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TITLE: Improving Treatment for Patellar Instability to Reduce Recurrence and Cartilage Degradation

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14. ABSTRACT A lateral patellar dislocation is a traumatic event associated with cartilage degradation and a high risk of progression to patellofemoral osteoarthritis. The study focuses on identification of patients likely to progress to recurrent dislocations, characterization of cartilage degradation due to delaying surgical intervention until after recurrent dislocations, and evaluation of reconstruction of the medial patellofemoral ligament (MPFL) as a surgical tool to restore patellar stability.					
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1. INTRODUCTION

A lateral patellar dislocation is a traumatic event associated with cartilage degradation and a high risk of progression to patellofemoral osteoarthritis. The standard of care for an initial dislocation is physical therapy, although approximately 40% of patients experience additional dislocations that are associated with an even greater risk of osteoarthritis. Continued dislocations, or recurrent patellar instability, is commonly addressed with surgical stabilization, with reconstruction of the medial patellofemoral ligament (MPFL) the most common approach. The investigators hypothesized that selective early surgical intervention for patellar instability will improve knee function and long term outcomes. The study focused on characterization of cartilage degradation due to delaying surgical intervention until after recurrent instability, identification of patients likely to progress to recurrent instability based on anatomy and alignment, and establishment of the anatomical parameters for which MPFL reconstruction can successfully restore patellar stability. For the first aim of the study, MRI-based T1 ρ relaxation time mapping of patellofemoral cartilage was used to characterize cartilage degradation for a group of patients being treated for an initial patellar dislocation, a group of patients being treated for recurrent instability, and a group of control subjects. For the second aim, a statistical shape model was developed based on the knees imaged for Aim 1 to characterize modes of variation in knee anatomy and alignment associated with recurrent patellar instability. For the third aim, a model for multibody dynamic simulation of knee function was developed to simulate an activity that causes a patellar dislocation and subsequent MPFL reconstruction. The simulation model was used to evaluate parameters of MPFL reconstruction associated with recurrent patellar instability. The proposed aims were designed to create a paradigm shift for treatment of patellar instability. The goals were to identify patients at high risk for post-traumatic osteoarthritis to preserve cartilage and optimize treatment approaches to provide stability and preserve cartilage.

2. **KEYWORDS:** patellar instability, osteoarthritis, medial patellofemoral ligament reconstruction, cartilage properties, computational simulation, statistical shape model

3. ACCOMPLISHMENTS:

○ What were the major goals of the project?

Specific Aim 1 (MRI characterization of cartilage)	Timeline	Completion
Initiate Enrollment	Months	
Amend IRB approval used for preliminary study	1-2	100%
Initiate enrollment for control group	1	100%
Initiate enrollment for initial instability group	2	100%
Initiate enrollment for recurrent instability group	2	100%
Imaging		
Finalize imaging protocols	1	100%
Imaging of control group	1-12	100%
Imaging of initial instability group	2-20	100%
Imaging of recurrent instability group	2-20	100%
Evaluation of cartilage properties		
T1 ρ sub-region analysis		
Reconstruction of cartilage surfaces	2-20	100%
Create T1 ρ relaxation time maps	3-22	100%
Statistical analysis between 3 groups	23-24	100%
T1ρ VBR analysis (replaced by regional analysis)		
Select reference image	18-20	50%
Create T1 ρ relaxation time maps	21-23	0%
Statistical analysis between 3 groups	23-24	0%
Specific Aim 2 (Influence of anatomy and alignment)		
Influence of anatomy		
Reconstruct computational models from MRI	2-22	100%
Create template mesh	12-14	100%
Create statistical shape models and modes of variation	12-22	100%

Relate modes of variation to anatomy	23-24	100%
Statistical analysis of varying anatomy between groups	23-24	100%
Relate anatomy to cartilage T1p relaxation times	23-24	100%
Influence of alignment		
Models from loaded MRI (replaced with unloaded)	6-22	100%
Measure alignment from MRI	14-22	100%
Add alignment to principal component analysis	22-24	25%
Relate alignment to cartilage properties	24	100%
Specific Aim 3 (multibody dynamic simulation)		
Simulation models with varying anatomy/alignment	16-22	100%
Create instability loading condition	18-22	100%
Evaluate MPFL reconstruction		
Run instability and MPFL reconstruction cases	20-24	100%
Statistical analysis of modes of variation	23-24	100%
Run alternative MPFL reconstruction cases	23-24	100%

What was accomplished under these goals?

The primary components of Specific Aim #1 were enrollment, imaging, and evaluation of cartilage properties. Savings in some budgeted categories and some parallel studies were taken advantage of to expand enrollment. Final enrollment with acquired imaging is 26 patients following an initial patellar dislocation, with 18 of those returning for imaging at 6 months. Final enrollment of patients being treated for recurrent instability is 19. Seven of those patients also returned for follow up imaging. Final enrollment of controls is 22 subjects. The acquired imaging includes a dual echo steady state (DESS) fat saturated sequence for reconstruction of cartilage surfaces for relaxation time mapping, a T1p sequence scan for characterization of relaxation times, and a non-fat saturated Sampling Perfection with Application optimized Contrasts using different flip angle Evolution (SPACE) sequence to highlight bones and soft tissues for reconstruction of computational models. Imaging was processed with artificial intelligence based algorithms including automated segmentation, registration, and division into primary and sub-regions of cartilage. Due to the increased number of subjects enrolled and consistent differences identified between regions, sub-region analysis was emphasized while voxel-based relaxometry was de-emphasized.

One paper has been published based on comparison of cartilage properties between knees being treated for an initial dislocation, contralateral knees, and healthy controls (see Appendix). The results show knees with a dislocation had longer cartilage T1p relaxation times (loss of proteoglycan content) than the contralateral knees and control group at the medial patella and longer ($p < 0.05$) relaxation times than the control group at the lateral tibia (Fig. 1). T1p relaxation times at the medial patella also decreased with time from injury ($r^2 = 0.21$, $p = 0.037$). The results indicate the initial injury to cartilage is primarily due to direct traumatic impact, but recovery from impact is possible for the first few months following injury.

Further analysis shows that ongoing degradation beyond the first few months after injury is more widespread throughout the knee. Cartilage degradation was primarily identified for adolescent patients (< 20 years old). For adolescents, knees with a single dislocation at 5 or more months beyond injury and knees being treated for multiple dislocations both had significantly higher cartilage T1p relaxation times than controls for multiple regions throughout the knee (Fig. 2). Elevated T1p relaxation times were also noted for contralateral knees. This analysis indicates biomechanical loading conditions and/or inflammatory effects influencing the whole knee become the factors influencing cartilage degradation beyond the acute phase of the first dislocation.

Additional analysis has focused on the demographic features that influence cartilage properties following patellar dislocation. The primary

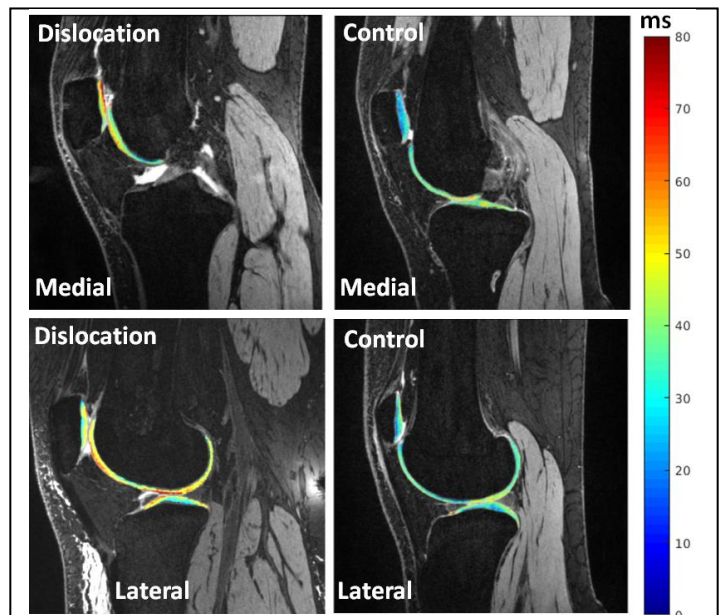


Figure 1: T1p maps showing elevated relaxation times for injured knees at the medial patella (top) and lateral tibiofemoral joint (bottom).

finding is that the relationship between body mass index (BMI) and cartilage properties changes following patellar dislocation. For healthy controls, patellofemoral T1p relaxation times increase with BMI (Fig. 3). On the contrary, following one or more patellar dislocations, T1p relaxation times decrease as BMI increases. All of the relationships for cartilage on the patella are statistically significant. This analysis excludes knees for morbidly obese subjects (BMI > 40). Cartilage degradation in the acute phase following patellar dislocation is primarily limited to subjects with a BMI less than 25. The results may indicate activity level influences cartilage degradation following patellar dislocations or body mass can dampen the impact during dislocation.

The primary components of Specific Aim 2 are evaluating the influence of knee anatomy and alignment on cartilage properties and risk of recurrent dislocations. Statistical shape models were developed to analyze anatomy. Statistical shape models have been created to represent the femur and patella from control knees, knees with an initial patellar dislocation, and knees with multiple patellar dislocations. The current shape models represent each bone individually, creating a mean geometry plus orthonormal modes of variation, with the modes ranked based on the contribution to overall shape variations. Each bone included in the shape model is also being represented by a linear combination of the modes of variation of the shape model. The coefficients assigned to each mode characterize how an individual bone is represented by the combination of variations within the shape model.

Based on statistical shape models, the primary characteristic of the multiple dislocation group is a shallow trochlear groove (Fig. 4). The mean patella shapes for both dislocation patient groups displayed a medial shift of the patellar ridge and a decreased medial-lateral width compared to the control group, with the multiple dislocation group being the most extreme. Statistical significance for individual modes was primarily established with respect to the control group. A larger sample size is needed to identify differences between the initial dislocation and recurrent dislocation groups. Not all of the knees imaged have been added to the statistical shape models yet, so significant differences between initial and recurrent dislocations may be established with ongoing analysis.

The shape models have also been used to relate anatomy to cartilage properties following patellar dislocation. Some relationships have been established for patellar shape for patients being treated for multiple patellar dislocations. For cartilage on the patella, T1p relaxation times for the central region were significantly correlated with mode 6 ($r^2 = 0.38$, $p = 0.026$, Fig. 5). Long T1p times were associated with a relatively long and shallow lateral patellar facet due to a medial shift in the patellar ridge. For the trochlear groove, T1p values at the central region were similarly correlated with mode 6 ($r^2 = 0.33$, $p = 0.041$). The relationships indicate limited articular constraints acting on the patella and sub-acute instability during daily function are related to cartilage degeneration. T1p values for the lateral trochlear groove were significantly correlated with mode 5 ($r^2 = 0.40$, $p = 0.020$). Long T1p relaxation times were associated with a relatively deep anterior-posterior distance. This relationship indicates that patellofemoral compression can also be related to cartilage degeneration.

Analysis of the data also showed that alignment between bones was more strongly correlated with cartilage properties than bone shape in some cases. Alignment between bones was characterized based on measurements directly from MRI scans related to patellofemoral alignment, trochlear groove depth, and position of the tibial tuberosity with respect to the trochlear groove. Again focusing on

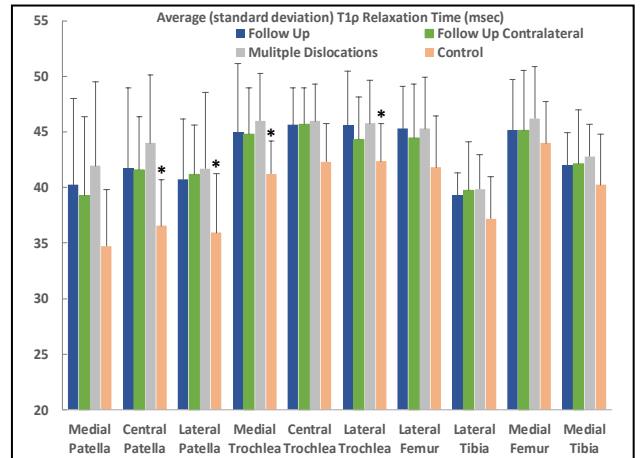


Fig. 2. Elevated T1p relaxation times for patellar dislocations for young patients. A symbol (*) indicates at least one significant ($p < 0.05$) difference is identified with respect to the controls.

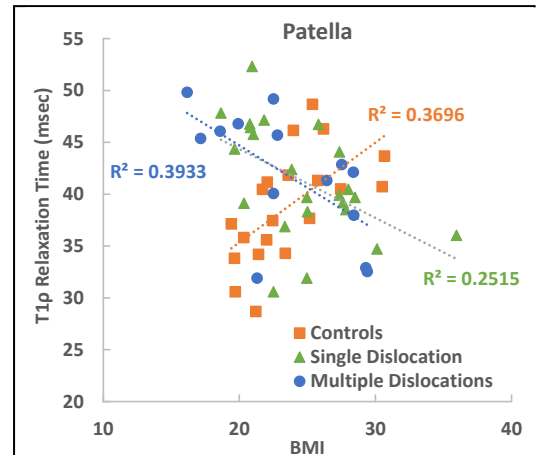


Fig. 3. Relationship between T1p relaxation times and BMI for control subjects and patients being treated for a first or multiple patellar dislocations.

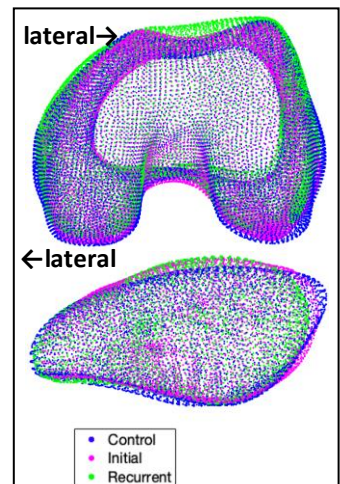


Fig. 4. Representation of average shapes for the femur and patella for the control, initial dislocation and recurrent dislocation groups.

cartilage properties following multiple dislocations, limited to adolescent subjects, the maximum overlap of patellofemoral cartilage in the axial plane was significantly correlated with increasing T1 ρ relaxation times for trochlear groove cartilage (Fig. 6). This result helps support the data that patellofemoral constraint or compression can contribute to cartilage degradation. The result is contrary to conventional wisdom that cartilage degradation is primarily related to lateral patellar malalignment and limited constraint.

The primary goals of Aim 3 are to simulate a dislocation event with computational models representing a range of anatomy and alignment, and evaluate options for MPFL reconstruction. The approach is based on multibody dynamic simulation, with bones of the knee treated as rigid structures with reaction forces developed at articulating surfaces based on Hertzian contact (Fig. 7). Springs represent the relevant ligaments, tendons, and retinacular structures. Quadriceps and hamstrings muscle forces and body weight, combined with simulated hip and ankle joints, induce motion governed by the joint reaction forces and spring forces.

Dynamic simulation of knee function was used to represent loading conditions that induce dislocations and routine functional activities with and without an MPFL graft. Within the models, MPFL reconstruction is simulated with springs representing a dual strand gracilis tendon graft, with a stiffness of 20 N/mm, applied to the standard attachment point on the femur, wrapping around the medial condyle, and attached at the medial edge of the patella. Patellar tracking is quantified within an anatomical coordinate system with an origin in the femur. Patellofemoral contact pressures are quantified for flexion angles with the patella constrained by the trochlear groove. The contact pressure distribution is quantified using a discrete element analysis approach that balances patellofemoral reaction forces and moments quantified from multibody dynamic simulation with joint reaction forces and moments quantified from overlap of the patellofemoral cartilage surfaces based on linear elastic theory. The overlap of the cartilage surfaces determines the contact pressure distribution.

Thirteen computational models based on knees with recurrent patellar instability have been used to represent a pivoting maneuver that causes a patellar dislocation and a stable dual limb knee squat. The pivoting maneuver includes a total quadriceps force that increases from 180 N at contact to 1000 N with the knee at 90° of flexion, coupled with an external torque of 12 N-m applied to the distal tibia to represent an internal pivot with the foot set in the ground (publication in Appendix). The squatting motion is based on lower quadriceps and gravitational forces without torque applied to the tibia. The MPFL graft restored patellar stability during pivoting for 11 of the 13 models. Anatomical parameters related to patellar height, trochlear dysplasia and orientation of the patellar tendon were measured from the models to identify conditions that contribute to ongoing patellar instability following MPFL reconstruction. These parameters were correlated with lateral patellar shift with the knee at 40° of flexion, representing a position at which the patella should be captured by the trochlear groove (Fig. 8). Patellar shift at 40° was significantly correlated with both patellar height (Caton-Deschamps index, $r^2 = 0.49$, $p = 0.008$) and trochlear dysplasia (lateral trochlear inclination angle, $r^2 = 0.55$, $p = 0.004$), but not with orientation of the patellar tendon (tibial tuberosity to

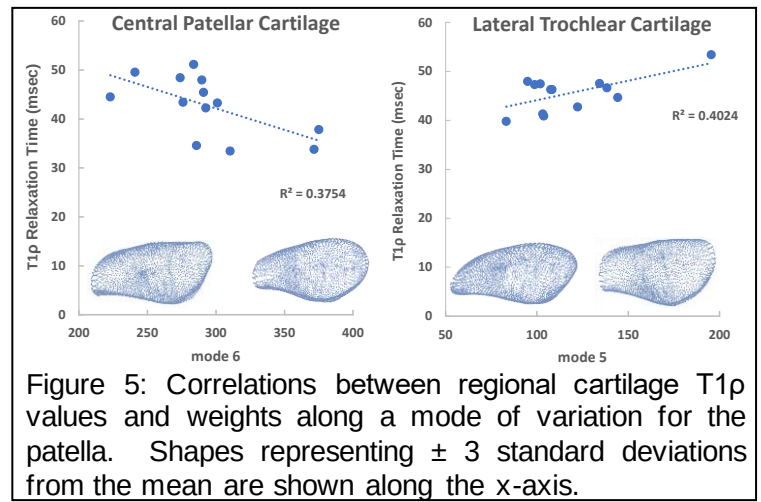


Figure 5: Correlations between regional cartilage T1 ρ values and weights along a mode of variation for the patella. Shapes representing ± 3 standard deviations from the mean are shown along the x-axis.

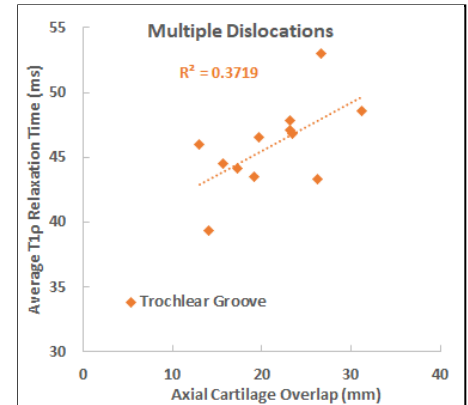


Figure 6: Correlation between cartilage T1 ρ values and patellofemoral cartilage overlap in an axial plane.

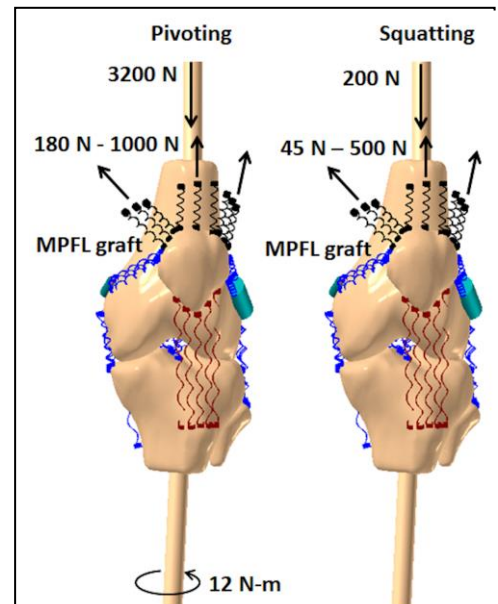


Figure 7: A computational model for dynamic simulation of knee function showing the loading conditions to represent a dislocation event (pivoting) and stable motion (squatting).

trochlear groove distance, $p > 0.6$). The analysis indicates that excessive patellar height and a shallow trochlear groove place a knee at risk for patellar dislocation following MPFL reconstruction. Alternatives have been explored to improve stability for knees with pathologic anatomy. Tightening the MPFL graft and shifting the tibial tuberosity medially have both shown some promise for improving patellar stability but both can also increase pressure applied to medial cartilage. Optimal solutions need to be further explored for the combinations of anatomical factors that create a risk of ongoing instability.

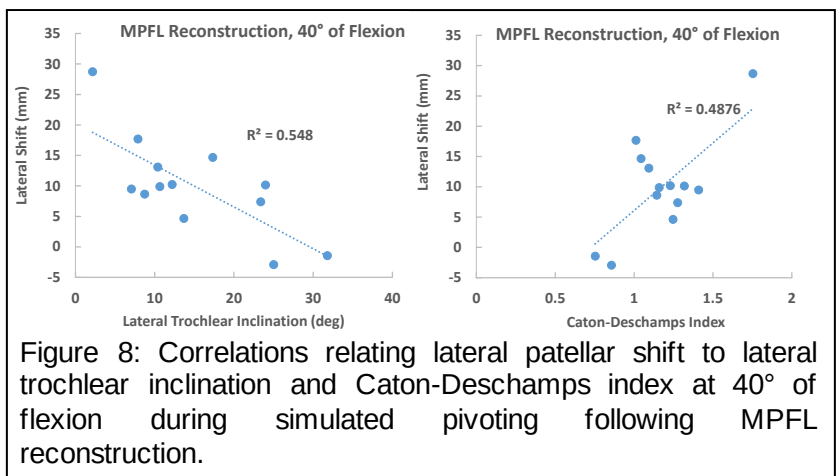


Figure 8: Correlations relating lateral patellar shift to lateral trochlear inclination and Caton-Deschamps index at 40° of flexion during simulated pivoting following MPFL reconstruction.

- **What opportunities for training and professional development has the project provided?**

Roles were identified for students, fellows and residents to participate in the study through a combination of onsite and remote work, and mentorship was provided through lab and project meetings. Currently, four orthopedic residents are working on the project to measure anatomical parameters and quantify patient-reported outcomes. This data will be related to cartilage properties. One other resident worked with the dynamic simulation models. Two post-doctoral fellows and one graduate student have worked on the project to produce T1p relaxation time maps. One other post-doctoral fellow has been updating the approach for statistical shape modeling. The residents and students have been authors on several conference presentations, one submitted manuscript and two published manuscripts.

- **How were the results disseminated to communities of interest?**

The PI made efforts to keep in contact with all patients enrolled in the study. The subjects were given opportunities to discuss results periodically throughout the study or have a summary of the results sent by email.

- **What do you plan to do during the next reporting period to accomplish the goals?**

See transition plan

4. **IMPACT**

- **What was the impact on the development of the principal discipline(s) of the project?**

The study provided the first characterization of cartilage properties throughout the knee in the acute phase following a patellar dislocation. The data confirms that traumatic impact at the medial patella is the primary source of injury to cartilage. Cartilage at this site can partially recover, however. For young patients, patellofemoral cartilage degradation is also noted away from the site of traumatic impact after the acute phase of a first dislocation. No other study has shown that young patients are more prone to early cartilage degradation following a patellar dislocation than older patients. The analysis also shows that cartilage degradation in the acute phase following first-time and multiple dislocations are similar, indicating that ongoing dislocations are not directly accelerating cartilage degradation but may be preventing recovery that can occur with time from injury. Knees that experience a patellar dislocation are at risk of degradation of cartilage within the tibiofemoral joint, which has not been previously described for this population.

The comparison of anatomical features between control subjects, subjects experiencing a single dislocation and subjects experiencing multiple dislocations indicate there are specific features characteristic of patellar dislocations. The primary feature is a shallow trochlear groove, which has been identified in several previous publications. Previously undescribed features related to shape of the patella are also identified. As the number of scanned subjects included in the statistical shape models increase, related to expanded enrollment beyond the original proposal, the combination of features that indicate risk of recurrent dislocations may be

more accurately characterized to help clinicians identify subjects who should consider surgical treatment after an initial dislocation to prevent multiple dislocations.

The data shows that patients with low body mass have higher levels of cartilage degradation following injury than those with high body mass, which was unexpected. More work is needed to understand the mechanisms contributing early cartilage degradation that could be influenced by body mass, such as activity level, impact level, and inflammatory response. Data also relates specific anatomical features to cartilage degradation. Specifically, limited constraint of the patella can contribute to cartilage degradation for patients experiencing multiple dislocations, but so can high levels of patellofemoral constraint. Understanding the balance between maintaining stability without over constraining the patella is needed to develop effective strategies for cartilage preservation.

The data on simulated knee function following reconstruction of the MPFL indicates the approach does not consistently stabilize the patella during activities such as landing and pivoting on one foot. In particular, a shallow trochlear groove and elevated patellar height are correlated with lateral patellar maltracking during pivoting, indicating standard MPFL reconstruction may not be suitable for patients with these characteristics. Alternatives to standard MPFL reconstruction are available, but may increase pressure applied to patellofemoral cartilage, increasing the risk of progressive cartilage degradation. Further analysis of options for MPFL reconstruction for patient-specific pathologic anatomy is needed to improve the ability to stabilize the patella and preserve cartilage. Prior to this study, MPFL reconstruction had not been evaluated while representing functional activities that place the patella at risk of dislocation.

- **What was the impact on other disciplines?**

Nothing to Report

- **What was the impact on technology transfer?**

Nothing to Report

- **What was the impact on society beyond science and technology?**

Nothing to Report

5. CHANGES/PROBLEMS:

- **Changes in approach and reasons for change**

Minor changes were made within the approach without altering the aims of the study. Due to cost savings from the original budget and some parallel analyses, the sample size for control subjects, initial dislocations, multiple dislocations, and follow up analyses were increased compared to the initial plan. The larger sample size increased the power of the statistical analyses. Due to the consistent differences between groups, especially for adolescents, analysis focused more on improving automated reconstruction of relaxation time maps than developing a voxel based relaxometry assessment of differences between the groups. Due to strong correlations between cartilage properties and anatomical shape features, we focused on improving automated reconstruction of bone models and development of the shape model more than characterizing loaded patellofemoral alignment. For alignment between the bones, relationships between the bones based on measures from MRI have shown more promise for relating alignment to cartilage properties than developing a statistical shape model of aligned bones, so ongoing analysis and upcoming submissions are currently based on the alignment measures from MRI. Due to the strong correlations between knee anatomy and patellar tracking for the multibody dynamic simulation models, we focused on evaluation with the existing models more than integrating a statistical shape model into multibody dynamic simulation. The existing models include a wide range of pathological anatomy.

- **Actual or anticipated problems or delays and actions or plans to resolve them**

The primary disruption for the initial study period was related to the covid-19 pandemic. The pandemic altered the work environment, access to students and ability to recruit subjects. The investigators developed new processes to address all these issues. The investigators overcame delays in enrollment to exceed the planned enrollment. One other source of a delay has been development of automated algorithms for sub-

region identification. Some of the knees have not had the sub-region data processed, so some analyses are based on all the cartilage on the patella and within the trochlear groove instead of for the sub-regions.

- **Changes that had a significant impact on expenditures**

Expenses were limited in years 1 and 2 to allow a no cost extension to complete enrollment, imaging and analysis. Some cost savings for imaging allowed an increase in the sample size.

- **Significant changes in use or care of human subjects**

After a temporary pause in recruiting due to covid-19, full enrollment has been allowed over the past 24 months.

- **Significant changes in use or care of vertebrate animals.**

Nothing to report

- **Significant changes in use of biohazards and/or select agents**

Nothing to report

6. **PRODUCTS:**

- **Publications, conference papers, and presentations**

Conference presentations

Yang M, Elias JJ, Sunshine K, Lee J, Colak C, Winalski C, Farrow L, Li X. Variations in Bone Shape Related to Initial and Recurrent Patellar Dislocations. Orthopaedic Research Society Annual Meeting, Feb 12-16, 2021, virtual, podium 142. Federal funding acknowledged.

Watts JC, Farrow LD, Elias JJ. Computational Simulation of MPFL Reconstruction Stabilizing the Patella during a Pivot Landing. Orthopaedic Research Society Annual Meeting, Feb 12-16, 2021, virtual, poster 1289. Federal funding acknowledged.

Li M, Elias JJ, Yang M, Lartey R, Farrow LD, Winalski CS, Li X. Relationships Between Anatomy, Alignment, and Cartilage Degradation in the Patellofemoral Joint: Application to Patellar Dislocations. Orthopaedic Research Society Annual Meeting, Feb 12-16, 2021, virtual, poster 667. Federal funding acknowledged.

Elias JJ, Yang M, Li M, Ma J, Lartey R, Gaj S, Colak C, Winalski C, Farrow L, Li X. Cartilage Degradation Related to Patellar Dislocations: Comparing T1p Relaxation Times to Anatomical Characteristics from Statistical Shape Models. OARSI Virtual World Congress, April 29 - May 1, 2021, poster 404. Federal funding acknowledged.

Elias JJ, Watts JC, Farrow LD. Anatomical Characteristics Contributing to Patellar Dislocations Following MPFL Reconstruction. American Society of Biomechanics Annual Meeting, August 10-13, 2021, virtual, poster 336. Federal funding acknowledged.

Watts JC, Elias JJ, Farrow LD. Anatomical Characteristics Contributing to Patellar Dislocations Following MPFL Reconstruction. American Society of Biomechanics Regional Meeting, September 16-17, 2021, Cleveland, OH, podium. Federal funding acknowledged.

Watts JC, Farrow LD, Jones TJ, Elias JJ. Computational Simulation of MPFL Reconstruction Stabilizing the Patella during a Pivot Landing. ISAKOS Congress 2021, paper Federal funding acknowledged.

Elias JJ, Yang M, Li M, Lartey R, Murray J, Farrow LD, Winalski CS, Li X. Patellar Dislocation Alters the Relationship between Cartilage T1p Relaxation Times and Femoral Shape. ORS Annual Meeting, Feb 4-8, 2022, Tampa, FL, poster 0583 Federal funding acknowledged.

Elias JJ, Yang M, Li M, Lartey R, Murray J, Farrow LD, Winalski CS, Li X. Elevated Patellofemoral and Tibiofemoral Cartilage T1p Relaxation Times Following an Initial Patellar Dislocation. ORS Annual Meeting, Feb 4-8, 2022, Tampa, FL, podium 0286 Federal funding acknowledged.

Elias JJ, Li M, Yang M, Lartey R, Murray J, Winalski C, Farrow L, Li X. T1p-Based Cartilage Degradation Following Patellar Dislocation: First-Time vs. Multiple Dislocations. OARSI Hybrid World Congress, April 7 - April 10, 2022, poster 215 Federal funding acknowledged

Elias JJ, Yang M, Li M, Lartey R, Farrow LD, Winalski CS, Li X. Patellar Anatomy Related To Cartilage Properties Following Multiple Patellar Dislocations: Correlating Anatomical Modes From Statistical Shape Models With T1p Relaxation Times. ORS Annual Meeting, Feb 10-14, 2023, Dallas, TX, podium 344. Federal funding acknowledged

Elias JJ, Li M, Yang M, Lartey R, Farrow LD, Winalski CS, Li X. Time Course Of Early Cartilage Response To Injury Following Patellar Dislocation. ORS Annual Meeting, Feb 10-14, 2023, Dallas, TX, poster 956.

Federal funding acknowledged

Farrow LD, Elias JJ, Li M, Yang M, Winalski CS, Li X. Patellar Dislocation in Adolescent Patients: Influence on Patellofemoral and Tibiofemoral Cartilage based on T1ρ Relaxation Times. AOSSM Specialty Day, Las Vegas, NV, March 11, 2023, paper 05. Federal funding acknowledged

Manuscripts

Elias JJ, Li M, Yang M, Lartey R, Murray JP, Farrow LD, Winalski CS, Li X. Elevated Patellofemoral and Tibiofemoral T1ρ Relaxation Times Following a First-Time Patellar Dislocation. Cartilage. 2022;13(2):19476035221102570. Federal funding acknowledged

Watts JC, Farrow LD, Elias JJ. Anatomical Characteristics Contributing to Patellar Dislocations Following MPFL Reconstruction: A Dynamic Simulation Study. J Biomech Eng. 2023;145(4):041003. Federal funding acknowledged

Farrow LD, Elias JJ, Li M, Yang M, Lartey R, Winalski CS, Li X. Patellar Dislocation in Adolescent Patients: Influence on Cartilage Properties based on T1ρ Relaxation Times. Am J Sports Medicine (under review).

○ Website(s) or other Internet site(s)

Nothing to Report

○ Technologies or techniques

Nothing to Report

○ Inventions, patent applications, and/or licenses

Nothing to Report

○ Other Products

Within the existing framework for MRI-based relaxation time mapping of cartilage properties, machine-learning algorithms for automated processing of imaging data, which were originally developed to focus on tibiofemoral osteoarthritis following ACL injury, have been expanded to include patellofemoral compartments and account for pathologic patellofemoral anatomy. Automated algorithms to reconstruct bone models and add them to statistical shape models have also been developed. Within the existing framework for dynamic simulation of knee function, loading and boundary conditions have been developed to consistently represent a pivoting maneuver causing a patellar dislocation. Models representing knees that are not adequately stabilized by MPFL reconstruction have been developed for evaluation of alternative surgical parameters to stabilize the patella. A database has been developed including the subjects from all groups. The database contains demographic information for each subject, T1ρ relaxation times for the tibiofemoral and patellofemoral cartilage at baseline and follow up evaluations, weighting factors along each mode of variation from the statistical shape models, measures of patellofemoral anatomy and alignment from MRI, and patient-reported outcome measures.

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

○ What individuals have worked on the project?

Name:	John Elias
Name:	Mingrui Yang
Name:	Mei Li
Name:	

○ Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to Report

○ What other organizations were involved as partners?

Nothing to Report

8. **SPECIAL REPORTING REQUIREMENTS**

Nothing to Report

9. **APPENDICES**

Elias JJ, Li M, Yang M, Lartey R, Murray JP, Farrow LD, Winalski CS, Li X. Elevated Patellofemoral and Tibiofemoral T1ρ Relaxation Times Following a First-Time Patellar Dislocation. Cartilage. 2022;13(2):19476035221102570.

Watts JC, Farrow LD, Elias JJ. Anatomical Characteristics Contributing to Patellar Dislocations Following MPFL Reconstruction: A Dynamic Simulation Study. J Biomech Eng. 2023;145(4):041003.

Elevated Patellofemoral and Tibiofemoral T1ρ Relaxation Times Following a First Time Patellar Dislocation

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Abstract

Objective. The study was performed to evaluate cartilage within the knee following a first-time patellar dislocation, using elevated MRI-based T1ρ relaxation times as an indicator of low proteoglycan concentration. The hypothesis is that MRI-based T1ρ relaxation times for patellofemoral and tibiofemoral cartilage are significantly longer for knees being treated for patellar dislocation than for healthy control knees. **Design.** Twenty-one subjects being treated for a first-time, unilateral dislocation of the patella and 16 healthy controls participated in MRI-based T1ρ relaxation time mapping. Mean relaxation times were quantified for patellofemoral and tibiofemoral regions for injured knees, the contralateral knees, and healthy controls. T1ρ values for each region were compared between the 3 groups with generalized estimating equations. Linear regressions were also performed to correlate T1ρ relaxation times with time from injury. **Results.** The knees with a dislocation had longer T1ρ relaxation times than the contralateral knees and control group at the medial patella and longer relaxation times than the control group at the lateral tibia ($P < 0.05$). T1ρ relaxation times at the medial patella also decreased with time from injury ($r^2 = 0.21$, $P = 0.037$). **Conclusions.** Compositional changes to cartilage on the medial patella are related to traumatic impact during a dislocation. Potential exists for cartilage properties at the medial patella to improve with time. Cartilage degradation at the lateral tibia is not directly related to traumatic impact. The current baseline data are a starting point to characterize the pathway from a first-time dislocation to progressive cartilage degradation and osteoarthritis.

Keywords

patellar dislocation, cartilage, T1ρ

Introduction

A lateral patellar dislocation is a traumatic event with annual incidence rates of approximately 150 and 50 per 100,000 person years for age ranges of 14 to 18 and 19 to 24 years, respectively.¹ In the acute phase following a first-time dislocation, more than 50% of subjects show signs of cartilage lesions on the medial or central patella, likely related to impact of the medial patella against the lateral femoral condyle during a dislocation.^{2–4} Cartilage lesions are also noted at the lateral femoral condyle and lateral trochlear groove for approximately one-third of patients.^{3–6} Follow-up evaluations show cartilage lesions on the patella for more than 95% of patients,^{2,7,8} with an increased frequency of lesions within the trochlear groove and tibiofemoral joint.² Cartilage lesions following patellar dislocation can progress to patellofemoral post-traumatic osteoarthritis (PTOA). Patellofemoral OA is identified for approximately 50% of patients by 25 years following a

patellar dislocation,⁹ accounting for more than 25% of all cases of patellofemoral OA.¹⁰ Progression to tibiofemoral OA following patellar dislocation has not been characterized to date.

A more quantitative assessment of cartilage properties is needed to characterize the pathway from patellar dislocation to OA. Quantitative MRI is increasingly being used to

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identify cartilage matrix degeneration¹¹⁻¹⁴ that could progress to OA¹³ based on elevated T1 ρ and T2 relaxation times. T1 ρ relaxation times are more sensitive to concentration of proteoglycans, and T2 relaxation times are more sensitive to collagen structure.¹⁵ Previous studies focused on general patellar instability,⁸ multiple dislocations,^{16,17} and surgical treatment for patellar dislocation¹⁸ have shown elevated T2 relaxation times for cartilage on the patella.¹⁸ A specific focus on the acute phase following a first-time patellar dislocation is lacking, but needed for longitudinal characterization of cartilage degradation. Quantitative MRI-based evaluation of cartilage within the trochlear groove and tibiofemoral joint is also lacking. Only one of the previous studies¹⁷ evaluated contralateral knees to specifically relate cartilage degradation to traumatic impact. Characterization of the influence of demographic parameters on T1 ρ and T2 relaxation times following patellar dislocation is also lacking. Studies that have related T1 ρ and T2 relaxation times for patellofemoral and tibiofemoral cartilage to demographic parameters have shown that the relationships vary with the type of knee disorder.^{19,20} Relationships between patellofemoral T1 ρ /T2 relaxation times and demographic parameters are also lacking for healthy knees.

The current study was performed to characterize cartilage properties throughout injured and contralateral knees following a first-time patellar dislocation to address cartilage degradation related to the initial traumatic injury and set the baseline for characterization of longitudinal cartilage degradation. The hypothesis of the study is that T1 ρ relaxation times for patellofemoral and tibiofemoral cartilage are significantly longer for knees being treated for a first-time patellar dislocation than for healthy knees. The study also includes characterization of the influence of demographic parameters on T1 ρ relaxation times for healthy knees and following patellar dislocation.

Methods

Subjects

Twenty-one injured subjects between the ages of 14 and 36 years were prospectively recruited from January 2019 to December 2021. The study was approved by the Cleveland Clinic Institutional Review Board (ID # 18-1388), and all subjects (plus a guardian for minors) signed a consent or assent form prior to participating. Patients were recruited based on treatment for a first-time, complete, traumatic dislocation of the patella from the trochlear groove for one knee. All dislocations were confirmed by identification of a bone bruise on the medial patella and lateral femoral condyle on MRI. Exclusion criteria were: (1) age less than 13 years, (2) prior patellar dislocation for either knee, (3) prior surgery for either knee, (4) more than 6 months since the initial dislocation, (5) existing OA, and (6) soft tissue injuries or fractures that required surgical treatment. All patients

were initially treated conservatively with activity modification, physical therapy, and bracing. Most patients were no longer wearing a brace by the time of evaluation. An additional 16 subjects between the ages of 13 and 33 years with no history of prior surgeries, injuries, or OA for either knee were recruited to participate in the control group.

Demographic data collected from the injured subjects and controls included age, sex, and body mass index (BMI). Time from dislocation to imaging was also acquired for the injured subjects. Skeletal maturity was assessed for each subject, based on the MRI data.²¹ Subjects were considered skeletally mature if all growth plates on the femur, tibia, and fibula were fully closed.

Magnetic Resonance Imaging

MRI scans were performed on a 3T scanner (Prisma, Siemens) using a 1Tx/15Rx knee coil (Quality Electrodynamics). Both knees were scanned for the injured subjects, and one knee for the controls. Anatomical parameters were measured from a 3D non-fat saturated Sampling Perfection with Application optimized Contrasts using different flip angle Evolution (SPACE) scan. Cartilage was segmented from a 3D fat saturated Dual Echo Steady State (DESS) scan. Relaxation times were quantified using a fat saturated T1 ρ Magnetization-prepared Angle-modulated Partitioned-k-space Spoiled gradient-echo Snapshots (MAPSS) imaging sequence.^{22,23} The major parameters of the MRI protocol are shown in **Table 1**.

Anatomical measurements characterized trochlear depth, patellar height, and position of the tibial tuberosity for each knee. Trochlear depth was based on lateral trochlear inclination, as the angle between a line along the lateral ridge of the trochlear groove and a line tangent to the posterior condylar axis of the femur (**Fig. 1**).²⁴ The measurement was made in an axial plane, using the most proximal slice showing cartilage spanning the trochlear groove to represent the lateral ridge and a slice with the largest anterior-posterior dimension of the femoral condyles to represent the posterior condylar axis. A lateral trochlear inclination less than 11° was considered trochlear dysplasia.²⁵ Position of the tibial tuberosity was based on the tibial tuberosity to trochlear groove (TT-TG) distance, measured as the lateral distance from the deepest point on the trochlear groove to the most prominent point of the tibial tuberosity.²⁴ TT-TG distance was measured in an axial plane, using the same slices for the posterior condylar axis and deepest point of the trochlear groove, with a separate slice at the patellar tendon attachment to identify the tibial tuberosity point. A TT-TG distance exceeding 20 mm was considered lateral malalignment.²⁶ Patellar height was based on the Caton-Deschamps index, calculated by dividing the distance from the most distal point of the articular surface of the patella to the most superior-anterior point on the tibia by the superior-inferior length of the cartilage on the patella. Measurements were made from a sagittal slice with the largest superior-inferior

Table 1. Parameters for 3D MRI Scans.

	SPACE	DESS	MAPSS T1 ρ ^a
Plane	Sagittal	Sagittal	Sagittal
Acquisition time	9:15	7:10	7:10
TR (ms)	1000	17.55	6.37
TE (ms)	28	6.02	2.9
Matrix (freq $\times$ phase)	320 $\times$ 304	384 $\times$ 307	320 $\times$ 160
Number of slices	176	160	24
FOV (mm)	160	140	140
Slice thickness (mm)	0.5	0.7	4
Skip (mm)	0	0	0
Flip angle (deg)	VFA	25	VFA
Fat suppression	Non-fat saturated	Fat saturated	Fat saturated
Measurement	Anatomical measurements	Cartilage segmentation	Cartilage composition

SPACE = Sampling Perfection with Application optimized Contrasts using different flip angle Evolution; DESS = Dual Echo Steady State; MAPSS = Magnetization-prepared Angle-modulated Partitioned-k-space Spoiled gradient-echo Snapshots; VFA, variable flip angle; FOV = field of view; TR = Repetition time; TE = Time to echo.

^aTime of spin-lock for T1 ρ = 0, 10, 30, 70 ms, spin-lock frequency = 500 Hz.

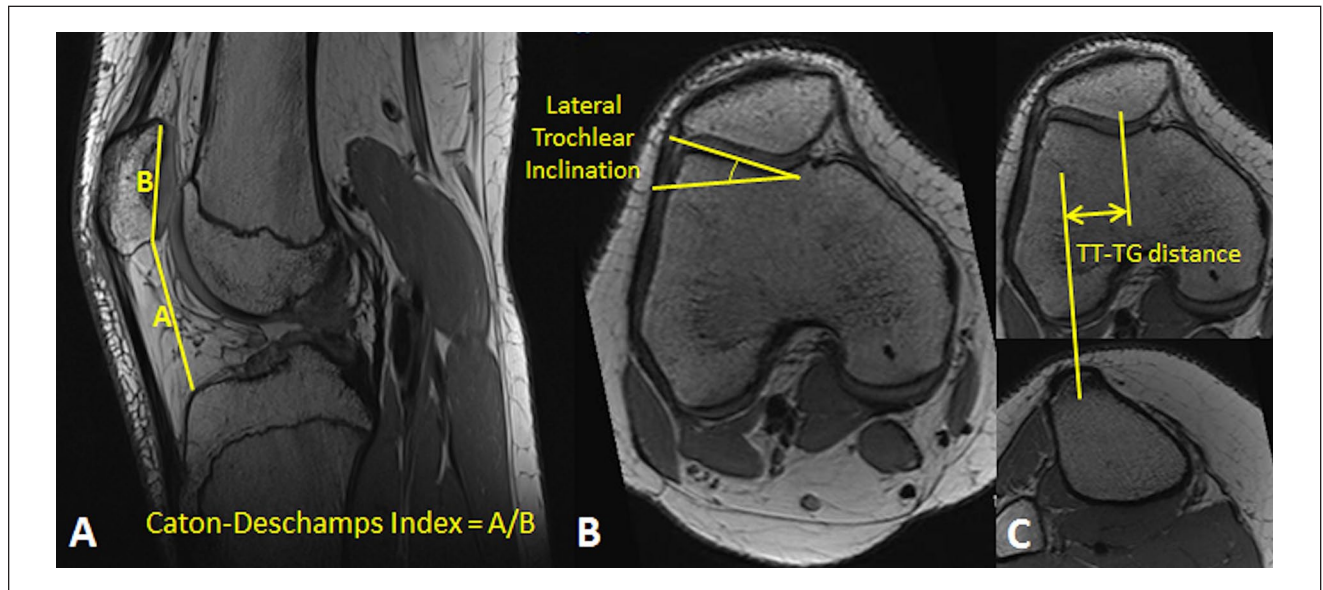


Figure 1. Measurements used to characterize knee anatomy. The lines drawn to calculate the Caton-Deschamps index (A) represent the distance from cartilage on the patella to the superior-anterior tibia and the superior-inferior length of the patellar cartilage. Lateral trochlear inclination (B) is the angle between a line along the lateral ridge of the trochlear groove and a line parallel to the posterior condylar axis of the femur. The posterior condylar axis is identified on a separate slice with the largest anterior-posterior distance of the femoral condyles. TT-TG distance (C) is the distance from the most prominent point on the tibial tuberosity to the deepest point of the trochlear groove along the posterior condylar axis. TT-TG = tibial tuberosity to trochlear groove.

dimension of the patella.²⁴ A Caton-Deschamps index ≥ 1.2 was considered patella alta.²⁴

Cartilage Mapping

Regions of patellofemoral and tibiofemoral cartilage were segmented from the DESS scan for T1 ρ cartilage mapping. Cartilage compartments representing the medial and lateral femoral condyle, medial and lateral tibial plateau, trochlear

groove, and patella were automatically segmented with a custom, deep learning algorithm that combines conditional generative adversarial networks and convolutional neural networks to identify cartilage borders at the articular surface and interface with underlying bone.²⁷ Manual corrections were applied to the segmentation if automated segmentation failed.

Cartilage on the patella and within the trochlear groove were further divided into medial, lateral, and central regions

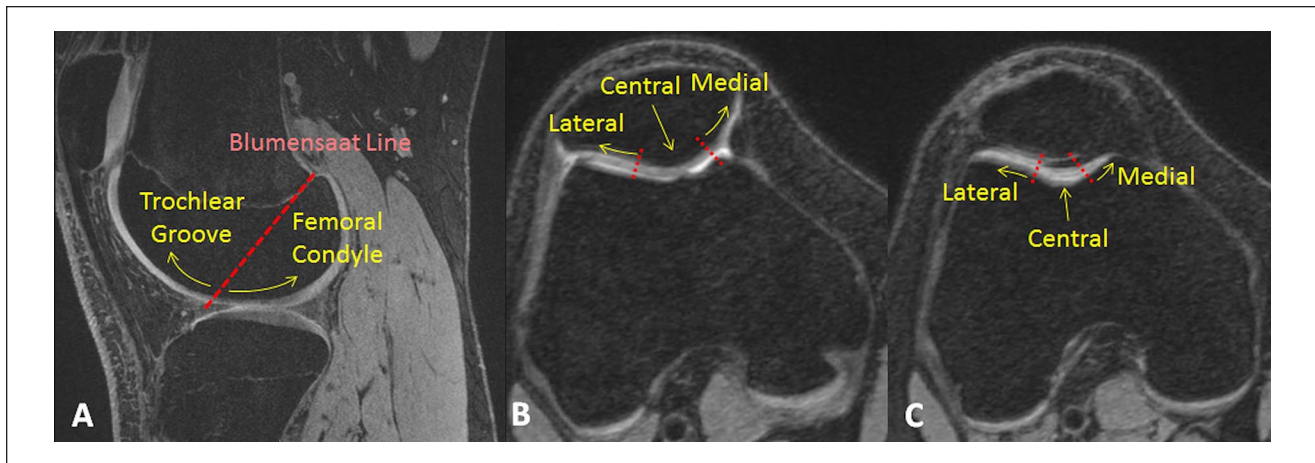


Figure 2. A sagittal view showing separation of cartilage on the femur into trochlear groove and femoral condyle regions based on a projection of Blumensaat's line (**A**). Axial views show separation of cartilage on the patella into a central region centered on the patellar ridge, plus medial and lateral regions (**B**), and separation of cartilage in the trochlear groove into a central ridge centered on the deepest point of the trochlear groove, plus lateral and medial regions (**C**).

(Fig. 2). Landmarks were identified on the surfaces of the bones with an automated closed-contour mapping algorithm. For the patella, the most medial and lateral points and the most prominent point on the patellar ridge were identified within axial slices through the patella. The central region extended from the patellar ridge, one-third of the distance to the medial and lateral edges of the patella. The remaining cartilage on the facets were identified as the medial and lateral regions. A similar approach was applied to the trochlear groove, with points identified on axial slices at the medial and lateral edges of the cartilage and the deepest point of the trochlear groove. The landmarks were individually examined for each knee and manually corrected if necessary. A division between cartilage in the trochlear groove and on the femoral condyles was based on a projection of Blumensaat's line, which traces the roof of the intercondylar notch on a sagittal view, through the cartilage on the femur.

T1 ρ relaxation times were mapped to the reconstructed cartilage surfaces (Fig. 3).^{28,29} Images from the DESS scan were rigidly registered with the first echo of the T1 ρ images, using piecewise rigid registration to account for variations in the positions of the bones. An intensity-based, multi-resolution pyramidal approach was used for non-rigid registration between the first echo and a template mask covering areas surrounding the patella, tibia, fibula, and femur to obtain a predefined mask for precision. The resulting transformation was applied to a rigid registration of the later echoes of the T1 ρ images to the first echo. The T1 ρ images were fit pixel by pixel based on a 2 parameter, monoexponential Levenberg-Marquardt algorithm relating image signal to exponential decay based on time of spin lock to T1 ρ relaxation time. The average T1 ρ relaxation time was calculated based on all voxels within each sub-region. Using the

same techniques, the scan-rescan root mean square coefficient of variation for T1 ρ values has been reported to be less than 5%.^{23,30}

Statistical Analysis

Statistical analysis focused on comparisons between injured and control knees for each region to characterize cartilage degradation that could lead to PTOA. Comparisons between injured and contralateral knees were also performed to focus on the influence of traumatic impact on cartilage degradation. Age and body mass index were compared between injured and control subjects with a Mann-Whitney *U* test, based on assessment of normality from Shapiro-Wilk tests (SPSS version 24, IBM). Distribution of sex and skeletal maturity was compared between injured and control subjects with a chi-square test. Anatomical parameters and T1 ρ relaxation times were compared between the groups with generalized estimating equations accounting for unpaired comparisons between injured and control knees and paired comparisons between injured and contralateral knees. Due to a weak trend for higher BMI for injured subjects than controls, BMI was treated as a covariate in the generalized estimating equations for T1 ρ relaxation times. The sample size was designed to achieve a power of 0.95 for an effect size of 1.3 and statistical significance set at $P < 0.05$ based on previous studies that compared injured knees to controls, but did not focus on the acute phase of injury.^{8,16}

To characterize the influence of demographic parameters on T1 ρ relaxation times, linear regressions were performed to relate age and BMI to T1 ρ relaxation times in each region for the dislocation and control groups. Data were analyzed to confirm assumptions of normally distributed residuals based on a PP-plot and homoscedasticity based on a

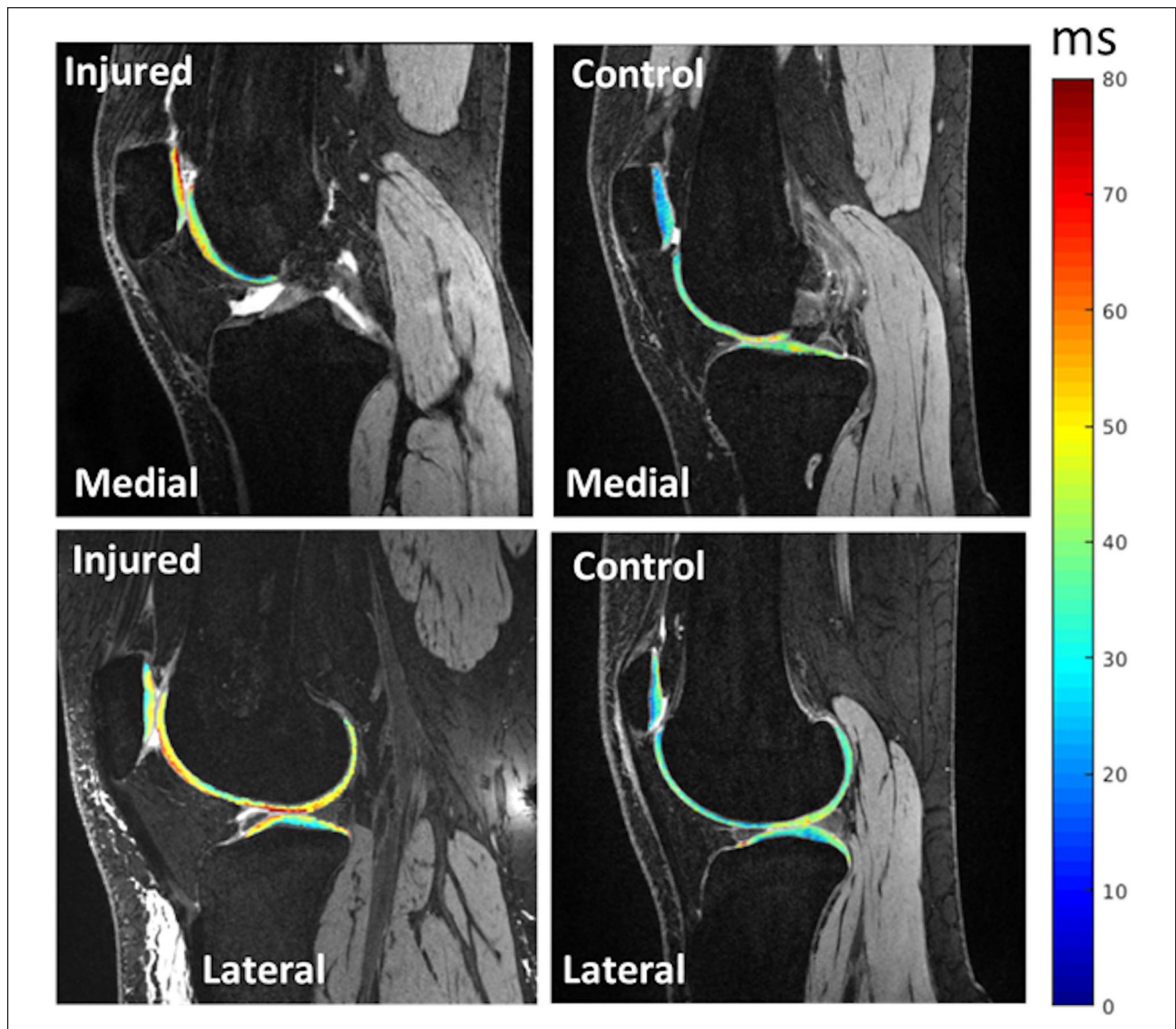


Figure 3. T1 ρ relaxation times mapped to patellofemoral and tibiofemoral cartilage from a Dual Echo Steady State scan for injured and uninjured knees. The images give examples of elevated relaxation times for cartilage at the medial patella and lateral tibia for an injured knee.

scatterplot of the residuals. Standardized β coefficients were quantified to determine the strength of correlations. Time from dislocation to imaging was included in the regressions for the dislocation group. T1 ρ relaxation times were also compared between males and females and between skeletally mature and immature subjects for injured and control knees with t tests. The groups were checked for normality and for equality of variances with Levene tests.

Results

Anatomical parameters differed between injured knees and healthy controls, but demographic parameters were similar

(Table 2). The median time from initial injury to imaging was 48 days (range: 3-151). Lateral trochlear inclination was significantly smaller for the injured knees than the control and contralateral knees ($P \leq 0.01$). Lateral trochlear inclination was less than 11° for 5 injured knees. TT-TG distance was significantly larger for the injured knees than the control and contralateral knees ($P < 0.01$). TT-TG distance exceeded 20 mm for 5 injured knees. Caton-Deschamps index did not vary significantly between the 3 groups ($P = 0.17$). Caton-Deschamps index was ≥ 1.2 for 11 injured knees. Distribution of sex, skeletal maturity, and age were similar for injured subjects and controls. The injured subjects also tended to have a higher BMI, although

Table 2. Demographic and Anatomical Characteristics for the Control, Dislocation, and Contralateral (Anatomical Only) Groups.

	Control	Dislocation	Contralateral	P values		
				Dislocation vs. Control	Dislocation vs. Contralateral	Contralateral vs. Control
				(All 3 groups)		
Sex (male/female)	9/7	10/11		0.85		
Skeletally mature (yes/no)	11/5	13/8		0.67		
Age (years)	20.8 ± 7.2	21.7 ± 8.0		0.69		
Body mass index (kg/m ²)	23.6 ± 3.4	27.3 ± 8.4		0.34		
TT-TG distance (mm)	13.0 ± 2.6	16.7 ± 4.7	14.1 ± 4.5	0.002	0.007	0.35
Lateral trochlear inclination (°)	20.0 ± 3.8	15.8 ± 6.0	17.6 ± 5.2	0.007	0.010	0.096
Caton-Deschamps index	1.11 ± 0.12	1.17 ± 0.18	1.19 ± 0.16		(0.17)	

Continuous data are presented as mean ± standard deviation. *P* values between injured subjects and controls are shown for demographic parameters. For anatomical characteristics, *P* values are shown for comparisons between pairs if significant differences exist, or for all 3 groups if no significant differences exist. Statistically significant *P* values are in bold.

TT-TG = tibial tuberosity to trochlear groove.

Table 3. Mean (± Standard Deviation) T1ρ Relaxation Times (ms) for the 3 Groups.

	Control	Dislocation	Contralateral	P values		
				Dislocation vs. Control	Dislocation vs. Contralateral	Contralateral vs. Control
				(All 3 groups)		
Patella						
Medial	37.0 ± 6.3	43.0 ± 7.0	38.5 ± 7.1	0.012	0.006	0.66
Central	38.7 ± 5.2	42.1 ± 6.4	41.1 ± 4.5		(0.28)	
Lateral	38.0 ± 6.0	40.9 ± 5.0	40.2 ± 4.0		(0.36)	
Trochlea						
Medial	42.7 ± 3.4	44.4 ± 5.9	44.4 ± 4.2		(0.79)	
Central	43.5 ± 3.6	45.2 ± 4.2	44.9 ± 4.3		(0.56)	
Lateral	43.3 ± 3.2	44.8 ± 5.3	45.6 ± 5.8		(0.50)	
Femur						
Medial	44.8 ± 3.5	46.1 ± 4.5	47.0 ± 4.6		(0.34)	
Lateral	42.8 ± 4.3	45.8 ± 3.6	45.9 ± 4.2		(0.12)	
Tibia						
Medial	40.9 ± 4.4	41.9 ± 2.8	42.4 ± 4.2		(0.67)	
Lateral	37.6 ± 3.2	40.7 ± 2.3	40.5 ± 4.2	0.006	0.78	0.055

P values are shown for comparisons between pairs of groups if significant differences exist, or for all 3 groups if no significant differences exist. Statistically significant *P* values are in bold.

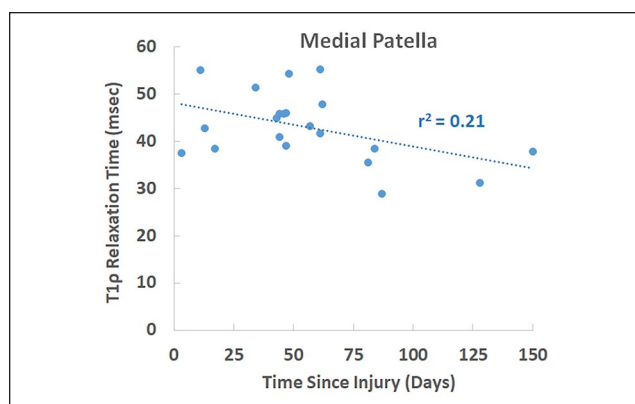
the difference did not reach statistical significance ($P = 0.34$). Due to the mean difference of 3.7 kg/m², the tendency for higher BMI for the injured subjects was accounted for as a covariate in the generalized estimating equations comparing T1ρ relaxation times between injured knees and controls.

T1ρ relaxation times were longer for the dislocation group than the control group at the medial patella and lateral tibia (Table 3). At the medial patella, the mean

relaxation time was 6.0 ms longer for the dislocation group than the control group ($P = 0.012$). The mean relaxation time was also longer for the dislocation group than the contralateral knees (difference = 4.5 ms, $P = 0.006$). At the lateral tibia, the difference between injured and control knees was 3.1 ms ($P = 0.006$). Relaxation times were not significantly longer for the injured knees than the contralateral knees at the lateral tibia ($P = 0.78$). T1ρ relaxation times tended to be longer for the dislocation group than

Table 4. Significant ($P < 0.05$) and Nearly Significant ($P < 0.10$) Correlations Relating T1 ρ Relaxation Times to Demographic Parameters.

	Region	r^2	P value	Standardized β
Dislocation group ($n = 21$)				
Time since dislocation (days)	Medial patella	0.21	0.037	-0.46
Body mass index (kg/m^2)	Lateral tibia	0.17	0.066	0.41
Control group ($n = 16$)				
Body mass index (kg/m^2)	Medial patella	0.28	0.033	0.53
Body mass index (kg/m^2)	Central patella	0.51	0.002	0.71
Body mass index (kg/m^2)	Lateral patella	0.37	0.012	0.61
Body mass index (kg/m^2)	Medial trochlea	0.52	0.002	0.72
Body mass index (kg/m^2)	Central trochlea	0.34	0.017	0.59
Body mass index (kg/m^2)	Lateral trochlea	0.30	0.029	0.54
Age (years)	Medial patella	0.25	0.048	0.50
Age (years)	Central patella	0.34	0.017	0.58
Age (years)	Lateral patella	0.29	0.032	0.53
Age (years)	Medial trochlea	0.42	0.007	0.65

**Figure 4.** T1 ρ relaxation time at the medial patella versus the number of days since dislocation. The decrease in T1 ρ relaxation time with days since injury was statistically significant ($P = 0.037$).

control knees for other patellofemoral regions, but no other statistically significant differences were identified.

For the dislocation group, the only parameter correlated with T1 ρ relaxation time was time from dislocation, while age and BMI were correlated with T1 ρ relaxation time for the control group (**Table 4**). For the dislocation group, T1 ρ relaxation time at the medial patella decreased with time from injury ($r^2 = 0.21$, $P = 0.037$). The trend was primarily driven by patients evaluated longer than 2 months after dislocation (**Fig. 4**). No other statistically significant correlations were identified between T1 ρ relaxation time and time from injury, age, or BMI for any region. For the control group, T1 ρ relaxation time increased with BMI for all 6 patellofemoral regions ($P < 0.04$). T1 ρ relaxation time also increased with age for all 3 regions on the patella and the medial trochlear groove ($P < 0.05$). The standardized β coefficients were larger for BMI than age for every region

in which both were significantly correlated with T1 ρ relaxation time. For the control group, no correlations between T1 ρ relaxation time and demographic parameters were identified for any region of the tibiofemoral joint.

Significant differences between injured and control knees related to sex and skeletal maturity were limited. The only significant difference between males and females was longer relaxation times for females than males at the lateral patella for the dislocation group (43.0 ± 4.2 vs. 38.7 ± 5.0 ms, $P = 0.045$). The only significant difference related to skeletal maturity was longer relaxation times for skeletally mature than immature subjects at the lateral patella for the control group (40.2 ± 4.9 vs. 33.3 ± 5.8 ms, $P = 0.026$).

Discussion

The primary result is that a first-time patellar dislocation is associated with elevated T1 ρ relaxation times for cartilage on the medial patella and lateral tibia. The longer T1 ρ relaxation times indicate loss of proteoglycan concentration within the cartilage that reduces cartilage integrity and could be an initiation point for progression to OA. Elevated T1 ρ relaxation times at the medial patella are consistent with previous studies focused on T2 relaxation times for patients being treated for patellar instability.^{8,16,31} The previous studies did not focus on acute first-time patellar dislocations. The current results are also consistent with cartilage lesions on the medial facet of the patella for approximately 60% of patients following a first-time patellar dislocation.²⁻⁴ In addition to the patellofemoral joint, the current study provides the first analysis of cartilage composition in the tibiofemoral joint after patellar dislocation, to the best of the authors' knowledge. Relaxation times at the lateral tibia were elevated following patellar dislocation. Previous studies have identified cartilage lesions on the lateral femoral

condyle for approximately one-third of patients following patellar dislocation.^{3,5,6}

Traumatic injury during a dislocation episode contributes to longer T1 ρ relaxation times at the medial patella following a lateral patellar dislocation. The medial patella impacts against the lateral femoral condyle during a dislocation event, with bruises forming on each bone at the location of impact.^{2,4} Relaxation times at the medial patella were longer for injured knees than controls, indicating early cartilage degradation, and were also longer for injured than contralateral knees, indicating the traumatic impact was a primary contributor to the cartilage degradation. In contrast, one study evaluated patients with multiple dislocations at least 5 years after the initial dislocation and identified longer T2 relaxation times within superficial cartilage on the medial patella for uninjured contralateral knees than injured knees.¹⁷ The decrease in T1 ρ relaxation times at the medial patella beyond 2 months after dislocation indicates potential for cartilage to recover from the initial injury. Any recovery may be partial and short term. A study based on delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) indicated proteoglycan concentration at the medial patella decreases with time for patients evaluated at least 6 months following a recurrent dislocation.³² Furthermore, a previous study indicated early cartilage lesions are still evident an average of 8 years following patellar dislocation.²

The lateral tibia is not considered a site of direct trauma during a patellar dislocation. At the lateral tibia, T1 ρ relaxation times were longer for injured knees than healthy controls, but not longer than for injured knees than contralateral knees. Elevated T1 ρ values at the lateral tibia did not decrease with time from injury. Direct trauma does not seem to be the primary factor influencing cartilage degradation at the lateral tibia.

Multiple factors other than direct trauma can contribute to cartilage degradation observed following a patellar dislocation. Pathologic anatomy contributes to patellar dislocations. Injured knees demonstrated a shallow trochlear groove and a lateral position of the tibial tuberosity in comparison to contralateral knees and the control group, based on TT-TG distance and lateral trochlear inclination, respectively. Both conditions are commonly associated with patellar dislocations^{24,33} and could contribute to re-dislocations³⁴ that are associated with an increased risk of patellofemoral OA.⁹ Without weightbearing full limb anterior-posterior radiographs, valgus alignment that could contribute to both patellar dislocations³⁵ and degradation of lateral tibiofemoral cartilage³⁶ was not characterized. Pathologic anatomy and alignment could contribute to longer T1 ρ relaxation times at the medial patella and lateral tibia. Inflammatory effects that contribute to cartilage degradation following anterior cruciate ligament (ACL) injury^{37,38} could also contribute to elevated T1 ρ relaxation times. The current study lacks characterization of T1 ρ relaxation times for knees

with high levels of pathologic anatomy but without the direct impact and inflammatory effects associated with a dislocation episode to distinguish between these 3 factors. Further studies including a more comprehensive characterization of anatomy, analysis of inflammatory biomarkers, and evaluation of knees with pathologic anatomy prior to dislocation are warranted.

The current data provide a baseline measure of cartilage properties following patellar dislocation for comparison to longitudinal measures mapping the pathway to PTOA. Approximately 50% of patients progress to patellofemoral OA by 25 years after a first-time patellar dislocation.⁹ Progressive cartilage degradation and OA are not isolated to the medial patella. Studies focused on patients being treated for multiple dislocations and general instability identified significant differences between injured knees and controls at the central^{8,16} and lateral⁸ patella. Increased prevalence of cartilage lesions at the central and lateral patella, within the trochlear groove, and within the tibiofemoral joint have been noted at approximately 8 years following a first-time dislocation.² Progressive cartilage degradation is likely related to several factors in addition to the initial injury. Abnormal function related to pathologic anatomy and injury to the medial patellofemoral ligament during the initial dislocation could contribute to progressive cartilage degradation. Trochlear dysplasia, in particular, has been related to an elevated risk of OA.⁹ Inflammatory effects could also contribute to progressive cartilage degradation.

The results suggest patellar dislocation alters the relationship between T1 ρ values and demographic factors. For control subjects, T1 ρ values for patellofemoral cartilage increased with age and BMI. The correlations were stronger for BMI than age (suggested by the larger standardized β coefficients, **Table 4**). These relationships were not identified for tibiofemoral cartilage. A previous study showed T1 ρ relaxation times increase with BMI for cartilage on the tibia but not the femur.³⁹ The minimum age for the previous study was 22 years, as opposed to 13 for the current study. The authors are not aware of other previous publications correlating age and BMI with patellofemoral and tibiofemoral cartilage T1 ρ relaxation times for healthy knees. For injured knees, neither age nor BMI was correlated with patellofemoral T1 ρ relaxation times, likely due to the influence of traumatic injury on T1 ρ values. Longer T1 ρ relaxation times for females than males were identified at the lateral patella following dislocation. This difference was not observed for control subjects, suggesting potential for differing responses to injury between sexes. Trends between demographic factors and relaxation times seem to be injury specific. For patients treated surgically for ACL injury, one study reported T1 ρ relaxation times for patellofemoral and tibiofemoral cartilage increased with age, but decreased with BMI¹⁹; females also had higher T1 ρ relaxation times than males.¹⁹ For patients treated for other forms of knee

pain or injury, not including patellar dislocation, patellar cartilage T2 relaxation times decreased with age and were greater in males than females.²⁰ Follow-up studies are warranted to longitudinally evaluate correlations between cartilage health and demographics, including potential differences based on sex, following patellar dislocation.

The increase in patellofemoral relaxation times with age for the control group but not for the injured subjects gives an indication that relatively short T1ρ relaxation times for the young controls contribute to the difference noted at the medial patella and trends noted for the other patellofemoral regions. The T1ρ relaxation times were also longer at the lateral patella for skeletally mature than immature controls. Without a significant correlation relating age to T1ρ relaxation times for the control subjects for the tibiofemoral regions, the difference at the lateral tibia does not seem to be driven by young subjects. Further studies with a larger sample size seem warranted to divide the subjects into young and old sub-groups.

The primary limitation of the study is the relatively small sample size for identifying elevated T1ρ relaxation times for regions other than the medial patella and lateral tibia. Effect sizes for comparisons between injured knees and controls at the central and lateral regions of patellar cartilage exceeded 0.5. Approximately 50 subjects would be needed per group to reach a power of 0.8 for comparisons between dislocation subjects and controls. Analysis of cartilage degradation is based only on T1ρ relaxation times, which are related to proteoglycan concentration. Additional analysis based on T2 relaxation times could also assess cartilage properties based on water and collagen content, along with organization of collagen fibrils. The current data provide a baseline assessment of post-injury cartilage degradation. Longitudinal evaluation is needed to characterize progression of cartilage degradation to PTOA and identify patients at greatest risk.

In conclusion, the current study indicates a first-time patellar dislocation is associated with early cartilage degradation within multiple regions of the knee when compared with asymptomatic healthy controls. Compositional changes to cartilage on the medial patella are related to the traumatic impact during a dislocation event. In the acute phase of the injury, potential exists for cartilage properties at the medial patella to improve with time. Traumatic impact has less influence on cartilage degradation at the lateral tibia. Additional studies including a more comprehensive characterization of anatomy, analysis of inflammatory biomarkers, and evaluation of knees with pathologic anatomy prior to dislocation are warranted to identify factors that contribute to cartilage degradation. The current baseline data can be considered a starting point to characterize the pathway from a first-time dislocation to progressive cartilage degradation and OA.

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Declaration of Conflicting Interests

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Ethical Approval

The study was approved by the Cleveland Clinic Institutional Review Board.

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Anatomical Characteristics Contributing to Patellar Dislocations Following MPFL Reconstruction: A Dynamic Simulation Study

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Pathologic anatomy is a primary factor contributing to redislocation of the patella following reconstruction of the medial patellofemoral ligament (MPFL). A pivot landing was simulated following MPFL reconstruction, with the hypothesis that position of the tibial tuberosity, depth of the trochlear groove, and height of the patella are correlated with lateral patellar maltracking. Thirteen dynamic simulation models represented subjects being treated for recurrent patellar instability. Simplified Hertzian contact governed patellofemoral and tibiofemoral joint reaction forces. Pivot landing was represented with and without an MPFL graft in place. Measurements related to patellar height (Caton-Deschamps index), trochlear groove depth (lateral trochlear inclination), and position of the tibial tuberosity (lateral tibial tuberosity to posterior cruciate attachment distance, or lateral TT-PCL distance) were measured from the models and correlated with patellar lateral shift with the knee extended (5 deg of flexion) and flexed (40 deg). The patella dislocated for all models without an MPFL graft and for two models with a graft represented. With an MPFL graft represented, patellar lateral shift was correlated with Caton-Deschamps index ($r^2 > 0.35$, $p < 0.03$) and lateral trochlear inclination ($r^2 \geq 0.45$, $p < 0.02$) at both 5 deg and 40 deg of flexion. For a simulated pivot landing with an MPFL graft in place, lateral patellar tracking was associated with a high patella (alta) and shallow trochlear groove. The study emphasizes the importance of simulating activities that place the patella at risk of dislocation when evaluating patellar stability.

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Keywords: patellar instability, MPFL reconstruction, computational simulation

Introduction

Medial patellofemoral ligament (MPFL) reconstruction is currently the most common surgical approach for patellar stabilization following lateral patellar dislocation [1,2]. Continued instability following MPFL reconstruction is generally reported for less than 4% of patients [2,3], although rates as high as 8% to 20% have also been reported [4–8]. Anatomical risk factors, such as trochlear dysplasia, patella alta, or a laterally positioned tibial tuberosity, are commonly associated with poor outcomes following MPFL reconstruction [4,9–13]. A laterally positioned tibial tuberosity increases the lateral component of the force applied to the patella by the quadriceps muscles and patellar tendon, contributing to postoperative patellar maltracking. Patella alta and trochlear dysplasia reduce articular constraints that resist lateral maltracking, due to delayed entry of the patella into the trochlear groove during flexion and a shallow trochlear groove, respectively. MPFL reconstruction is typically considered for patients with limited pathologic anatomy. Higher levels of pathology are typically addressed with procedures such as tibial tuberosity realignment or deepening of the trochlear groove [1,14]. Some recent studies have advocated for broader use of MPFL reconstruction [15–17], in order to minimize surgical complications, postoperative pain, and recovery time associated with procedures including bone cuts.

Numerous computational and in vitro biomechanical studies have been performed to characterize patellar stability following MPFL reconstruction. These studies have primarily characterized patellar stability based on motion during simulated activities of daily living [18–20] or patellar shift in response to a laterally directed force [21–24]. Dynamic functional activities that place the knee at risk of patellar dislocation, such as multidirectional twisting [25,26], have yet to be represented, limiting the current understanding of how pathologic anatomy contributes to patellar dislocations following MPFL reconstruction.

The current study focuses on biomechanical function of MPFL grafts while preventing a patellar dislocation. The study uses computational simulation to represent knees being treated for patellar dislocation performing a dynamic pivot landing, while characterizing knee anatomy, graft tension, and patellofemoral kinematics. The hypothesis of the study is that pathologic anatomy related to a laterally positioned tibial tuberosity, trochlear dysplasia, and patella alta are correlated with lateral patellar tracking during a pivot landing. The study also compares graft function and patellofemoral kinematics between pivot landing and knee squatting, which is a stable activity more commonly used to assess patellar stability.

Methods

Computational Models of Subjects. Computational models representing 13 knees about to undergo surgical patellar stabilization for recurrent lateral patellar instability were used to simulate pivot landing and knee squatting. The models were based on

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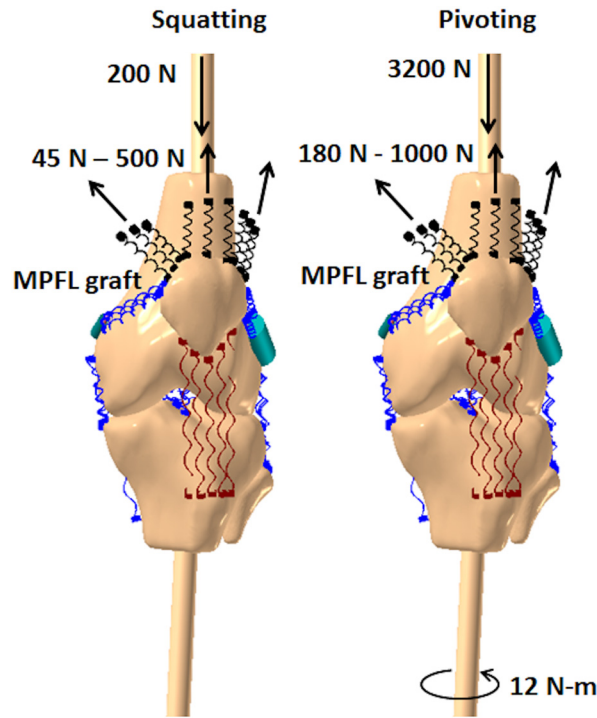


Fig. 1 Computational model for multibody dynamic simulation of knee squatting and a pivot landing. The pivot landing was represented with a larger peak quadriceps force (1000 N), force at the hip (3200 N), and external tibial torque (12 N-m) than squatting.

subjects ranging from 14 to 43 years old (mean = 22 years). For one of the knees, the tibial tuberosity had been surgically realigned to stabilize the patella prior to model development, but the subject experienced a subsequent dislocation. The local institutional review board provided approval for the study.

Accuracy of the computational output has been evaluated by comparison to data generated from subjects through a series of prior studies. For each computational model, an activity performed by the corresponding subject during diagnostic imaging was simulated for comparison to the kinematics data from the subjects. The activity was either knee extension against gravity during a dynamic CT scan [27] or isometric extension at multiple positions of knee flexion within an MRI scanner [28]. For fifteen models, root-mean-square errors measured over multiple flexion angles per subject were 2.5 mm and 4.0 deg for lateral patellar shift and tilt, respectively [20]. For a subgroup of patients with postoperative imaging, the average ($\pm$ standard deviation) pre-operative to postoperative (MPFL reconstruction or tibial tuberosity realignment) decrease in patellar lateral shift and tilt were 1.4 ± 3.8 mm and $2.5 \text{ deg} \pm 4.1$ deg, respectively, for the subjects, compared to 2.4 ± 4.8 mm and $2.3 \text{ deg} \pm 5.9$ deg for simulated motions [29]. A similar accuracy assessment for tibiofemoral kinematics reported root-mean-square errors of 5.5 deg and 1.8 mm for tibial external rotation and lateral shift, respectively [30].

Simulation of Knee Motion. Representation of knee function with the multibody dynamic simulation models (RecurDyn, FunctionBay, Seongnam, Korea) has been described in detail previously [20,29,30] (Fig. 1). Bones, cartilage surfaces, and soft tissue attachment points were reconstructed from MRI scans of the extended and unloaded knee (twelve 3.0 T and one 1.5 T, proton density weighted, slice thickness ranging from 0.5 mm to 3.0 mm). Cartilage surfaces and the underlying bones were treated as rigid bodies. Contact at the patellofemoral and tibiofemoral

cartilage surfaces generated reaction forces based on simplified Hertzian contact [31–33] according to

$$F_c = k\delta^n + B(\delta)\delta' \quad (1)$$

where F_c is the contact force in the cartilage, k is the contact stiffness coefficient (1000 N/mm), δ is the penetration of surfaces, δ' is the penetration velocity, n is the compliance exponent (1.5), and $B(\delta)$ is the damping coefficient (5 N-s/mm).

Multiple tension-only springs were used to represent the medial and lateral collateral ligaments (three springs each), anterior and posterior cruciate ligaments (2), patellar tendon (5), posterior capsule (4), lateral retinaculum (2), and medial retinaculum minus the native MPFL (1). Properties for stiffness, damping, and prestrain at full extension were assigned based on previous publications [34–36]. Quadriceps forces were divided among the vastus medialis obliquus, vastus lateralis, and combination of the vastus intermedius, rectus femoris, and vastus medialis longus based on previous publications, with a weak vastus medialis obliquus represented by applying 5% of the total quadriceps force [37]. Quadriceps forces were applied through springs representing the quadriceps tendon.

An MPFL graft was represented for each knee. Each graft attached to the femur at the Schöttle point [38] and wrapped around the femoral condyle to the patellar attachment positioned between the medial edge of the vastus medialis obliquus attachment and the medial edge of the patella (Fig. 1). The portion from the wrapping surface to the patella was represented by two springs with a total stiffness of 20 N/mm to represent a dual strand gracilis tendon graft fixed to the femur [39]. An intra-operative technique was represented to set the resting length of the graft [6,40]. The knee was set at 30 deg of flexion. The patella was centered in the trochlear groove and shifted laterally by one-eighth of the medial-lateral width of the patella. The resting length was set to the length with the patella in the shifted position to avoid over constraining the patella [29]. The total force within the two springs, or graft tension, was quantified at each flexion angle during simulated function.

The models were used to simulate landing on one foot while turning toward the opposite foot (pivot landing) with and without an MPFL graft. Loading and boundary conditions representing a pivot landing were based on previous in vitro studies [41,42]. Motion was initiated with the knee at 5 deg of flexion. Forces were applied through the quadriceps and hamstrings muscles. The total quadriceps force increased from 180 N at 5 deg to 1000 N at 90 deg, while the medial and lateral hamstrings forces combined to apply 40% of the total quadriceps force. A force of 3200 N was applied at the hip to represent peak impulse force during landing (approximately four times body weight), and an external rotation torque of 12 N-m was applied to the tibia. Three rotational degrees-of-freedom were allowed at the ankle and flexion/extension, varus/valgus rotation, and superior/inferior translation allowed at the hip. Dual limb knee squatting was also simulated with an MPFL graft applied to represent a lower energy, uniplanar activity. Loading and boundary conditions were based on an in vitro knee simulator [43]. The total quadriceps force increased from 45 N at 5 deg to 500 N at 90 deg of flexion. A force of 200 N represented body weight applied to one hip, and no torque was applied to the tibia. The simulations used a Generalized-Alpha integrator with 200 time steps. Run time on a PC with a 2.5 GHz processor and 32 GB RAM was approximately 20 min.

Characterization of Patellofemoral Kinematics and Anatomy. Patellofemoral kinematics was quantified at every 5 deg of knee flexion. A local coordinate system was created for the femur based on the transepicondylar axis and long axis, with similar coordinate systems created for the patella and tibia, allowing characterization of knee kinematics based on the floating axis convention [44]. Analysis focused on patellar lateral shift and lateral tilt

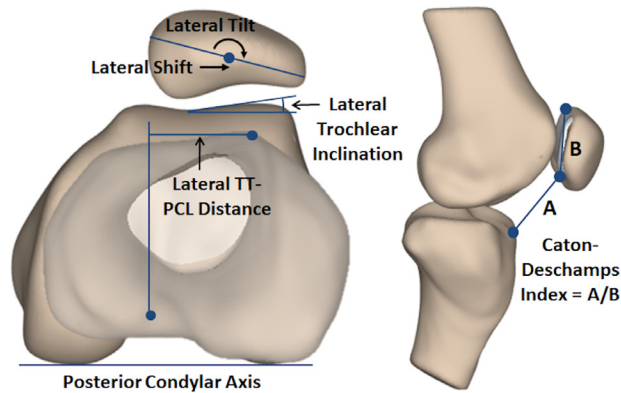


Fig. 2 A computational model with landmarks and axes indicated to quantify parameters related to trochlear depth (lateral trochlear inclination), patellar height (Caton-Deschamps index), and position of the tibial tuberosity (lateral TT-PCL distance). The directions for patellar lateral shift and tilt are also shown. The tibia is partially transparent to show the PCL fossa.

as measures related to patellar tracking with respect to the femur (Fig. 2).

Anatomical parameters related to lateral position of the tibial tuberosity, patella alta, and trochlear dysplasia were quantified for each model using automated algorithms. The anatomical parameters are related to alignment of multiple bones. To characterize these parameters based on motion without patellar dislocation, they were determined from squatting rather than pivoting, as described previously [20,45]. For trochlear dysplasia, depth of the trochlear groove was characterized based on lateral trochlear inclination with the knee at 5 deg of flexion (Fig. 2). Lateral trochlear inclination was measured within an axial plane perpendicular to the long axis of the patella, using a slice through the model that included the most anterior point of the lateral ridge of the groove. Lateral trochlear inclination was measured as the maximum slope of the lateral ridge of the trochlear groove with respect to the posterior condylar axis. The position of the tibial tuberosity was characterized at 5 deg of flexion. The lateral tibial tuberosity to posterior cruciate attachment (TT-PCL) distance was measured within the same plane used for lateral trochlear inclination. Lateral TT-PCL distance was measured from the midpoint of the patellar tendon attachment on the tibial tuberosity to the medial edge of the PCL attachment within the PCL fossa on the tibia, along the posterior condylar axis. Patella alta was characterized in

terms of patellar height based on Caton-Deschamps index with the knee at 30 deg. Caton-Deschamps index was quantified within a sagittal plane as the ratio of the distance from a point on the distal edge of articular surface of the patella to the superior-anterior point on the tibia to the articular length along the patella.

Statistical Analysis. The primary analysis related patellar shift and tilt to anatomy with an MPFL graft in place for both a pivot landing and squatting. Linear regressions (SPSS, IBM, Armonk, NY) related patellar shift and tilt to anatomy with the knee extended (5 deg of flexion) and flexed to a position at which the patella should be captured by the trochlear groove (40 deg). Assumptions of normally distributed residuals were confirmed based on PP-plots and Shapiro-Wilks tests. Coefficients of determination (r^2), standardized beta (β) coefficients, and unstandardized β coefficients with standard errors were quantified to evaluate the strength of the linear regressions. For standardized β coefficients, dependent and independent variables are standardized to produce variances equal to 1, allowing comparisons between different anatomical factors for the influence on kinematics. For paired comparisons of patellar tracking and graft tension between pivoting and squatting, Shapiro-Wilks tests were performed to determine if the residuals of the comparisons were normally distributed, with a paired t -test or Wilcoxon signed-rank test used as needed. Statistical significance was set at $p < 0.05$.

Results

Without an MPFL graft represented, the patella dislocated laterally during simulated pivot landing for all thirteen models. For two models, the patella also dislocated during pivoting with a graft represented. No patellar dislocations occurred during simulated squatting with an MPFL graft represented. Statistical analysis focused on early flexion (5 deg to 40 deg). The knee reached 40 deg of flexion without complete dislocation of the patella for all simulations with an MPFL graft represented.

Lateral patellar tracking was positively correlated with Caton-Deschamps index and negatively correlated with lateral trochlear inclination. Average values for Caton-Deschamps index, lateral trochlear inclination, and lateral TT-PCL distance were 1.2 ± 0.3 , $15 \text{ deg} \pm 9 \text{ deg}$, and $21 \pm 6 \text{ mm}$. For pivoting and squatting, at 5 deg and 40 deg of flexion, patellar shift was significantly correlated with both Caton-Deschamps index and lateral trochlear inclination ($p < 0.04$, $r^2 > 0.3$) (Table 1). Standardized β coefficients relating anatomy to lateral shift were 5%–12% larger for lateral trochlear inclination than Caton-Deschamps index, indicating

Table 1 Significant correlations relating patellofemoral kinematics to anatomical parameters for simulated pivot landing and squatting with an MPFL graft represented

		p -value	r^2	Standardized β	Unstandardized β	Standard error β
Pivot landing lateral shift (mm)						
5 deg	LTI (deg)	0.012	0.45	−0.67	−0.58 mm/deg	0.19 mm/deg
	CDI (mm/mm)	0.026	0.38	0.61	18.4 mm	7.2 mm
40 deg	LTI (deg)	0.004	0.55	−0.74	−0.69 mm/deg	0.19 mm/deg
	CDI (mm/mm)	0.008	0.49	0.70	22.3 mm	6.9 mm
Pivot landing lateral tilt (deg)						
5 deg	LTI (deg)	0.006	0.51	−0.72	−0.81 deg	0.24 deg
40 deg	LTI (deg)	0.002	0.59	−0.77	−0.87 deg	0.22 deg
Squatting lateral shift (mm)						
5 deg	LTI (deg)	0.024	0.38	−0.62	−0.51 mm/deg	0.19 mm/deg
	CDI (mm/mm)	0.036	0.34	0.59	16.6 mm	6.9 mm
40 deg	LTI (deg)	0.014	0.44	−0.66	−0.49 mm/deg	0.17 mm/deg
	CDI (mm/mm)	0.032	0.35	0.59	15.1 mm	6.2 mm
Squatting lateral tilt (deg)						
5 deg	LTI (deg)	0.007	0.50	−0.71	−0.82 deg	0.25 deg
40 deg	LTI (deg)	0.032	0.35	−0.60	−0.56 deg	0.23 deg

LTI: lateral trochlear inclination; CDI: Caton-Deschamps index.

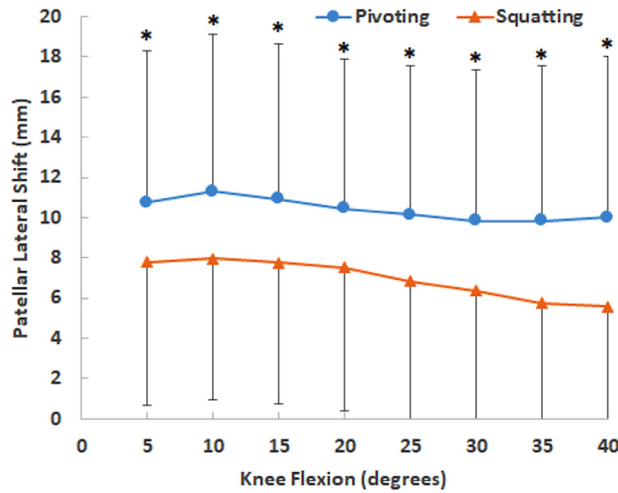


Fig. 3 Average ($\pm$ standard deviation) patellar lateral shift. A symbol (*) at a position of knee flexion indicates a significant difference between pivot landing and knee squatting.

lateral trochlear inclination was the primary parameter influencing patellar shift. The strongest correlations relating lateral shift to lateral trochlear inclination and Caton-Deschamps index occurred for pivoting at 40 deg ($r^2 \geq 0.49$, $|\text{standardized } \beta| \geq 0.7$). For pivoting and squatting, at both 5 deg and 40 deg, patellar tilt was significantly correlated with only lateral trochlear inclination ($p < 0.04$, $r^2 > 0.3$). The strongest correlation between lateral tilt and lateral trochlear inclination occurred for pivoting at 40 deg ($r^2 = 0.59$, $|\text{standardized } \beta| = 0.77$). No significant correlations were identified for lateral TT-PCL distance.

With an MPFL graft represented, patellar lateral shift and tilt were larger for pivot landing than squatting. The differences were statistically significant from 5 deg to 40 deg of flexion for patellar shift ($p < 0.001$, Fig. 3) and graft tension ($p < 0.01$, Fig. 4), and from 5 deg to 35 deg for tilt ($p < 0.05$, Fig. 5). Patellar lateral shift, lateral tilt, and graft tension peaked at 5 deg to 10 deg of knee flexion for pivoting and squatting. Average lateral shift was 3 to 4 mm larger for pivoting than squatting. Average lateral tilt was 1 deg to 3 deg larger for pivoting than squatting. Average graft tension peaked at approximately 50 N for pivoting, with the lowest value approximately 30 N. For squatting, average graft tension peaked at approximately 10 N and was minimal by 30 deg.

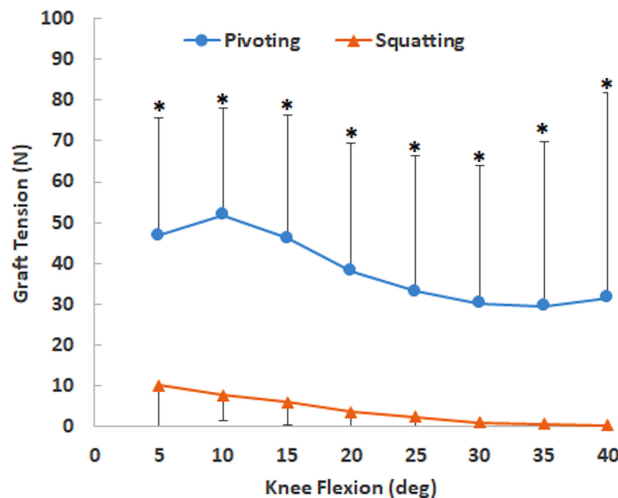


Fig. 4 Average ($\pm$ standard deviation) graft tension. A symbol (*) at a position of knee flexion indicates a significant difference between pivot landing and knee squatting.

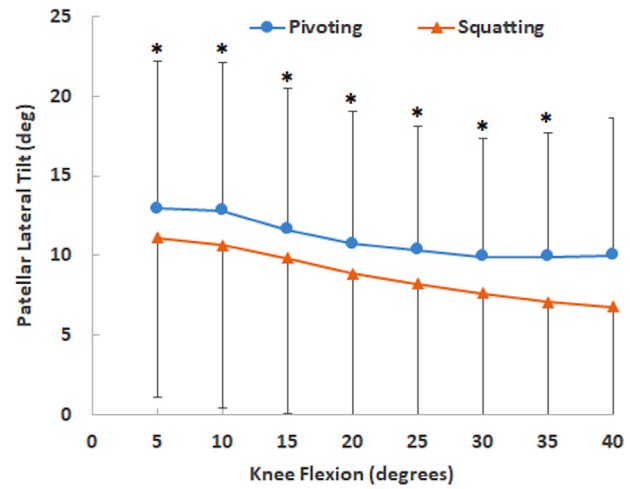


Fig. 5 Average ($\pm$ standard deviation) patellar lateral tilt. A symbol (*) at a position of knee flexion indicates a significant difference between pivot landing and knee squatting.

Discussion

The results indicate patella alta and trochlear dysplasia are risk factors for patellar dislocation following MPFL reconstruction, especially for an activity including multidirectional twisting. During simulated pivoting, tension within an MPFL graft was sufficient to constrain the patella and initiate flexion, but the patella was not consistently captured by the trochlear groove as the knee flexed. For two knees, the patella started tracking lateral to the trochlear groove (large lateral shift) and completely dislocated beyond 40 deg of flexion. A large Caton-Deschamps index (patella alta that delays entry of the patella into the trochlear groove during flexion) and small lateral trochlear inclination (shallow trochlear groove) both limit the articular constraint resisting lateral patellar maltracking. Both parameters significantly influenced patellar lateral shift, with the strongest correlation occurring for lateral trochlear inclination with the knee at 40 deg. Based on the unstandardized β coefficient, for pivoting at 40 deg, a 1 deg decrease in lateral trochlear inclination increases lateral patellar shift by approximately 0.7 mm. Also for pivoting at 40 deg, a 0.1 increase in Caton-Deschamps index (the increment typically used clinically) increases lateral patellar shift by approximately 2.2 mm. Similar to the current results, previous biomechanical studies that represented MPFL reconstruction identified a shallow trochlear groove and patella alta as factors that limit the constraint applied to the patella by the trochlear groove [21,45,46]. Lateral tilt was correlated with lateral trochlear inclination during simulated pivot landing, largely due to the lateral facet of the patella articulating along the lateral ridge of the trochlear groove.

For knee squatting, tension within an MPFL graft was sufficient to guide the patella into the trochlear groove at low flexion angles. As the patella was captured by the trochlear groove, articular constraints stabilized the patella, lateral tracking decreased, and graft tension dissipated. These trends have been noted for previous simulation studies [20,23,29]. Knee squatting produced lower values for patellar lateral shift and tilt and graft tension than pivoting, and no dislocations occurred. Kinematics differences between squatting and pivoting were more relevant for patellar shift than tilt, as the differences were larger than previously reported error levels for the simulations for lateral shift (2.5 mm), but not for lateral tilt (4.0 deg) [20]. The correlations relating lateral trochlear inclination and Caton-Deschamps index to patellofemoral kinematics were also weaker for squatting than pivoting. The differences between knee squatting and pivoting emphasize the importance of representing activities likely to cause patellar dislocation when evaluating surgical patellar stabilization.

The current study did not identify any statistically significant relationships between position of the tibial tuberosity and patellofemoral kinematics with an MPFL graft represented for either squatting or pivoting. A previous simulation study that evaluated knee squatting following MPFL reconstruction indicated patellar lateral shift was positively correlated with lateral TT-PCL distance [45], while an in vitro experimental study indicated lateralizing the tibial tuberosity increased lateral patellar tracking with an MPFL graft represented [47]. Lack of statistically significant correlations for the current study may be due to the experimental methods. The previous computational study represented lateral shift based on position within the trochlear groove (bisect offset index) instead of with respect to femoral reference frame along the transepicondylar axis and included variations between flexion angles within knees to identify significant correlations. The current study used the femoral reference frame to obtain normally distributed data for extreme values of lateral maltracking. The current study also focused on individual flexion angles. The knees used for the in vitro study did not reflect trochlear dysplasia or patellar alta associated patellar dislocations.

The computational approach uniquely represented MPFL reconstruction while simulating a dynamic activity that places the knee at risk of patellar dislocation. Dislocations during simulated squatting can be attributed to large forces applied by the quadriceps and patellar tendon, as well as external tibial rotation increasing the lateral orientation of the patellar tendon. By representing knees being treated for recurrent instability, the models also included representation of pathologic anatomy that contributes to patellar dislocations. The average Caton-Deschamps index was 1.2, which is considered borderline for patella alta [48,49]. The average lateral TT-PCL distance was 21 mm. The average TT-PCL distance for patients being treated for patellar instability is 22 mm when measured along the posterior tibial axis [50]. The posterior condylar axis was used for the current study to account for rotation of the tibia with respect to the femur. The average lateral trochlear inclination was 15 deg. The value was less than 11 deg for five knees, indicating trochlear dysplasia [51]. The lateral trochlear inclination values may also have been slightly higher than clinical measurements due to basing the computational measurements on maximum slope.

The dynamic simulation approach includes several limitations. The computational models were constructed based on manual segmentation of MRI scans, and generalized material properties were assigned based on previously published data, rather than individualized for the subjects. Also, menisci were not represented within the tibiofemoral joint. These limitations emphasize the importance of the previous accuracy assessments for the computational models. Representation of pivot landing includes some simplification. Pivoting on a planted foot was represented with an external torque applied to the tibia, with the analysis focused on early knee flexion. The approach allowed representation of pivoting with only quadriceps and hamstrings forces, similar to in vitro mechanical models representing pivoting [41,42]. The approach was sufficient to induce a dislocation for all models in the injured condition. The models only represented knees being treated for recurrent instability, so the correlations lack representation of less pathologic anatomy from healthy controls or knees that experienced only a single instability episode.

In conclusion, MPFL reconstruction is the preferred surgical approach for patellar stabilization to minimize surgical complications, postoperative pain, and recovery time. High energy, multiplanar activities such as a pivot landing place the knee at risk of patellar dislocation following MPFL reconstruction. Computational simulation demonstrated the potential for patellar dislocation during pivot landing despite MPFL reconstruction, emphasizing the importance of simulating activities that place the patella at risk of dislocation when evaluating patellar stability. The primary parameters associated with a risk of postoperative patellar dislocation were patella alta and a shallow trochlear groove.

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Nomenclature

MPFL = medial patellofemoral ligament
TT-PCL = tibial tuberosity to posterior cruciate ligament attachment

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