed-Flexion technique[23], and axial (skyline) views were obtained of the PF joint. For the TF compartment, both knees were assessed radiographically with a posteroanterior projection using a positioning frame (SynaFlexer; Synarc, San Francisco, CA) in order to fix knee flexion (between 20° and 30°) and external rotation of the feet at 10° for each subject. For the PF view, each knee was imaged separately with the participant in a standing position and the limb flexed at 30–40° during weight bearing[24].

Knee X-rays were obtained in a subset (595) of subjects, with knee pain (in at least one knee), at two time points; year 2 and year 5 (mean follow-up 36 months). Films were read paired and joint space narrowing (JSN) was scored on a 0–3 scale using the Osteoarthritis Research Society International atlas[25]. We defined progression of PF OA as any increase in JSN score in either the medial or lateral PF joint. The films were read by one trained observer and reliability was established at the beginning and drift was assessed through the course of reading. The intra-observer reproducibility for reading JSN ranged from 0.82 to 0.90 (kappa).

PF ALIGNMENT

The assessment of PF motion was made from a weight bearing skyline film. There are a number of different methods to characterize abnormal motion of the patella relative to the femur and attempts to standardize these have been described previously[26]. The measures chosen include one of femoral dysplasia, one of tilt, and one of lateral displacement. The measures are widely recognized and have been used in previous studies[26,27].

Three measures of *patella alignment* were made on the skyline radiograph from the year 2 visit: *patella subluxation medially or laterally* (*bisect offset* which measures the patellar width medial and lateral to the deepest portion of the trochlear groove – Fig. 1)[28], dysplasia of the femoral trochlea (the sulcus angle – Fig. 2)[29]; and patellar tilt (the patella tilt angle – Fig. 3)[30]. These measures have been developed and used using more dynamic techniques such as cine magnefic resonance imaging (MRI) or computer tomography (CT). These other investigative techniques may provide more information as they are assessed at multiple flexion angles. However these techniques are not available in all centers and their processing is much more labor intensive meaning that applying them to large data sets such as the one here is not practical.

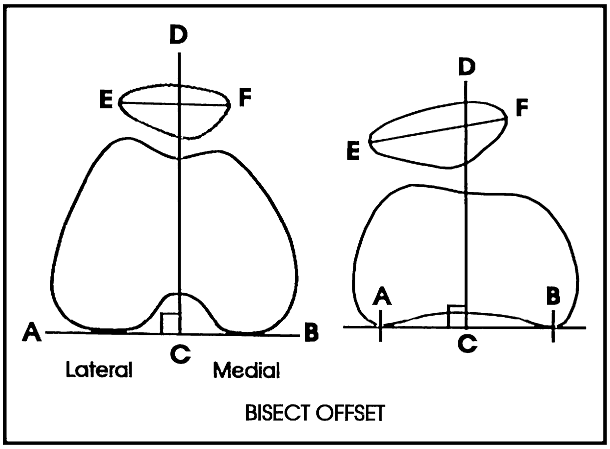

Fig. 1. Method used to measure medial and lateral displacement using the bisect offset measurement[28]. This was determined by drawing a line connecting the posterior femoral condyles (AB) and then projecting a perpendicular line anteriorly through the deepest portion of the trochlear groove (CD) to a point where it bisected the patellar width line (EF) (left). To obtain data when the trochlear groove was flattened, the perpendicular line was projected anteriorly from the bisection of the posterior condylar line (right). The bisect offset represents the extent of the patella lying lateral to the midline and is expressed as the percentage of patellar width.

The reading of alignment on the baseline film was done at the same reading session and prior to the evaluation of the individual radiographic features on the baseline and follow-up film. For all films there was a single reader who thus was unblinded to sequence in reading the individual radiographic features. Intra-observer intraclass correlation coefficients (ICCs) for reading alignment ranged from 0.81 to 0.95. Inter-observer ICCs were assessed on 15 paired films and ranged from 0.68 to 0.86.

STATISTICAL ANALYSIS

We assessed the relation between baseline patella malalignment to the pain severity (WOMAC) and

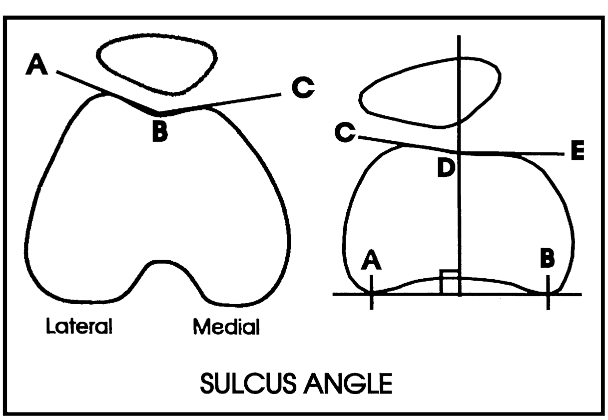

Fig. 2. Method used to measure the sulcus angle[30]. This angle was defined by lines joining the highest points of the medial and lateral condyles and the lowest point of the intercondylar sulcus (AB and CB) (left). In order to obtain data when the trochlear groove lacked discernible depth, the center of the sulcus angle was defined by a perpendicular line that was projected anteriorly from the bisection of the posterior condylar line (right). All sulcus angle measurements are reported in degrees.

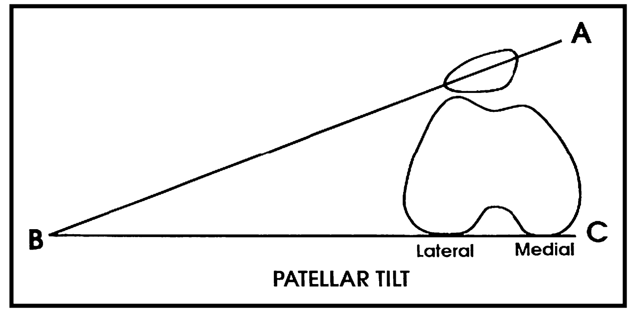

Fig. 3. Method used to assess patellar tilt[29]. *Patellar tilt* was defined as the angle formed by lines joining the maximum width of the patella (AB) and the posterior femoral condyles (BC). All tilt measurements will be reported in degrees. Normal tilt ranges from 0° to 5°, and tilt angles of greater than 10° are abnormal.

compartment specific PF OA progression. Initially analyses were conducted in specific genders and then when results were found to be similar between genders, the data were combined and analyses adjusted for gender. For the cross sectional relationship at baseline between patella malalignment (the predictor) and pain severity, we conducted a linear regression with WOMAC pain score as the dependent variable. We obtained a standardized beta coefficient using generalized estimating equations (GEE − to adjust for correlation between knees in knee specific analysis) from the linear regression model. The power to detect the relation of baseline WOMAC pain to tilt observed in the paper was 87% given the sample size we had.

For the analysis of PF OA radiographic progression we classified the continuous measures of patella alignment into quartiles. The number of cases of PF JSN progression despite the large sample size used in this study was small. In order to provide more equal distribution of knees between the quartiles we have used population-based quartiles of alignment using the first alignment measure (bisect offset) to provide this quartile assignment. We used this approach since we were interested in more than one dichotomous outcome, i.e., medial and lateral PF JSN progression. We performed multivariable adjusted logistic regression, adjusting for age, gender, race and body mass index (BMI) to assess the relation of baseline patella alignment to PF OA progression using GEE, to generate adjusted odds ratios (OR) and 95% confidence intervals (95% CI). We assessed the significance of trend across the quartiles by creating a four level variable with the median value for the quartiles of alignment as the value for each level thus generating a linear test for trend, and for sulcus angle where the relationship did appear J-shaped we added a quadratic term of alignment measurement.

Results

Of the 1137 subjects who had an X-ray at the baseline examination 595 had a further examination at the year 5 examination. In comparing these with the 542 participants who did not have the follow-up OA examination the subjects were comparable in age, gender and race. These samples did differ in relation to the proportion with PF OA at baseline 49% vs 33% and mean WOMAC pain at baseline 7.3 vs 4.2 in those with follow-up vs those without, respectively.

At the baseline examination, the 595 subjects had a mean age 73.6 (SD 2.9), BMI 28.8 (SD 4.9), 40.3% male, and 46% were Black. Forty-nine percent of persons

Table I
Demographic characteristics of study population at baseline

Age (year) (mean ± SD)	73.6 ± 2.9
BMI (kg/m^2) (mean ± SD)	28.8 ± 4.9
Gender, women (%)	59.7
Race, Blacks (%)	45.7
K&L ≥ 2 (%)	46.8
PF ROA	49.1
K&L (%)	
0	35.5
1	17.7
2	15.5
3	16.9
4	14.4
WOMAC pain (mean ± SD)	7.3 ± 4.5
Pain on most days in last 30 days (%)	78.1
Pain on most days in last 12 months (%)	79.7

had PF radiographic osteoarthritis (ROA), and 47% of persons had TF ROA. Amongst those with TF ROA 16% were Kellgren and Lawrence (K&L) = 2, 17% were K&L = 3, and 14% were K&L = 4 (see Table I). Among 362 knees with PF ROA at baseline, the distribution of PF JSN (0, 1, 2, and 3) was 68.8%, 19.6%, 9.7%, and 1.9% in the medial compartment, and 51.5%, 19.1%, 19.4%, and 10.0% in the lateral compartment, respectively. The proportion of subjects with PF JSN progression was 5.7% lateral and 7.1% medial.

The results of the association between WOMAC pain and the patella alignment measures are presented in Table II. With increasing tilt angle there is a trend to a decrease in WOMAC pain. The other measures of PF alignment showed no relation to pain severity.

The correlation between the three exposures (offset, sulcus angle and tilt) used in this study was weak at best. The correlation between bisect offset and sulcus angle was −0.06 ($P = 0.04$), between bisect offset and tilt was −0.21 ($P = 0.0001$) and sulcus angle and tilt was 0.08 ($P = 0.004$).

The most profound effects of patella malalignment on structural progression were seen with bisect offset (patella subluxation), and results for the association with JSN progression are presented in Table III. Bisect offset measures the medial and lateral shift of patella. As the patella became more laterally located, i.e., as the percentage of lateral offset increased, the risk lateral JSN progression increased. The reference group we have chosen is the most laterally displaced quartile (a physiologic offset is approximately 0.40)[27,28,31]. With increasing medial displacement there is increased odds of medial PF JSN progression (P for trend = 0.03). Similarly with increasing lateral displacement there is increased odds of lateral JSN progression (P for trend = 0.02).

The results of sulcus angle association with JSN progression are presented in Table IV. The second and third quartiles demonstrate a trend to increased odds of medial JSN progression with a non-significant test for a J-shaped trend (P for J-shaped trend = 0.07). The extreme quartiles (first and fourth) demonstrate a significant trend to lateral JSN progression (P for trend = 0.04).

The results of patella tilt association with JSN progression are presented in Table V. A negative patella tilt angle indicates tilt toward the medial side and a positive angle tilt to the lateral side. With increasing tilt there is a protective effect on medial JSN progression (P for trend < 0.0001) with no trend to lateral JSN progression.

Table II
Relationship between standardized patella subluxation measures and WOMAC pain

Measure of subluxation	Estimate (95% CI)	P value
Offset	0.02 (−0.26 to 0.30)	0.87
Sulcus angle	0.04 (−0.20 to 0.30)	0.70
Tilt	−0.21 (−0.45 to 0.03)	0.09

Adjusted for age, BMI, gender and race.

Discussion

Patella subluxation is associated with PF OA progression. Medial displacement of the patella predisposes to medial JSN progression, whilst increasing lateral displacement predisposes to lateral JSN progression. Patella tilt is also associated with disease progression and a trend to increasing pain severity.

The most common symptoms of knee OA occur with activities that preferentially engage the PF joint, and generate the highest forces and torques, such as descending stairs, and arising from a chair[32,33]. These activities load all compartments of the knee; however, the forces are greatest in the PF joint. Patellar tilt appears to predispose to pain presumably through an aberrant dispersion of the forces through the PF joint. Specifically Grelsamer[16] hypothesized that if the patella is tilted painful stresses can develop[16,17,34].

Each measure provides different information about the exposure of PF malalignment. The measurement of bisect offset provided strong effects as an exposure for both medial and lateral PF JSN progression. In contrast measurement of tilt and sulcus angle appeared to influence the risk of medial progression more than lateral progression. One potential explanation for this is that medial PF JSN progression was more common than lateral providing greater opportunity to assess the effect of these exposures on this outcome.

The etiopathogenesis of OA is widely believed to be the result of local mechanical factors acting within the context of systemic susceptibility. OA is characterized by changes in structure and function of the joint with the central component being degradation and subsequent loss of articular cartilage with related changes in the underlying bone[35]. Patellae that are located centrally in the trochlear groove and not malaligned are thought to be less likely to develop OA[14,19,20]. When the cartilage in a compartment is under stress due to the aberrant biomechanics of the patella, there is an increased risk of JSN, while when it is unloaded JSN is less likely to occur.

The potential relation of alterations in patellar alignment predisposing to symptoms has been explored in PF pain syndrome; a condition that typically manifests in a much younger spectrum of the population than PF OA. Previous studies in persons with PF pain syndrome have identified abnormalities in both kinematics and joint stress[36–38]. More recently there have been suggestions that one of the long term sequelae of PF pain syndrome may be PF OA warranting joint replacement[39].

To appreciate the forces that potentially can lead to increased PF loading it is helpful to consider the unique biomechanics of this joint; thus providing insights to risk factors for PF OA[15]. The patella increases the mechanical advantage of extensor muscles by transmitting forces across the knee at greater distance (moment) from the axis of rotation. In so doing, it increases the functional lever arm of quadriceps as well as changing the direction of pull of the quadriceps mechanism. It is the principal site of insertion

Table III
Relationship between bisect offset and PF JSN progression

Quartile of subluxation	1 Reference group ($n = 291$ knees)	2 ($n = 292$ knees)	3 ($n = 291$ knees)	4 ($n = 293$ knees)	*P* for trend
Offset measure	0–0.38 (most lateral displacement)	>0.38–0.43	>0.43–0.47	>0.47–0.60 (most medial displacement)	
Lateral PF JSN progression					
N of case knees	22	17	15	9	
OR (95% CI)	1	0.70 (0.34–1.44)	0.62 (0.30–1.27)	0.35 (0.15–0.83)	0.02
Medial PF JSN progression					
N of case knees	16	17	17	30	
OR (95% CI)	1	1.15 (0.56–2.35)	1.17 (0.58–2.36)	2.23 (1.10–4.50)	0.03

Adjusted for age, BMI, gender, and race.

of quadriceps, and it transmits the tensile forces generated by the quadriceps to the patellar ligament. Stability of the PF joint is dependent on the passive, dynamic and static restraints around the knee. The primary dynamic restraint is the quadriceps muscles. The primary static constraint is the articular anatomy of the femoral condyles in particular the trochlear depth/sulcus angle and the shape of the retropatellar surface[40].

The dynamic and static stabilizing forces of the patella cause the patella to compress [joint reaction force (JRF)] against the femur. This is termed the PFJR force and this force increases with increasing knee flexion. The JRF during walking (10–15° of flexion) is approximately 50% of bodyweight. Walking up stairs (60°) the JRF is 3.3 × bodyweight. During squats (130°), the JRF is 7.8 × bodyweight[17]. Previous studies have suggested that PF joint kinematics and mechanics may directly contribute to PF OA[19,41–43].

The three measures patella alignment assessed on the skyline radiographs are those most frequently cited in the literature[16,27,30]. In the mid 1990s, Harrison *et al.* examined skyline view knee X-rays of 109 knees in 65 patients with symptomatic PF OA. They found that the amount (defined as summary score of radiographic changes, i.e., joint space loss, osteophyte (OST) formation, and bone cystic changes, in the PF joint) and site of PF arthrosis were correlated with patella position and limb alignment. Patellae that were located centrally in the trochlear grove had the lowest radiographic score for arthritis. Subluxation of the patella either medially or laterally was associated with an increased risk for radiographic scores[19]. The findings of this study suggest that patella malalignment appeared to be associated with the severity of overall radiographic changes in PF OA patients.

Our results add to this by demonstrating that patella malalignment predisposes to progression. The few studies that have explored PF OA show that the lateral PF compartment is more frequently affected than the medial[11,14,19]. Previous studies have shown that the PFJR force may directly contribute to PF OA[41,42]. One parameter that may influence the PFJR force is patella malalignment. The lateral compartment likely has higher contact pressures as a result of increased patella tilt and lateral subluxation[14,19]. This may be why an application of a medial glide to the patella (forcing the patella medially and away from an overloaded lateral compartment) in previous studies of taping leads to a positive effect on knee symptoms[44,45]. The potential for therapies that realign the patella to have a structure modifying effect has not been explored.

Our findings have a number of potential limitations that warrant consideration. One concern is the potential for collinearity in our analyses. For example lateral PF JSN itself allows increased lateral subluxation through alteration in the structure of the PF joint. In the absence of observational studies of longer duration with more time points the precise sequence of events awaits further exploration. Further the number of cases particularly in the extreme quartiles was often small hence the often wide CI. We would commend replicating this analysis in a larger data set.

The self reported assessment of pain in the knee is for the knee as a whole. Knee symptoms can emanate from a number of different tissues including the subchondral bone, synovium, retinaculum, skin, muscle and nerves. In addition it can come from the PF joint or the TF joint. Assessment of the alignment of the PF joint provides only one small keyhole view into a complex array of possible sources of knee pain. Further this study suggests that if a relationship exists between patella alignment and pain it is weak.

We studied elderly subjects who were well-functioning 1 year prior to the baseline OA assessments. Our findings

Table IV
Relationship between sulcus angle and PF JSN progression

Quartile of subluxation	1 Reference group ($n = 291$ knees)	2 ($n = 252$ knees)	3 ($n = 341$ knees)	4 ($n = 280$ knees)	*P* for trend
Sulcus	108–125	126–129	130–135	136–156	
Lateral PF JSN progression					
N of cases	16	9	12	25	
OR (95% CI)	1	0.63 (0.30–1.33)	0.72 (0.33–1.61)	2.09 (0.99–4.41)	0.04
Medial PF JSN progression					
N of cases	10	27	30	13	
OR (95% CI)	1	3.38 (1.56–7.34)	2.99 (1.39–6.43)	1.49 (0.60–3.73)	Linear 0.76 U-shaped 0.067

Adjusted for age, BMI, gender, and race.

Table V
Relationship between tilt angle and PF JSN progression

Quartile of subluxation	1 Reference group (*n* = 288 knees)	2 (*n* = 292 knees)	3 (*n* = 252 knees)	4 (*n* = 334 knees)	*P* for trend
Tilt	−7 to 2	3 to 4	5 to 6	7 to 18	
Lateral PF JSN progression					
N of cases	20	12	9	22	
OR (95% CI)	1	0.61 (0.28−1.29)	0.58 (0.26−1.32)	1.13 (0.57−2.24)	0.70
Medial PF JSN progression					
N of cases	32	25	15	8	
OR (95% CI)	1	0.74 (0.41−1.34)	0.51 (0.25−1.03)	0.19 (0.09−0.43)	<0.0001

Adjusted for age, BMI, gender, and race.

may not apply to other groups. The population was older at the age of inception than many other OA cohorts. A distinct advantage of this sample is the inclusion of a large sample of Blacks however this may detract from the ability to compare the findings directly with other predominantly Caucasian cohorts such as Framingham. A large proportion of those who attended the baseline knee X-ray exam did not attend for follow-up X-ray exam. Those who did attend for follow-up tended to have more OA and more symptoms thus representing a more severe OA group than the whole sample. This may have afforded us greater power to detect the associations we did find.

The selection methods ensured that at the baseline examination of the parent study, eligible participants were free of disability in activities of daily living and free of functional limitations (defined as difficulty walking a quarter of a mile or up 10 steps). This may have biased the sample selection at the year 1 follow-up exam for the present study such that those with the most severe knee OA may have been excluded. However this population has been used in other analyses which suggests that the pattern of OA is similar to that in other cohorts[22,46]. Similarly the control sample (those free of knee symptoms at baseline) was limited in number in comparison with the true prevalence of those without knee symptoms in the community. The analyses presented in this manuscript pertain to the relation between patella alignment and PF OA. If there were a bias it would be toward not finding a relationship between patella alignment and PF OA as more disabled (and potentially with that those with the most severe OA/most progression) would have been excluded. In addition, the contrast between a small asymptomatic sample and those with symptoms may have reduced our opportunity to find an association between patella alignment and pain.

The WOMAC scale was not normally distributed (25% subjects had WOMAC pain score as zero) and despite trying standard methods to normalize this distribution we could not make this more normally distributed. This said linear regression is robust to violation of assumptions of normality.

The X-rays taken in our study were not acquired dynamically and were taken at one knee flexion angle. A laterally displaced patella (higher BO) and/or lateral border of patella tilted down on these images likely indicates the tightness of the structures that hold patella in a lateral position (lateral retinaculum, vastus lateralis, iliotibial band). In this situation, during dynamic movement of the knee greater load and therefore greater shear force will be placed on the lateral PF compartment, in comparison to the situation where patella is located directly against trochlear sulcus and the load forces are divided equally between lateral and medial PF compartments. A static view of the knee taken at one flexion angle is likely to underestimate the true exposure to patella malalignment. Further evaluation using dynamic imaging techniques such as MRI would allow further evaluation of this exposure. For all films there was a single reader who was unblinded to sequence in reading alignment and the individual radiographic features. This may have biased the reader in detecting and reading progression.

In sum we have found that patella subluxation, sulcus angle and patella tilt are associated with PF OA progression. These findings warrant replication in other data sets. Assuming they are replicated, and these findings reinforce the importance of PF alignment both for symptoms and PF OA progression, this has important implications. PF alignment is potentially modifiable through footwear advice[47], taping and/or knee bracing[45,48].

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