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

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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 hypothesize that selective early surgical intervention for patellar instability will improve knee function and long term outcomes. The study focuses 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 $\rho$  and T2 relaxation time mapping of patellofemoral cartilage is being 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 is being 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 is being developed from the statistical shape model to simulate an activity that causes a patellar dislocation and subsequent MPFL reconstruction. The simulation model is being used to optimize parameters of MPFL reconstruction for the modes of variation associated with recurrent patellar instability. The proposed aims are designed to create a paradigm shift for treatment of patellar instability. Patients at high risk for post-traumatic osteoarthritis will be identified for early surgical intervention to preserve cartilage. Optimal treatment approaches will be designed to provide stability with limited risk of complications. Achieving the aims will result in improved short-term and long-term function for patients.

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

## 3. ACCOMPLISHMENTS:

### o What were the major goals of the project?

<b>Specific Aim 1 (MRI characterization of cartilage)</b>	<b>Timeline</b>	<b>Completion</b>
<b>Initiate Enrollment</b>	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%
<b>Imaging</b>		
Finalize imaging protocols	1	100%
Imaging of control group	1-12	67%
Imaging of initial instability group	2-20	33%
Imaging of recurrent instability group	2-20	33%
<b>Evaluation of cartilage properties</b>		
T1 $\rho$ /T2 sub-region analysis		
Reconstruction of cartilage surfaces	2-20	40%
Create T1 $\rho$ /T2 relaxation time maps	3-22	40%
Statistical analysis between 3 groups	23-24	25%
T1 $\rho$ /T2 VBR analysis		
Select reference image	18-20	0%
Create T1 $\rho$ /T2 relaxation time maps	21-23	0%
Statistical analysis between 3 groups	23-24	0%
<b>Specific Aim 2 (Statistical shape modeling)</b>		
<b>Statistical shape models of bones</b>		
Reconstruct computational models from MRI	2-22	25%

Create template mesh	12-14	50%
Create shape model and modes of variation	12-22	20%
Relate modes of variation to anatomy	23-24	20%
Statistical analysis between 3 groups	23-24	25%
<b>Add alignment to shape model</b>		
Reconstruct models from loaded MRI	6-22	5%
Represent aligned knees with shape model	14-22	0%
Add alignment to principal component analysis	22-24	25%
Statistical analysis between 3 groups	24	0%
<b>Specific Aim 3 (multibody dynamic simulation)</b>		
Create simulation model from shape model	16-22	0%
Create instability loading condition	18-22	100%
Evaluate MPFL reconstruction		
Run instability and MPFL reconstruction cases	20-24	25%
Statistical analysis of modes of variation	23-24	0%
Run alternative MPFL reconstruction cases	23-24	0%

○ **What was accomplished under these goals?**

The primary components of Specific Aim #1 are enrollment, imaging, and evaluation of cartilage properties. IRB approval was previously obtained to collect preliminary data. The amendment submitted to support the current study was approved on January 31, 2020. Enrollment of subjects was suspended March 17 due to the covid-19 pandemic, but enrollment of patients (initial and recurrent dislocation groups) was re-approved on May 22. The institution allowed resumption of enrollment of control subjects in July. Since then, four subjects with recurrent patellar instability have been enrolled in the study and participated in imaging. Nine subjects with an initial dislocation have been enrolled and participated in baseline imaging following the injury. One of those subjects completed the MRI scan six months after injury, after completing physical therapy and returning to function. The other eight will be contacted for the MRI scan at six months over the coming months. Five new control subjects have been enrolled and scanned.

Data from newly enrolled subjects is being combined with preliminary data acquired prior to the start date for the grant. To date, imaging has been obtained for eleven subjects in the control group, six subjects with recurrent instability, and fourteen subjects with an initial dislocation. Imaging included a dual echo steady state (DESS) fat saturated sequence for reconstruction of cartilage surfaces for relaxation time mapping, a T1 $\rho$  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. Functional imaging was also performed with low resolution, fast T1 turbo spin echo scans of the knee acquired at multiple flexion angles using an MRI-compatible loading frame that applies an adjustable force at the foot. Imaging was performed for both the injured and contralateral knee of dislocation subjects and one knee for the controls. Techniques for processing the imaging data were developed and T1 $\rho$  mapping of cartilage properties has been completed for all but one initial instability subject and one recurrent instability subject.

Relaxation times were characterized within lateral, medial and central regions of the patellar and trochlear groove cartilage, along with medial and lateral regions of the tibiofemoral joint. Images from the DESS scan were rigidly registered with the first echo of the T1 $\rho$  images. T1 $\rho$ -weighted images were fit pixel by pixel based on a two parameter, monoexponential Levenberg-Marquardt algorithm relating image signal to exponential decay based on time of spin lock to T1 $\rho$  relaxation time.

The primary variation between groups for patellofemoral cartilage is elevated T1 $\rho$  relaxation times for the medial sub-region of the patella following an initial dislocation (Fig. 1), with an average of  $40 \pm 8$  ms for the injured knees vs.  $34 \pm 9$  ms for the control group ( $p = 0.08$ , t-test) and  $36 \pm 7$  ms for the contralateral knees ( $p = 0.06$ , paired t-test). The medial aspect of the patella is primarily injured due to traumatic impact against the lateral femoral condyle during a dislocation event. Completion of enrollment is needed to determine if these differences will reach statistical significance. Additional subjects need to be added to the recurrent instability and 6 month follow up groups to allow sufficient power for statistical comparisons with these groups.

Differences between groups were noted for the lateral compartment of the tibiofemoral joint. For the initial dislocation group, the average T1 $\rho$  values on the lateral tibia ( $41 \pm 3$  ms) and femoral condyle ( $47 \pm$

3 ms) were significantly ( $p < 0.04$ ) larger than the values for the control group ( $38 \pm 3$  ms and  $43 \pm 3$  ms for the tibia and femoral condyle, respectively). These differences indicate that patellar dislocations should be evaluated as a disorder of the whole knee, instead of just the patellofemoral joint.

The primary components of Specific Aim 2 are creating a statistical shape model of the knee and adding alignment of the bones to the shape model. The shape model will be used to identify variations in anatomy and alignment of the bones between the control, initial instability and recurrent instability groups. This information will be used to identify patients who should be considered surgical candidates following an initial patellar dislocation due to a high risk of recurrent instability. The techniques for creating a statistical shape model have already been developed, and a preliminary shape model has been created to represent the femur and patella from control knees, knees with an initial patellar dislocation, and knees with recurrent patellar dislocations.

A shape model is being constructed for each bone, creating a mean geometry plus modes of variation. A training set is being developed for the femur and patella, and a template mesh of approximately 10,000 points has been constructed for each bone. The vertices of the template mesh are mapped on all the surfaces of the bones in the training set using an automatic landmark-matching algorithm. The maximum and minimum local curvatures identified based on coherent point drift are used for coupling homologous points on two surfaces. Principal component analysis for statistical shape modeling of each bone is based on the distribution of all points of the template mesh among the bones in the training set. The mean surface for each bone is determined from the mean values of the corresponding points of the training set. A covariance matrix is created to quantify the variation in shape from the mean shape over all the mesh points of the training set. Eigenvector decomposition of the covariance matrix determines the primary orthonormal modes of variation, with the modes ranked based on the eigenvalues. Each bone can be 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.

To date, shape models have been developed for the femur and patella based on control knees, patients being treated for an initial dislocation and patients being treated for recurrent dislocations. To address the limited sample size to date, training sets were supplemented with knees from other studies. The shape models are based on 16 patients (9 females, age ranging from 14 to 36 years) with at least one patellar dislocation (10 with multiple dislocations) and 20 knees from 13 healthy subjects (6 females, age ranging from 13 to 30 years). The control, initial dislocation and recurrent dislocation groups were compared across the first 10 modes of each bone for significant differences. The initial and recurrent dislocation patient groups were also compared for significant differences. Clear anatomical differences were observed among the mean femur and patella surfaces of the control, initial dislocation and recurrent dislocation patient groups (Fig. 2A). The primary characteristic of the recurrent dislocation group was a shallow trochlear groove. The mean patella shapes for both dislocation

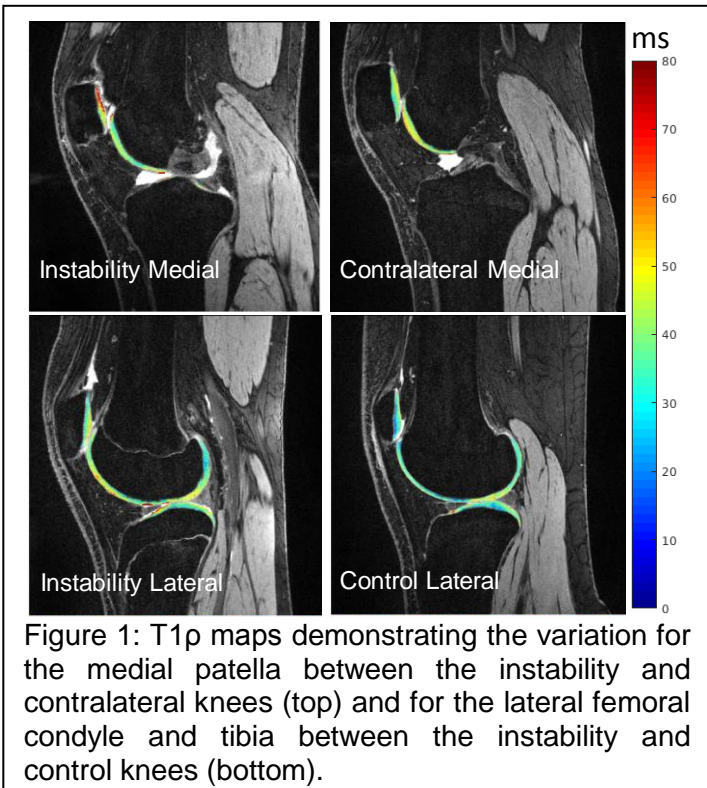


Figure 1: T1p maps demonstrating the variation for the medial patella between the instability and contralateral knees (top) and for the lateral femoral condyle and tibia between the instability and control knees (bottom).

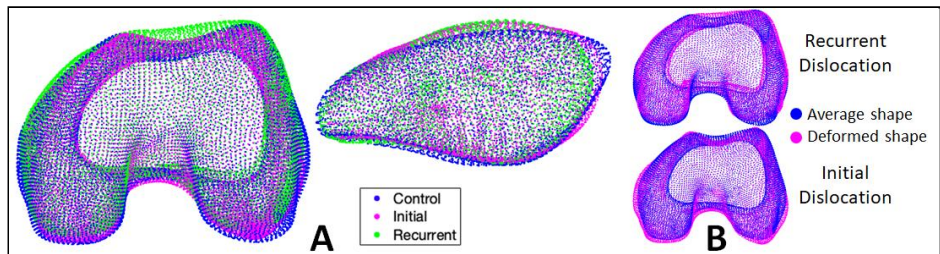


Figure 2: Mean shapes of the femur and patella (axial view) for the control, initial dislocation and recurrent dislocation groups (A). Change in shape of the femur for a mode of variation that distinguishes between the initial and recurrent dislocation groups (B).

patient groups displayed a more convex medial facet and a decreased medial-lateral width compared with the control group, with the recurrent dislocation group being the most extreme. Statistically significant differences ( $p < 0.05$ ) were identified between the control and patient group representations in three of the first ten modes of variation for the femur and two of the first ten modes for the patella. Furthermore, three modes for the femur and one mode for the patella were significantly different between the initial and recurrent dislocation patient groups. The modes with differences noted between the groups are being evaluated and related to anatomical characteristics, such as modes differentiating between initial and recurrent dislocations related to trochlear dysplasia (Fig. 2B).

Statistical shape modeling is being expanded to include all three bones of the knee and alignment with muscle activation to incorporate dysplasia influencing the shapes of the trochlear groove and patella, patella alta, and lateral position of the tibial tuberosity with respect to the trochlear groove. Alignment of each knee within an anatomical coordinate system fixed to the femur will be represented based on computational models constructed from the MRI scans performed with the knee loaded at full extension. The transformation matrices defining the rotations and translations of the tibia and patella with respect to the femur as components of a  $4 \times 4$  transformation matrix will be quantified. A composite matrix for principal component analysis will be constructed from the coordinates of all points of the femur, patella, and tibia within the respective template meshes for each knee, plus the 32 components of the transformation matrices for the patella and tibia with respect to the femur for each knee. The modes of variation determined from principal component analysis will incorporate the transformation matrices to include the alignment of the bones.

To date, reconstruction of computational models representing the aligned and loaded knees has been initiated, and completed for three dislocation subjects. Algorithms have been written to represent each computational model of a knee as the three bones in their own local coordinate systems and alignment of the local coordinate systems with respect to the global coordinate system. The investigators are in the process of incorporating the alignment components into the covariance matrix for the statistical shape model.

The primary goals of Aim 3 are to create a simulation model from the statistical shape model, simulate a dislocation event, and evaluate options for MPFL reconstruction. The shape model of the aligned knee at full extension will be incorporated into dynamic simulation. 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. 3). Springs represent the relevant ligaments, tendons, and retinacular structures. Cartilage surfaces and attachment points for the other soft tissues will be included in the training set of each knee used for shape modeling based on reconstruction of soft tissues from the SPACE scans. The new simulation model will be deformable to represent a loaded knee at full extension for any mode of variation associated with recurrent patellar instability. Quadriceps and hamstrings muscle forces and body weight, combined with simulated hip and ankle joints, will induce motion governed by the joint reaction forces and spring forces.

Dynamic simulation of knee function is being used to represent loading conditions that induce dislocations and routine functional activities with and without an MPFL graft. MPFL reconstruction is being 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. A clinical approach for graft tensioning is simulated by setting the graft length with the knee at  $30^\circ$  of flexion and allowing one-eighth of the patellar width of free lateral translation to avoid over tensioning. Tibiofemoral kinematics are characterized with respect to a standardized anatomical coordinate system for the knee. Patellar tracking is quantified based on clinically used parameters of bisect offset index and lateral patellar tilt, which express position of the patella with respect to the trochlear groove. These parameters are quantified based on anatomical landmarks that are either tracked during motion or automatically identified at each position of knee flexion. Patellofemoral contact pressures are quantified for flexion angles with the patella constrained by the trochlear groove. The

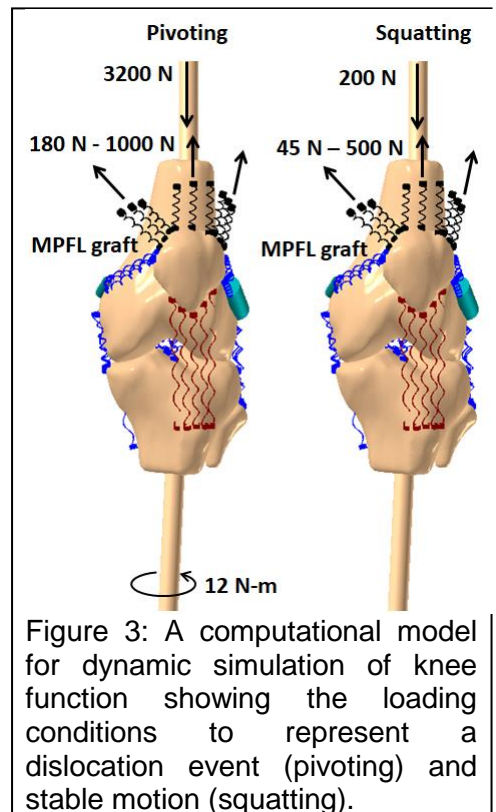


Figure 3: A computational model for dynamic simulation of knee function showing the loading conditions to represent a dislocation event (pivoting) and stable motion (squatting).

contact pressure distribution is quantified using a discrete element analysis approach that balances the 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.

To date, 12 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. The squatting motion is based on lower quadriceps and gravitational forces without torque applied to the tibia. The MPFL graft restored patellar stability for 11 of the 12 models. For 7 models, patellar tracking following MPFL reconstruction was similar to tracking for stable squatting, with bisect offset index and graft tension decreasing as the knee flexes (Fig. 4). For the other 5, bisect offset index and graft tension increased beyond mid-flexion, representing unstable motion. The simulation represents the initial analysis identifying knees that are not sufficiently stabilized by MPFL reconstruction. Additional analysis is needed to identify the anatomical characteristics of the knees that are not stable, and determine if modifying the parameters for the MPFL graft can restore stability.

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

Social distancing practices implemented by the institution due to covid-19 limited personal interaction of the lead investigators with students, fellows, and residents during the first year of the study. All travel for educational activities and professional development was also cancelled due to the institutional response to the virus. Roles were identified for students, fellows and residents to participate in the study through working remotely, and mentorship was provided through online lab and project meetings. Over the past year two undergraduate students, two post-doctoral fellows and two residents were mentored on the clinical concerns related to cartilage degradation following patellar dislocations and the technical aspects of MRI-based cartilage mapping, statistical shape modeling, and computational simulation, with all of these participants serving as authors for studies that are being presented at virtual conferences.

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

Nothing to Report

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

The primary goal for Aim #1 for the next funding period is to continue enrolling subjects and bringing back subjects for follow up evaluations to provide additional data to evaluate cartilage properties. Baseline recruitment for the initial dislocation group is proceeding at a steady pace. Eight initial instability subjects enrolled from August, 2020 to January, 2021 will become eligible for the follow up scan over the next six months. Recruitment for the recurrent dislocation group has been slower, due to the smaller number of patients experiencing multiple dislocations. The number of eligible patients has been lower than expected due to reduced participation in high school and college athletics during 2020 due to the pandemic. The investigators hope that all local schools will be able to return to sports by the fall of 2021. Enrollment of the control group is proceeding at a steady pace and being coordinated to match the demographic characteristics of the patients. The investigators have developed techniques for automated reconstruction of cartilage surfaces and mapping of cartilage properties so that data processing can keep

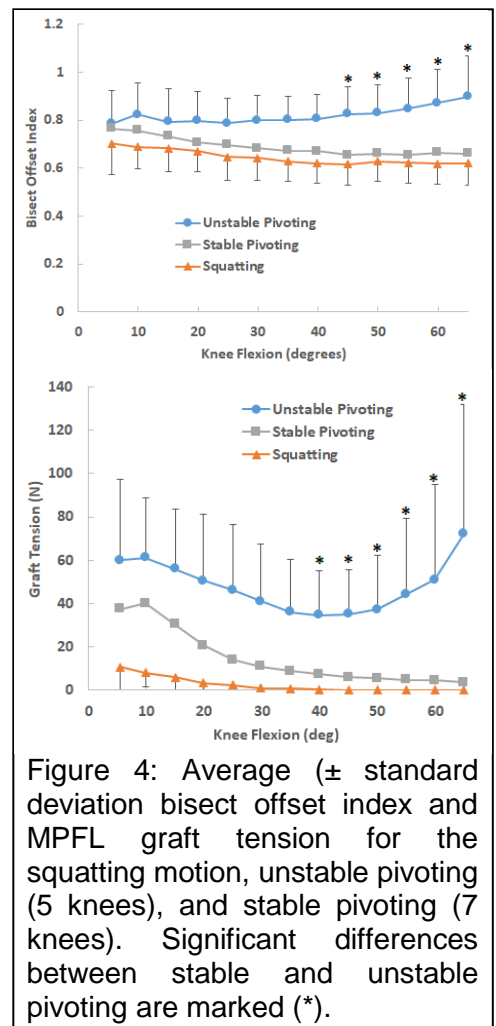


Figure 4: Average ( $\pm$  standard deviation) bisect offset index and MPFL graft tension for the squatting motion, unstable pivoting (5 knees), and stable pivoting (7 knees). Significant differences between stable and unstable pivoting are marked (\*).

up with imaging. With additional data, the investigators will be able to perform statistical analyses with increased power and perform sub-group analyses to determine the strength of the trends for demographic groups based on sex, age, and body mass index.

The primary goal for Aim #2 for the next funding period is to increase the number of models processed for statistical shape modeling from existing imaging and newly acquired imaging. Imaging is currently available from eight initial dislocation subjects, six recurrent dislocation subjects, and five control subjects to add to the statistical shape model. The investigators are working on developing automated techniques for reconstruction of bone models from the MRI scans to allow the shape models to keep pace with the acquired imaging. The investigators also plan to continue processing imaging from the loaded knee scans to provide data to incorporate the alignment parameters into the covariance matrix. Statistical analyses will continue to be performed to identify differences in the shape of the individual bones between the control, initial dislocation, and recurrent dislocation groups. The shape models will also be used to correlate individual bone shapes with T1 $\rho$  values for cartilage.

The primary goal for Aim #3 for the next funding period is to further evaluate MPFL reconstruction to stabilize the patella during a potential dislocation event. Additional models will be developed to identify knees that are considered unstable following MPFL reconstruction to identify anatomical characteristics of the unstable group. The anatomical characteristics will initially be identified based on clinical measures but eventually transitioned to shape features from the statistical shape model. For the models in the unstable group, modifications in graft tension and attachment points will be applied to determine if alterations to the MPFL reconstruction technique can stabilize the patella without overloading patellofemoral cartilage.

#### 4. **IMPACT**

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

The initial data on cartilage properties following a patellar dislocation indicate that the primary area of injury is cartilage on the medial patella due to impact of the medial facet against the femur during a dislocation event. A larger sample size is needed to determine if this initial injury improves or worsens with time following the injury and additional dislocations. The initial data on cartilage properties also indicates knees that experience a patellar dislocation are also at risk of degradation of cartilage within the tibiofemoral joint, which has not been previously described for this population. The initial comparison of anatomical features between control subjects, subjects experiencing a single dislocation and subjects experiencing multiple dislocations indicate there are specific features characteristic of multiple dislocations. The primary feature is a shallow trochlear groove, which has been identified in several previous publications. Other features related to shape of the patella and femoral condyles can also be identified, however. With a larger sample size, the combination of features that indicate risk of recurrent dislocations can be more accurately characterized to help clinicians identify subjects who should consider surgical treatment after an initial dislocation to prevent multiple dislocations. The initial data on knee function following reconstruction of the medial patellofemoral ligament (MPFL) indicates that the approach does not consistently stabilize the patella during activities such as landing and pivoting on one foot. The simulated pivoting event and models of knees that are not suitably stabilized provide a platform for identifying the anatomical features of knees that should be treated with an alternative approach and investigation of modified surgical parameters to improve post-operative stability.

- **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**  
Nothing to Report
- **Actual or anticipated problems or delays and actions or plans to resolve them**

The primary disruption for the initial study period has been related to the covid-19 pandemic. Non-essential employees of the Cleveland Clinic were instructed to work from home from mid-March to mid-May, limiting access to some of the facilities and equipment needed to conduct the work. Currently, non-essential employees are on a rotating schedule for working within the facilities of the Cleveland Clinic, with access 1 to 2 days per week. In addition, students acting as volunteers and paid interns were initially banned from campus in mid-March and phased back in steps from August through the end of 2020. Even though students are currently allowed back on campus, social distancing guidelines and continued work from home policies have limited the number of students that can be integrated into the project. The primary aspect of the work that is behind schedule due to loss of students is reconstruction of imaging data to create computational models for statistical shape modeling. Cleveland Clinic also suspended all human subjects studies that required an in person interaction in mid-March, except for those related to treatment of covid-19, which limited enrollment in the study for the several months. The institution phased in interaction with patients participating in research and control subjects in a few steps from May to September. Reduced participation in high school athletics throughout 2020 also led to fewer patellar dislocations than expected, especially for the recurrent instability group.

The investigators have been working through the challenges in multiple ways. The investigators have continued to meet with one another through web-based conferences held multiple times each month. These meetings have focused on project updates, technological developments, data analysis and workflow planning. Once enrollment of subjects was re-instituted, the investigators increased efforts focused on identifying and contacting potential subjects, resulting in enrollment that is only a few months behind the pace of the initial timeline and manageable to complete during a no cost extension period. Cartilage mapping has kept pace with enrollment due to implementation of automated algorithms for reconstruction of cartilage surfaces from MRI and mapping of T1 $\rho$  values based on deep learning. The investigators are working on expanding the automated segmentation to bone to allow reconstruction of bones for statistical shape modeling to catch up with enrollment. Students are currently being recruited to allow some progress with segmentation of bones while the automated techniques are under development. To overcome the limited number of new models available for statistical shape modeling to date, models of patients treated for recurrent instability and control subjects developed for previous studies have been used to develop the initial version of the statistical shape model of each bone. With limited access to fully developed models of subjects enrolled for the current study, computational simulation models representing knees being treated for recurrent instability from previous studies have been adapted to represent dislocation episodes and identify knees that are not adequately stabilized. These models can be integrated into the statistical shape model to identify modes of variation associated with a high risk of dislocation following MPFL reconstruction.

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

The loss of paid students working on the project and suspension of enrollment for several months have led to lower expenditures for salary and imaging in the first year than originally budgeted. Conferences switching to an online format has also led to lower expenditures for travel than originally budgeted. Some other expenses were kept at below the budgeted amount to allow for a no cost extension to complete enrollment.

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

The institutional IRB granted approval for amendments to an existing study to meet the goals of the funded project on January 31, 2020. Enrollment of subjects was suspended by the Institutional Review Board according to the institutional response to the covid-19 pandemic on March 17, 2020. The IRB granted approval to reinstate enrollment on May 22, 2020.

- **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.

- **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. For development of a statistical shape model, algorithms have been developed to align a computational model representing a loaded knee with local coordinate systems for each bone and a global coordinate system to include the shape of each bone and the alignment within the modes of variation. 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. The data collected to date is being developed into a database including the subjects from all groups. The database contains demographic information for each subject, T1ρ relaxation times for the tibiofemoral and patellofemoral cartilage, weighting factors along each mode of variation from the statistical shape models, clinical measures of patellofemoral anatomy and alignment, and patient-reported outcome measures.

## 7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

- **What individuals have worked on the project?**

Name:	John Elias – no change
Name:	Mingrui Yang – no change
Name:	Jennifer Turczyk – no change
Name:	Mei Li – no change

- **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**