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Associations between patellofemoral joint cartilage $T_{1\rho}$ and T_2 and knee flexion moment and impulse during gait in individuals with and without patellofemoral joint osteoarthritis

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SUMMARY

Objective: This study aimed to investigate the associations between patellofemoral cartilage $T_{1\rho}$ and T_2 relaxation times and knee flexion moment (KFM) and KFM impulse during gait.

Method: Knee magnetic resonance (MR) images were obtained from 99 subjects with and without patellofemoral joint (PFJ) osteoarthritis (OA), using fast spin-echo, $T_{1\rho}$ and T_2 relaxation time sequences. Patellar and trochlear cartilage relaxation times were computed for the whole cartilage, and superficial and deep layers (laminar analysis). Subjects also underwent three-dimensional (3D) gait analysis. Peak KFM and KFM impulse were calculated during the stance phase. Linear regressions were used to examine whether cartilage relaxation times were associated with knee kinetics during walking while adjusting age, sex, body mass index (BMI) and walking speed.

Results: Higher peak KFM and KFM impulse were significantly related to higher $T_{1\rho}$ and T_2 relaxation times of the trochlear and patellar cartilage, with standardized regression coefficients

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- Analysis and interpretation of data: all authors Drafting of and revising the article for important intellectual content: all authors
- Final approval of the article: all authors

Conflict of interest

None of the authors have any financial and personal relationships with other people or organizations that could potentially and inappropriately influence (bias) this work and conclusions.

ranging from 0.21 to 0.28. Laminar analysis showed that overall the superficial layer of patellofemoral cartilage showed stronger associations with knee kinetics. Subgroup analysis revealed that in subjects with PFJ OA, every standard deviation change in knee kinetics was related to greater increases in PFJ cartilage $T_{1\rho}$ and T_2 (standardized coefficients: 0.29 to 0.41). Conversely, in subjects without OA, weaker relationships were observed between knee kinetics and PFJ cartilage $T_{1\rho}$ and T_2.

Conclusions: Our findings suggest that increased peak KFM and KFM impulse were related to worse cartilage health at the PFJ. This association is more prominent in superficial layer cartilage and cartilage with morphological lesions.

Keywords

Magnetic resonance imaging; Relaxation time; Gait; Patellofemoral joint

Introduction

Patellofemoral joint (PFJ) osteoarthritis (OA) is a prevalent knee condition[1–3] that is highly associated with pain and dysfunction[4,5]. Mechanical loading is integral to the onset and progression of OA[6,7], contributing to articular cartilage matrix deterioration and loss, the hallmark of OA[6,7]. It has been well-documented that increased external knee adduction moment and knee adduction moment impulse, which can result in higher mechanical load at the medial tibiofemoral joint (TFJ), are related to degeneration of the medial TFJ cartilage[8–10]. However, only few studies have investigated gait characteristics in individuals with PFJ OA[11–15] and limited information has been reported regarding knee kinetics associated with PFJ cartilage health.

Sagittal plane knee kinetic variables are indicative of PFJ mechanical loading during gait. Knee flexion moment (KFM) is the external moment acting in the sagittal plane to flex the knee joint. During the stance phase of gait, the quadriceps femoris contracts to counteract this external moment[16]. As such, an increase in KFM is indicative of a higher quadriceps force. Because PFJ reaction force is the resultant force of quadriceps force and patellar tendon force, an increase in KFM can result in a higher PFJ reaction force and stress[17,18]. Moreover, KFM impulse is calculated as the integral of KFM with respect to time. Thus, it takes into account both duration and magnitude of loading, and may be more related to knee OA than peak joint moment[19–22]. Both increased KFM and KFM impulse can result in higher mechanical loading at the PFJ[17,18,23] and have been shown to be related to morphological lesions of PFJ OA[24,25]. Yet, it remains unclear whether these biomechanical factors are associated with PFJ cartilage biochemical composition. Understanding these relationships is critical, as changes in cartilage composition can provide indications of early cartilage degeneration which can occur before morphological changes are visualized on radiographs and magnetic resonance (MR) images[26–28].

Quantitative MR $T_{1\rho}$ and T_2 relaxation times provide a noninvasive means to evaluate compositional changes related to cartilage degeneration. Specifically, an increase in cartilage $T_{1\rho}$ relaxation time is related to a loss of glycosaminoglycan[29–31]; and an increase in cartilage T_2 relaxation time is associated with an increase in water content and

disorganization of the collagen matrix[30,32,33]. Cartilage MR relaxation times can be quantified by the whole compartment or by separating the superficial and deep cartilage layers[34]. A previous study investigating knee OA following anterior cruciate ligament injury found that cartilage degeneration initiated from the superficial layer[35]. These imaging metrics have been widely used as imaging biomarkers of early cartilage degeneration[26–28], but have not been utilized to identify biomechanical factors related to PFJ OA. In addition, degenerative cartilage is less stiff and may be more susceptible to mechanical load[36].

The primary aim of this study was to evaluate the associations between sagittal plane knee kinetics during gait (i.e., peak KFM and KFM impulse) and PFJ cartilage $T_{1\rho}$ and T_2 relaxation times. The secondary aim was to examine these associations for the superficial and deep layers PFJ cartilage (laminar analysis). The tertiary aim of this study was to evaluate these associations in individuals with and without PFJ OA (subgroup analysis). We hypothesized that higher peak KFM and KFM impulse would be related to higher PFJ cartilage $T_{1\rho}$ and T_2 relaxation times and the superficial layer cartilage would show stronger correlation with knee kinetic variables than deep layer cartilage. Lastly, we hypothesized that the observed association would be stronger in individuals with PFJ OA than those without OA.

Methods

Subjects

Participants were recruited from the local community as a part of a longitudinal knee OA study. Fifty-six subjects with PFJ OA and 43 subjects without PFJ or TFJ OA (controls) were included in this study. All participants were above 35 years of age and did not have: (1) history of lower extremity or spine surgery, (2) total joint replacement of any lower extremity joint, (3) self-reported inflammatory arthritis, (4) any conditions that limited the ability to walk without assistant device, and (5) contraindications to MR imaging[24]. Because this study was a part of a primary study focused on TFJ OA, all participants underwent a weight-bearing, posteroanterior, fixed-flexion radiograph of the TFJs. The knee with higher Kellgren–Lawrence (KL) grade was chosen for MR imaging and biomechanical tests. When both knees presented the same KL grade, the test limb was determined randomly. The study was approved by the Committee of Human Research of the university. Prior to participation, all subjects signed a written informed consent. Moreover, all subjects completed the Knee injury and Osteoarthritis Outcome Score (KOOS) survey, which has a range from 0 to 100[37]. A higher KOOS score represents less pain and better function[37].

MR acquisition

MR images of the knee were acquired using a 3-T MR 750w Scanner (General Electric, Milwaukee, WI) and an 8-channel phased-array knee coil (Invivo, Orlando, FL). All subjects were positioned in supine with their knee in neutral rotation and full extension. To reduce movement, the test foot was secured in place, the study knee was stabilized with padding, and a belt was secured across the subject's waist. All subjects arrived at the imaging center and were unloaded (seated in a chair) for a 45-min period before imaging[38,39]. The following sequences were obtained for each participant: (1) high-resolution 3D intermediate-

weighted fast spin-echo (FSE) sequence for clinical grading and cartilage segmentation, (2) 3D $T_{1\rho}$ relaxation time sequence and (3) 3D T_2 relaxation time sequence (Table I).

MR analysis

Quantitative cartilage $T_{1\rho}$ and T_2 relaxation times—To facilitate image registration and cartilage segmentation, sagittal high-resolution FSE images were down-sampled to the same slice thickness as the $T_{1\rho}$ and T_2 relaxation time map images. FSE and first echo of T_2 images were then rigidly registered to the first echo of $T_{1\rho}$ images. Using this technique all images were aligned and differences in positioning were minimized. To account for potential motion artifacts during image acquisition of $T_{1\rho}$ and T_2 sequences, echoes 2 through 8 were each registered to the first echo of $T_{1\rho}$ and T_2 maps.

Whole compartment analysis—Patellar and trochlear cartilage were segmented semi-automatically (automated edge detection and manual correction) on multiple slices of the FSE images using an in-house program developed with MATLAB (MathWorks, Natick, MA) based on edge detection and Bézier splines[40]. Inferior border of the trochlear cartilage was defined by the anterior boundary of the medial and lateral menisci[38]. In this study, whole compartment refers to entire patellar or trochlear articular cartilage.

Laminar analysis—The segmented cartilage regions of interest were then partitioned automatically into two equal laminae: the deep layer (closer to the subchondral bone) and superficial layer (closer to articular surface) [Fig. 1(A)][34].

$T_{1\rho}$ and T_2 relaxation time quantification—$T_{1\rho}$ and T_2 relaxation time maps were constructed by 3-parameter fitting for all eight of the $T_{1\rho}$ and T_2 images, voxel by voxel, to the equations below using in-house developed program:

$$S(\mathrm{TSL}) \propto A\left[\exp\left(-\frac{\mathrm{TSL}}{\mathrm{T1}\rho}\right)\right] + B \text{ for } \mathrm{T}_{1\rho}$$

$$S(\mathrm{TE}) \propto A\left[\exp\left(-\frac{\mathrm{TE}}{\mathrm{T2}}\right)\right] + B \text{ for T2}$$

where S is the image signal at a given time point (time of spin-lock (TSL) for $T_{1\rho}$ maps or echo time (TE) for T_2 maps), A is initial magnetization, and B is a constant.

The cartilage regions of interest were overlaid on the previously co-registered $T_{1\rho}$ and T_2 maps. The cartilage splines were adjusted manually in order to avoid synovial fluid or surrounding anatomy. To eliminate artifacts due to partial volume effects with synovial fluid, voxels with relaxation time ≥130 ms for $T_{1\rho}$ or ≥100 ms for T_2 maps were excluded from quantification [Fig. 1(B)]. Mean $T_{1\rho}$ and T_2 values were calculated for defined cartilage regions.

Semiquantitative cartilage lesion assessment—Semiquantitative assessment of articular cartilage lesions was performed by a board-certified, fellowship-trained

musculoskeletal radiologist using the modified Whole Organ Magnetic Resonance Imaging Score (WORMS)[3,41]. Cartilage lesions were graded using a scale from 0 to 6 as described previously[24]. Gradings were performed at the articular cartilage overlying six regions: patella, trochlea, medial and lateral femoral condyle, and medial and lateral tibia plateau. WORMS cartilage lesion score was used to define the presence of OA in this study. PFJ OA was defined as present when the WORMS score was 2 or higher for cartilage lesion of the patella or trochlea[3]. TFJ OA was defined when the WORMS score was 2 and higher for cartilage lesion of the tibia or femur[3].

Gait analysis

3D lower extremity kinematics were recorded using a 10-camera motion capture system (Vicon, Oxford, UK) at a sampling rate of 250 Hz. Ground reaction force data were obtained using two embedded force platforms (Advanced Mechanical Technology, Watertown, MA) at a sampling rate of 1000 Hz. Marker and ground reaction force data were collected and synchronized using motion capture software (Nexus, Oxford, UK). Participants wore shorts and their personal sneakers during the evaluation.

Prior to the walking test, retro-reflective markers (14 mm spheres) were placed on the subjects bilateral lower limbs and pelvis as previously described[24,25]. Subjects were instructed to walk at a self-selected speed, which was described as “you have some place to be, but you are not late.” Five successful trials were obtained. A trial was considered successful when the foot of the tested limb fell within the borders of force platform from initial contact to toe-off. Walking speed of trial 2 to 5 was controlled to be within ±5% of the first successful trial.

Kinematic and kinetic data were computed using Visual3D (C-Motion, Germantown, MD) and MATLAB software (The MathWorks, Natick, MA). Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 6 Hz. The hip, knee and ankle joints were assigned three degrees of freedom for rotations. Joint kinematics was calculated using a Cardan rotation sequence in the order of flexion/extension, abduction/adduction, and internal/external rotation. Net joint moments were reported as external moments and normalized to each participant’s body mass (kg) and height (m). The positive and negative values of the sagittal plane knee moment were used to indicate knee flexion and extension moments, respectively. KFM impulse was calculated as the integral of KFM (Nm/kg·m) with respect to time (ms) (Fig. 2)[24]. The stance phase of gait was defined during the time when the vertical ground reaction force was greater than 20 N. Peak KFM and KFM impulse during the stance phase were calculated. Average data from five successful trials were exported for statistical analyses.

Statistical analysis

Descriptive statistics were used to analyze the demographic characteristics, KOOS, knee kinetics and cartilage $T_{1\rho}$ and T_2 relaxation times in control and PFJ OA subjects. Chi-squared and independent *t*-tests were used to compare group differences in demographics and cartilage $T_{1\rho}$ and T_2 relaxation times. Linear regression models were built to examine whether PFJ cartilage relaxation times (i.e., patellar and trochlear cartilage $T_{1\rho}$ and T_2 of the

whole compartment, superficial layer and deep layer) were related to peak KFM and KFM impulse while adjusting for age, sex, body mass index (BMI) and walking speed. This was performed by entering covariates in the regression model and then adding the independent variable (peak KFM or KFM impulse). When there were subjects with TFJ OA, linear regression models were also controlled for the presence of TFJ OA. Regression models were performed for all subjects (primary and secondary analyses), and individuals with PFJ OA and controls (tertiary analysis). All statistical analyses were performed using SPSS Statistics version 23.0 (IBM Corporation, Armonk, NY) with a significance level set at 0.05.

Results

Subject characteristics

A total of 99 subjects completing the MR and gait analysis were included in this study (56 PFJ OA, 43 control). Demographics, KOOS, walking biomechanics, and cartilage relaxation time of the control and PFJ OA groups are presented in Table II. Significant group differences were found in sex ($P = 0.003$), age ($P = 0.002$) and KOOS–Sports ($P = 0.035$). Moreover, independent *t*-tests revealed that PFJ OA group exhibited significantly higher cartilage $T_{1\rho}$ of the patellar whole compartment ($P = 0.015$), deep layer ($P = 0.010$) and superficial layer ($P = 0.042$) compared to the controls. After adjusting for age, sex and BMI, only the patellar whole compartment and deep layer $T_{1\rho}$ remained significantly different between groups ($P = 0.045$ and 0.024, respectively). Overall, the $T_{1\rho}$ and T_2 cartilage relaxation times were higher for the superficial layer than the deep layer (Table II).

Whole compartment analysis

Significant associations were found between knee kinetics and PFJ cartilage $T_{1\rho}$ and T_2 relaxation times based on whole compartment analysis across all subjects (Table III). Higher peak KFM was significantly related to higher $T_{1\rho}$ and T_2 of the trochlear and patellar cartilage, with standardized regression coefficients ranging from 0.21 to 0.25 after adjusting for age, sex, BMI, walking speed and presence of TFJ OA. Similarly, significant positive associations were observed between KFM impulse and $T_{1\rho}$ and T_2 of the trochlear and patellar cartilage, with the standardized regression coefficients ranging from 0.22 to 0.28.

Laminar analysis

Laminar analysis showed that overall, the superficial layer of PFJ cartilage showed stronger associations with knee kinetic variables (Table III). Both patellar and trochlear superficial cartilage $T_{1\rho}$ and T_2 showed significant positive correlations with peak KFM and KFM impulse, with the relationship between the superficial trochlea $T_{1\rho}$ and peak KFM trending toward statistical significance ($P = 0.054$). The standardized regression coefficients ranged from 0.22 to 0.33. For the deep layers of patellar and trochlear cartilage, only trochlea $T_{1\rho}$ and T_2 showed significant associations with KFM impulse. The standardized regression coefficients were 0.27 and 0.22, respectively.

Subgroup analysis

Results of linear regressions for the PFJ OA group are displayed in Table IV. Both peak KFM and KFM impulse showed significant positive correlations with trochlea $T_{1\rho}$ and T_2

(whole compartment and superficial layer) and patella $T_{1\rho}$ (superficial layer). The standardized regression coefficients ranged from 0.29 to 0.40. KFM impulse was also significantly associated with $T_{1\rho}$ and T_2 of deep layer trochlea (standardized regression coefficients = 0.34 and 0.38, respectively).

Table V displays results of linear regression for the control group. No significant associations were observed between knee kinetics and any of the whole compartment relaxation times. Laminar analysis showed significant correlations between KFM impulse and $T_{1\rho}$ and T_2 of superficial layer patellar cartilage (standardized regression coefficients = 0.33 and 0.31, respectively). Fig. 3 shows scatter plots of cartilage relaxation time and knee kinetics in control and PFJ OA groups.

Discussion

This study aimed to investigate the associations between sagittal plane knee kinetics during walking and PFJ cartilage $T_{1\rho}$ and T_2 relaxation times. At the whole compartment level, our findings showed that higher peak KFM and KFM impulse were significantly associated with higher $T_{1\rho}$ and T_2 of patellar and trochlear cartilage. After adjusting for age, sex, BMI, walking speed and presence of TFJ OA, every one standard deviation increase in peak KFM and KFM impulse corresponded to 0.21 to 0.25 and 0.22 to 0.28 standard deviation increase in cartilage relaxation times, respectively (approximately 0.5–1.0 ms increase). In addition, laminar analysis revealed that both the superficial layer of patellar and trochlear cartilage showed significant positive correlations with knee kinetics in $T_{1\rho}$ and T_2 relaxation times, whereas only the deep layer trochlear cartilage showed significant correlation with KFM impulse. Lastly, subgroup analysis showed significant positive associations between knee kinetics and trochlear and patellar $T_{1\rho}$ and T_2 in individuals with PFJ OA, whereas only KFM impulse showed significant correlations with patellar superficial layer $T_{1\rho}$ and T_2 in controls. Although statistically significant, it is important to keep in mind that peak KFM and KFM impulse only explain a small portion of variance in $T_{1\rho}$ and T_2 values. Overall, our findings suggest that knee kinetics are related to PFJ cartilage composition and thus may play a role in the pathomechanics of PFJ OA.

The observed positive associations between KFM and PFJ cartilage $T_{1\rho}$ and T_2 relaxation times are inconsistent with the previous study by Souza et al.[42]. In this previous study[42], higher KFM during hopping was found to be related to lower averaged $T_{1\rho}$ and T_2 of the entire knee cartilage. Young and healthy individuals were included in Souza *et al.* study (age, Mean ± SD, 22.7 ± 3.3 years), whereas older participants with more than half having PFJ OA were included in this current study (age, Mean ± SD, 52.0 ± 10.7 years). It has been reported that cartilage response to loading differed depending on disease state[43] and age[44]. This may help explain the discrepancies in the observed relationships between the two studies. Caution should therefore be taken when generalizing findings of this current study to a younger population.

Findings of this study are consistent with our recent reports that individuals with PFJ cartilage lesions demonstrated higher peak KFM and KFM impulse compared to controls[25], and that higher peak KFM and KFM impulse were predictive of progression of PFJ cartilage

lesions and/or bone-marrow lesions at one year[24]. While these previous studies focused on morphological changes related to PFJ OA, this current study further revealed that these knee kinetic variables are also associated with OA-related cartilage composition in PFJ (i.e., loss of glycosaminoglycan, increase in water content and disorganization of collagen matrix). These compositional changes in cartilage may precede morphological changes and thus are imaging biomarkers of early stage cartilage degeneration[26–28]. Based on these findings, prevention and intervention protocols of PFJ OA may need to include the examination and reduction of peak KFM and KFM impulse.

With regard to laminar analysis, our findings suggest that increased peak KFM and KFM impulse had stronger associations with superficial cartilage relaxation times when compared to the deep layer cartilage. For example, an one-standard deviation increase in peak KFM and KFM impulse corresponded to around 0.30 to 0.33 standard deviation increase in superficial layer patella $T_{1\rho}$, but only around 0.17 to 0.18 standard deviation increase in deep layer patella $T_{1\rho}$. Using a finite element model, Halonen et al.[45] reported higher stress and axial strain in the superficial layer of the knee cartilage than the deep layer during walking. As a result, the superficial layer PFJ cartilage may be more susceptible to mechanical load during walking and thus, show stronger association with knee kinetics than the deep layer cartilage. This finding is in line with a previous study by Li *et al.*,[35] which showed that early cartilage degeneration after anterior cruciate ligament injury initiated from the superficial layer cartilage.

MR relaxation times of superficial PFJ cartilage have been shown to be important biomarkers of OA. Carballido-Gamio et al.[34] reported that $T_{1\rho}$ and T_2 of the superficial PFJ cartilage showed better accuracy in classifying radiographic knee OA compared to the deep layer PFJ cartilage. Moreover, Liebl *et al.*[28] reported that higher T_2 of the superficial patellar cartilage at baseline was predictive of incident radiographic TFJ OA at 4-year follow up. Drawing from the results of these previous studies and the current study, PFJ and TFJ OA may both be associated with increased peak KFM and KFM impulse.

This study also revealed stronger relationships between knee kinetics and PFJ cartilage relaxation times in individuals with PFJ OA compared to controls. In subjects with PFJ OA (defined by morphological lesions of PFJ cartilage), higher peak KFM and KFM impulse were associated with higher trochlea $T_{1\rho}$ and T_2 (whole compartment, superficial and deep layers) and patella $T_{1\rho}$ (superficial layer). In control subjects, only the superficial patellar cartilage $T_{1\rho}$ and T_2 showed significant correlations with KFM impulse. Together, this suggests that once the morphological lesions are present, the cartilage is more susceptible to mechanical overloading. This may be explained by the fact that degenerative cartilage shows lower stiffness, which lead to compromised resistance and greater deformation under mechanical loading[36].

As demonstrated in Fig. 3 and Table III, control and PFJ OA subjects showed similar distributions in knee kinetics (without adjusting for covariates). The differences in correlations with cartilage relaxation time between the two groups might be driven by that PFJ OA subjects showed slightly higher $T_{1\rho}$ and T_2 values. It is important to note that some subjects showed high $T_{1\rho}$ and T_2 but low KFM and impulse. This suggests there might be

subgroups in the PFJ OA subjects, which increased cartilage $T_{1\rho}$ and T_2 were driven by other biological factors.

Interestingly, trochlear cartilage lesions showed a stronger relationship with knee kinetics than patellar cartilage in individuals with PFJ OA. This may be due to the fact that more severe cartilage lesions were observed in the patellar cartilage than the trochlear cartilage in PFJ OA subjects, with 25% of them having WORMS 4 cartilage lesions in patella. Due to the severe thinning and loss of the patellar cartilage, it may limit the effectiveness of cartilage relaxation time mapping on identifying changes in cartilage composition. Alternatively, this finding may suggest that trochlear cartilage showed greater change in composition under mechanical load than patellar cartilage and thus may be a more sensitive measure of PFJ pathology. Further studies are warranted to identify biomechanical factors related to patellar cartilage $T_{1\rho}$ and T_2 in individuals with PFJ OA.

Significant difference in cartilage relaxation time was observed between PFJ OA and control groups. Individuals with PFJ OA demonstrated higher $T_{1\rho}$ of the patellar whole compartment and deep layer cartilage than controls after adjusting for age, sex and BMI. Interestingly, no significant differences were observed in patella T_2 or trochlea $T_{1\rho}$ and T_2 values between the two groups. Previous studies reported increased cartilage $T_{1\rho}$ and T_2 in OA knees[26–28]. This discrepancy may be due to the fact that PFJ OA subjects in this study presented less advanced degenerative changes, with mean KOOS greater than 73 in all categories (Table II).

Age, sex and BMI were controlled in our statistical models. Post-hoc analysis showed that age, sex and BMI were significantly associated with knee kinetics and PFJ cartilage relaxation times. These findings are supported by previous studies. For instance, older age, female sex and higher BMI have been reported as risk factors of knee OA[46] and may contribute to higher cartilage $T_{1\rho}$ and T_2. In addition, age-, sex- and BMI-associated differences in gait patterns have been reported in the literature[47e49]. More specifically, older age is related to slower walking speed[47] and thus lower KFM and KFM impulse. Moreover, higher BMI was found to be related to higher KFM during walking[49]. Lastly, male and female adults showed different spatiotemporal characteristics in gait[48], which can lead to differences in knee kinetics.

There were several limitations of this study. First, due to the cross-sectional design of the study, causality cannot be determined. Longitudinal studies are warranted to elucidate casual-effect relationships between knee kinetics and PFJ cartilage relaxation times. Second, contralateral TFJ OA was present in 20.2% of subjects and might influence the observed gait patterns. Post-hoc analysis was performed to compare knee kinetics between subjects with and without contralateral TFJ OA and found no significant difference. This finding is consistent with a recent study showing no difference in gait kinematics and kinetics between unilateral and bilateral TFJ OA patients[50]. Third, gait biomechanics associated with medial and lateral PFJ OA may be different but were not evaluated in this study. Further studies are needed to investigate biomechanical factors uniquely associated with medial or lateral PFJ OA. Fourth, significant but low associations were observed between knee kinetics and PFJ cartilage relaxation times. This suggests that other variables need to be considered when

evaluating factors associated with PFJ cartilage relaxation times. Fifth, $T_{1\rho}$ and T_2 relaxation time images were acquired using 4 mm slice thickness sequence, which might result in partial volume effect. However, decreasing slice thickness may result in lower signal-to-noise ratio as well as much longer image acquisition time, thereby introducing higher risk of motion artifacts. Lastly, laminar analysis was performed by dividing the cartilage into two equal layers. This method was chosen to avoid partial volume effects between layers, especially in knees with severe cartilage thinning. It is important to note that this method may not provide enough spatial resolution of cartilage composition changes from articular to bone surfaces. Additionally, using this method, half of the cartilage was arbitrarily determined as superficial layer cartilage, which might not correspond to histological findings.

In conclusion, this study revealed that increased $T_{1\rho}$ and T_2 relaxation times of the patellar and trochlear cartilage are associated with higher peak KFM and KFM impulse after adjusting for age, sex, BMI, walking speed and presence of TFJ OA. Additionally, the observed associations were stronger for the superficial layer cartilage than the deep layer cartilage, suggesting that the superficial layer PFJ cartilage may be more susceptible to mechanical overload. Lastly, compared to controls, PFJ OA subjects showed stronger correlations between knee kinetics and PFJ $T_{1\rho}$ and T_2. This indicates that the presence of cartilage morphological lesions may predispose PFJ cartilage to greater deterioration under mechanical loading than those without morphological lesions. Overall, our findings suggest that higher peak KFM and KFM impulse are related to worse PFJ cartilage composition in the presence of OA, and therefore may be important biomechanical factors of PFJ OA.

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The funding source had no role in the study design, collection, analysis and interpretation of data; in the writing of the manuscript; and in the decision to submit the manuscript for publication.

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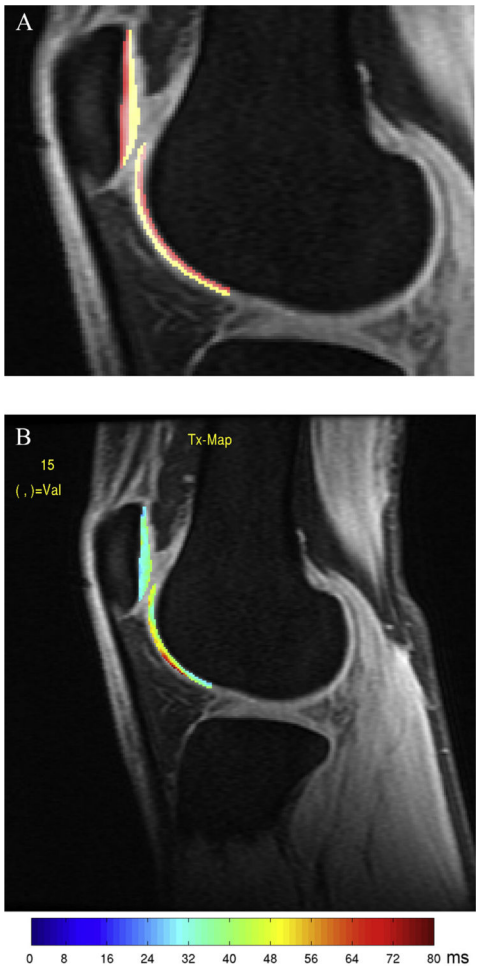

Fig. 1.

(A) Laminar analysis was performed by dividing the patellar and trochlear cartilage into two equal layers. Red regions correspond to deep layer cartilage. Yellow regions correspond to superficial cartilage. (B) $T_{1\rho}$ map of the PFJ for a control subject without OA.

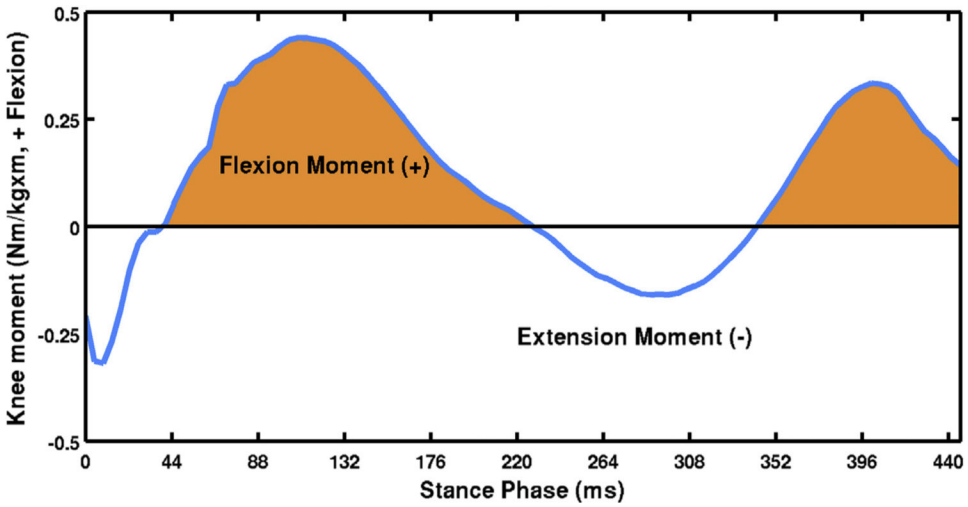

Fig. 2.

Sagittal plane knee moment curve during the stance phase of walking of a sample trial. Joint moment is expressed as external moment. Positive and negative values indicate knee flexion and extension moments, respectively. KFM impulse was calculated as the area under curve when sagittal plane knee moment is positive.

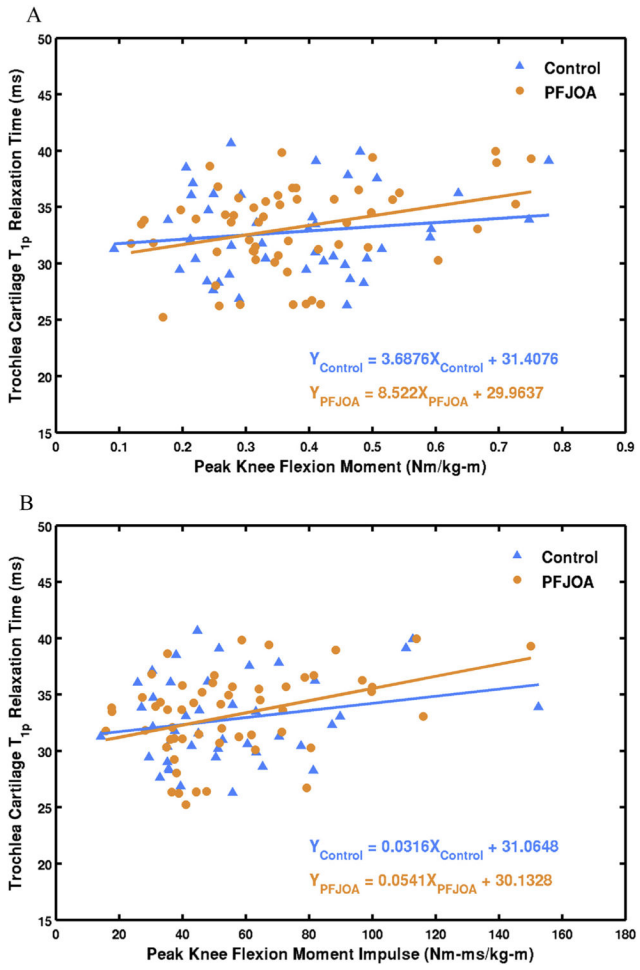

Fig. 3.

Scatter plots of trochlear cartilage $T_{1\rho}$ relaxation time (whole compartment) and peak KFM (A) and KFM impulse (B) with least-squares regression lines and equations for control and PFJ OA groups.

Table I

MRI sequences

Sequence	Parameters
3D intermediate-weighted fast spin-echo	TR/TE = 1500/26.69 ms, field of view = 16 cm, matrix = 384 × 384, slice thickness = 0.5 mm, echo train length = 32, bandwidth = 37.5 kHz, number of excitations = 0.5, acquisition time = 10.5 min
3D $T_{1\rho}$ relaxation time	TR/TE = 9/2.6 ms, time of recovery = 1500 ms, field of view = 14 cm, matrix = 256 × 128, slice thickness = 4 mm, bandwidth = 62.5 kHz, TSL = 0/2/4/8/12/20/40/80 ms, frequency of spin-lock = 500 Hz, acquisition time = 11 min
3D T_2 relaxation time	Same as the $T_{1\rho}$ quantification except for magnetization preparation TE = 1.8/3.67.3/14.5/29.1/43.6/58.2, acquisition time = 11 min

TR, Repetition time.

Table II

Descriptive statistics of subjects with PFJ OA and controls without TFJ or PFJ OA

		All *N* = 99 Mean (95% CI)	PFJ OA *N* = 56 Mean (95% CI)	Control *N* = 43 Mean (95% CI)
Sex, Male/Female		37/62	**14/42**	**23/20** *
Age, years		52.0 (49.9, 54.2)	**55.0 (52.2, 57.7)**	**48.2 (45.1, 51.4)** *
BMI, kg/m^2		24.6 (23.9, 25.2)	24.6 (23.7, 25.6)	24.5 (23.6, 25.5)
OA type, Isolated PFJ OA/Mixed PFJ & TFJ OA		34/22	34/22	
KOOS				
Pain		86.4 (82.3, 89.5)	84.2 (79.7, 88.7)	89.3 (85.2, 93.4)
Symptoms		86.7 (83.7, 89.7)	84.6 (80.2, 89.0)	89.4 (85.4, 93.3)
Activities of Daily Living		91.8 (89.3, 94.3)	89.9 (86.2, 93.6)	94.4 (91.3, 97.4)
Sports		82.1 (77.9, 86.3)	**78.2 (71.8, 84.5)**	**87.1 (82.3, 92.0)** *
Quality of Life		76.0 (71.3, 80.7)	73.3 (66.5, 80.1)	79.5 (73.2, 85.7)
Walking biomechanics				
Walking speed, m/s		1.52 (1.48, 1.57)	1.50 (1.43, 1.57)	1.56(1.50, 1.61)
Peak KFM, Nm/kg m		0.36 (0.34, 0.39)	0.36 (0.32, 0.40)	0.37 (0.32, 0.41)
KFM impulse, Nm ms/kg m		53.6 (48.6, 58,6)	52.7 (47.1, 60.4)	53.5 (45.6, 61.3)
Cartilage $T_{1\rho}$ relaxation times				
Trochlea	Whole compartment, ms	32.9 (32.2, 33.7)	33.1 (32.1, 34.2)	32.6 (31.5, 33.8)
	Superficial layer, ms	36.0 (35.1, 36,8)	36.4 (35.2, 37.6)	35.4 (34.1, 36.7)
	Deep layer, ms	29.8 (29.0, 30.5)	29.8 (28.8, 30.9)	29.6 (28.5, 30.8)
Patella	Whole compartment, ms	33.4 (32.6, 34.2)	**34.2 (33.3, 35.2)**	**32.3 (31.1, 33.6)** †
	Superficial layer, ms	37.1 (36.3, 38.0)	37.9 (36.8, 38.2)	36.1 (34.7, 37.6)
	Deep layer, ms	29.9 (29.1, 30.7)	**30.8 (29.8, 31.9)**	**28.7 (27.4, 29.9)** †
Cartilage T_2 relaxation times				
Trochlea	Whole compartment, ms	25.5 (25.0, 26.0)	25.8 (25.0, 26.5)	25.1 (24.6, 25.7)
	Superficial layer, ms	27.3 (26.7, 27.8)	27.7 (26.9, 28.5)	26.7 (26.1, 27.4)
	Deep layer, ms	23.7 (23.1, 24.2)	23.9 (23.0, 24.7)	23.4(22.8, 24.1)

Osteoarthritis Cartilage. Author manuscript; available in PMC 2019 January 26.

		All	PFJ OA	Control
		***N* = 99**	***N* = 56**	***N* = 43**
		Mean (95% CI)	**Mean (95% CI)**	**Mean (95% CI)**
Patella	Whole compartment, ms	24.4 (23.8, 24.9)	24.6 (23.9, 25.4)	24.0 (23.2, 24.8)
	Superficial layer, ms	26.7 (26.2, 27.3)	27.0 (26.2, 27.7)	26.5 (25.6, 27.3)
	Deep layer, ms	22.1 (21.5, 22.6)	22.4 (21.6, 23.2)	21.6 (20.8, 22.4)

CI, confidence interval.

Variables that reach statistical significant difference between PFJ OA and control groups ($P < 0.05$) are in bold.

*Significant differences between PFJ OA and control groups ($P < 0.05$).

†Significant differences between PFJ OA and control groups after adjusting for age, sex and BMI ($P < 0.05$).

Table III

Associations between knee kinetics and cartilage $T_{1\rho}$ and T_2 relaxation times of the patella and trochlea for all subjects ($n = 99$)*

		Whole compartment analysis				Laminar analysis							
		Trochlea	Patella	Trochlea	Patella	Trochlea		Patella		Trochlea		Patella	
		$T1_\rho$	$T1_\rho$	T2	T2	$T1_\rho$		$T1_\rho$		T2		T2	
		Whole	Whole	Whole	Whole	Superficial	Deep	Superficial	Deep	Superficial	Deep	Superficial	Deep
Peak KFM	β (95% CI)	**0.21**	**0.25**	**0.20**	**0.22**	0.20	0.19	**0.30**	0.17	**0.22**	0.18	**0.23**	0.18
		(0.05, 0.41)	**(0.04, 0.45)**	**(0.03, 0.40)**	**(0.05, 0.43)**	(−0.003, 0.41)	(−0.02, 0.40)	**(0.10, 0.51)**	(−0.04, 0.40)	**(0.18, 0.42)**	(−0.03, 0.39)	**(0.02, 0.44)**	(−0.03, 0.39)
	P value	**0.046**	**0.022**	**0.047**	**0.045**	0.054	0.072	**0.004**	0.107	**0.033**	0.087	**0.029**	0.095
KFM impulse	β (95% CI)	**0.28**	**0.25**	**0.26**	**0.22**	**0.25**	**0.27**	**0.33**	0.18	**0.25**	**0.22**	**0.25**	0.18
		(0.08, 0.47)	**(0.05, 0.45)**	**(0.07, 0.45)**	**(0.14, 0.42)**	**(0.05, 0.45)**	**(0.08, 0.47)**	**(0.14, 0.53)**	(−0.03, 0.38)	**(0.06, 0.44)**	**(0.02, 0.41)**	**(0.05, 0.45)**	(−0.03, 0.39)
	P value	**0.005**	**0.014**	**0.008**	**0.036**	**0.014**	**0.007**	**0.001**	0.090	**0.011**	**0.029**	**0.015**	0.087

* Linear regression adjusted for age, sex, body mass index, walking speed and presence of TFJ OA; β, standardized regression coefficients; CI, confidence interval. Associations that reach the statistical significance level ($P < 0.05$) are in bold.

Table IV

Associations between knee kinetics and cartilage $T_{1\rho}$ and T_2 relaxation times of the patella and trochlea for subjects with PFJ OA ($n = 56$)*

		Whole compartment analysis				**Laminar analysis**							
		Trochlea	**Patella**	**Trochlea**	**Patella**	**Trochlea**		**Patella**		**Trochlea**		**Patella**	
		$T1_\rho$	**$T1_\rho$**	**T2**	**T2**	**$T1_\rho$**		**$T1_\rho$**		**T2**		**T2**	
		Whole	**Whole**	**Whole**	**Whole**	**Superficial**	**Deep**	**Superficial**	**Deep**	**Superficial**	**Deep**	**Superficial**	**Deep**
Peak KFM	β (95% CI)	**0.30**	0.27	**0.29**	0.18	**0.30**	0.25	**0.33**	0.21	**0.29**	0.23	0.22	0.14 (−0.25, 1.03)
		(0.03, 0.57)	(−0.02, 0.55)	**(0.01, 0.56)**	(−0.10, 0.47)	**(0.03, 0.57)**	(−0.03, 0.53)	**(0.06, 0.60)**	(−0.08, 0.50)	**(0.01, 0.57)**	(−0.04, 0.51)	(−0.02, 0.50)	
	P value	**0.033**	0.064	**0.040**	0.205	**0.032**	0.082	**0.019**	0.150	**0.041**	0.096	0.123	0.435
KFM impulse	β (95% CI)	**0.35**	0.20	**0.40**	0.11	**0.31**	**0.34**	**0.31**	0.15	**0.36**	**0.38**	0.17	0.06 (−0.23, 0.35)
		(0.09, 0.61)	(−0.08, 0.48)	**(0.14, 0.66)**	(−0.18, 0.40)	**(0.05, 0.57)**	**(0.08, 0.60)**	**(0.04, 0.57)**	(−0.14, 0.43)	**(0.09, 0.62)**	**(0.12, 0.63)**	(−0.11, 0.45)	
	P value	**0.009**	0.154	**0.003**	0.440	**0.021**	**0.013**	**0.024**	0.304	**0.011**	**0.005**	0.222	0.683

* Linear regression adjusted for age, sex, body mass index, walking speed and presence of TFJ OA; β, standardized regression coefficients; CI, confidence interval. Associations that reach the statistical significance level ($P < 0.05$) are in bold.

Table V

Associations between knee kinetics and cartilage $T_{1\rho}$ and T_2 relaxation times of the patella and trochlea for controls ($n = 43$)*

		Whole compartment analysis				Laminar analysis							
		Trochlea	Patella	Trochlea	Patella	Trochlea		Patella		Trochlea		Patella	
		$T1_\rho$	$T1_\rho$	T2	T2	$T1_\rho$		$T1_\rho$		T2		T2	
		Whole	Whole	Whole	Whole	Superficial	Deep	Superficial	Deep	Superficial	Deep	Superficial	Deep
Peak KFM	β (95% CI)	0.04	0.16	0.02	0.23	−0.002	0.06	0.26	0.04	0.10	−0.09	0.25	0.22 (−0.13, 0.57)
		(−0.30, 0.39)	(−0.18, 0.51)	(−0.34, 0.37)	(−0.12, 0.58)	(−0.35, 0.34)	(−0.29, 0.40)	(−0.08, 0.60)	(−0.31, 0.39)	(−0.23, 0.43)	(−0.43, 0.26)	(−0.08, 0.58)	
	P value	0.803	0.347	0.93	0.194	0.991	0.737	0.134	0.810	0.534	0.609	0.137	0.210
KFM impulse	β (95% CI)	0.13	0.26	−0.01	0.30	0.09	0.17	**0.33**	0.14	0.08	−0.08	**0.31**	0.27 (−0.04, 0.60)
		(−0.19, 0.45)	(−0.06, 0.58)	(−0.33, 0.32)	(−0.02, 0.61)	(−0.24, 0.41)	(−0.15, 0.49)	**(0.03, 0.64)**	(−0.19, 0.46)	(−0.23, 0.39)	(−0.41, 0.24)	**(0.05, 0.61)**	
	P value	0.411	0.105	0.967	0.068	0.587	0.285	**0.034**	0.399	0.603	0.60	**0.047**	0.089

* Linear regression adjusted for age, sex, body mass index and walking speed; β, standardized regression coefficients; CI, confidence interval. Associations that reach the statistical significance level ($P < 0.05$) are in bold.