**A Patient-Specific Computational Model for Optimizing Surgical Planning to Treat Patellar Instability**

A Technical Report submitted to the Department of Biomedical Engineering


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**Abstract**

Patellar instability is an orthopedic disorder characterized by the patella sliding out of its intended position within the femur's trochlear groove. Forces generated by muscles and ligaments, such as the quadriceps muscles and medial patellofemoral ligament (MPFL), help to stabilize the patella as it tracks through the trochlear groove. Once there's an imbalance between these forces, the patella will no longer be adequately stabilized and subluxes, which means it undergoes a partial dislocation. Over 25% of patients who receive surgical treatment for patellar instability experience a recurrence of the condition, which is attributed to the lack of quantitative metrics being used in surgical planning. In order to address this issue, this project aimed to create a patient specific computational model of the knee to then quantify the force vector acting on the patella. MR images were segmented to obtain the patient's bone and muscle geometries. Anatomical landmarks were placed on the quadricep muscles, patellar tendon, and MPFL in nmsBuilder software to create the paths along which each body acts on the patella. Within OpenSim software, the force acting on the patella in the coronal plane was found for knee angles ranging from full extension to 180 degrees flexion. The force at full extension and 30 degrees flexion was of particular interest as it is most relevant in dislocation. It was found that the only instance that the force vector was in the lateral direction instead of the medial direction was in the pathological patient model within the range of interest. This is significant because it is consistent with expected results and is an indication that the model is accurately able to describe the force vector. Future work would include modeling a larger patient population in order to validate the accuracy of the model before its application in clinical settings.

**Introduction**

*Characterization of Patella Instability*

Patellar instability is a musculoskeletal condition characterized by recurrent subluxation, where the patella slides out of its intended position in the trochlear groove of the femur during knee movement. There are various degrees of severity for this condition, ranging from intermittent subluxation to complete dislocation of the patella.[1] The specific pathologies of the patellar instability, such as a shallow trochlear groove or a ruptured MPFL, will determine the severity of the disorder and the course of treatment. The large variety of causes of patellar instability have led to a lack of standardization among diagnosis, making it difficult for physicians to objectively determine the degree of patellar instability in a case.[2] This has led to a lack of standardization in treatment and subjectivity in the acting physician's final surgical plan. Such subjective surgical planning methods have led to a 25% chance of experiencing recurrent subluxation after the first surgical intervention.[3]

*Current Interventions*

The recurrence rate of patellar instability is high, and each episode of instability puts the individual at a greater risk of further soft tissue damage.[4] In order to combat the phenomenon, there are

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surgical and non-surgical interventions to treat the disorder. If non-surgical treatment methods, including braces to stabilize the patella, non-steroidal anti-inflammatory drugs, or physical therapy, are insufficient, a physician may decide to continue with surgical intervention.[5] A common operation for patellar instability is a medial patellofemoral ligament (MPFL) reconstruction. In order to recreate this primary medial stabilizer, a graft, typically the gracilis or semitendinosus tendon, is looped and secured to create a double-bundle anatomical structure, similar to the original MPFL ligamentous and biomechanical properties.[6,7]

Occasionally the MPFL reconstruction will be performed in conjunction with a tibial tubercle osteotomy (TTO). The choice to perform this bony realignment surgery has gained growing support, especially if presentation of the patients patellar instability includes an elevated tibial tubercle-trochlear groove (TT-TG) distance, patella alta, or extreme femoral anteversion.[8] The surgical procedure involves cutting the bony attachment of the patellar ligament off from the tibia and repositioning it either medially or distally. Opposition to including the TTO procedure with the current standard of care is based upon the added complication possibility when working with bony realignment, such as postoperative stiffness and arthrofibrosis.[8,9]

The goal of both procedures is to neutralize the lateral displacing force acting on the patella and stabilize the patella in the knee joint. Currently, there is no quantitative measurement which can accurately determine the distance laterally or distally to move the tibial tubercle such that the new lateral force falls within the range of normal. Complications from a tibial tubercle osteotomy depend largely on the surgical approach; therefore, there needs to be an assistive tool that quantitatively determines the optimal surgical plan that produces the desirable net force vector acting on the patella.[7]

Within this project, we addressed the subjectivity and lack of quantitative measurements currently present in surgical planning for patellar instability through the following aims:

Specific Aim #1: Creating a patient-specific computational model of the patient's lower extremity using nmsBuilder

Specific Aim #2: Using OpenSim to quantify the net force vector acting on the patient's patella and simulate surgical intervention

## Results

### *Patient-Specific Computational Model*
A healthy patient model and pathological patient model of the lower extremity were created. The models were initially developed in nmsBuilder software, where markers were successfully placed to define the vectors along which each body acted on the patella. These model versions were then able to be converted into OpenSim files that captured the unique musculoskeletal geometry of each patient (Figure 1).
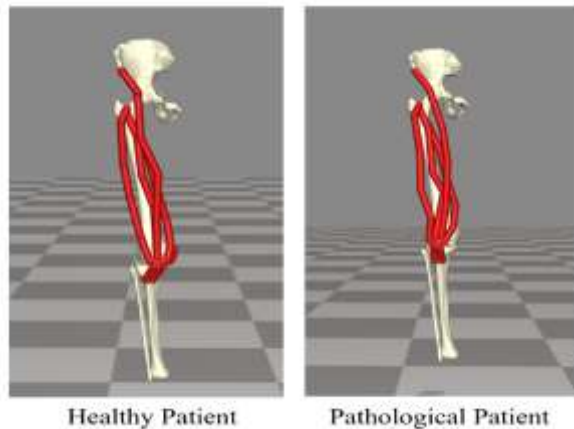
*Figure 1: OpenSim models for the Healthy and Pathological Patients. After segmenting the patients' MRI scans and segmenting the muscle architecture, tendons, and bones, it allowed for the patient-specific model to be created in OpenSim.*
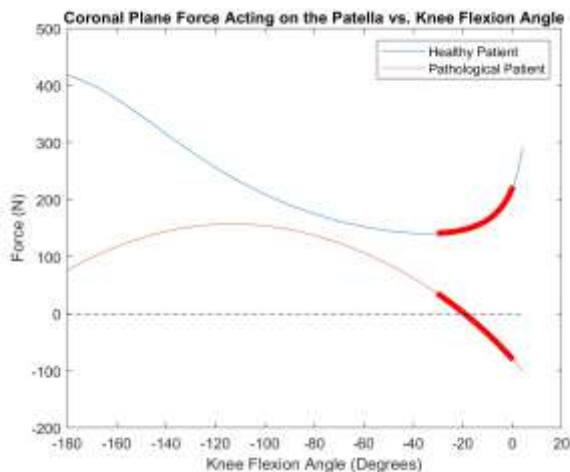


*Figure 2: Graph of the force acting on the patella vs the knee flexion angle. The range of interest for patella dislocation is bolded in red.*

## Angle vs Force

A plot showing the relationship between knee flexion angle and the resultant coronal plane force vector was generated for both the healthy patient model and the pathological patient model (Figure 2). Positive forces indicate a force vector pointing in the medial direction while negative forces indicate a lateral-oriented force vector. Although the graph depicts the forces generated from -180 degrees of flexion to 0 degrees of flexion, the range of interest for patellar instability forces is the region of the curves bolded in red. This focus on that specific bolded range is because the range of -30 degrees to 0 degrees of flexion is the range in which a patient is most susceptible to experiencing patellar dislocation. As can be seen on the graph, the pathological patient experiences a laterally-directed force in the range of interest while the healthy patient experiences a medially-directed force. This is consistent with the idea that a patient experiencing patellar instability would experience a lateral force at the beginning of knee movement, which would cause the patella to dislocate.

## Femoral Anteversion

The degree of hip anteversion is a necessary value for patellar instability planning. These values inform the physician the degree at which the patient's femur twists inward.[10] Normally these values are obtained through CT scans; however, CT scans expose patients to high levels of radiation. Using the computational model methods, the degree of hip anteversion was able to be calculated using MRI scan slices. In order to calculate the values, the angle that the femoral neck formed with the horizontal was calculated using the hip MRI slice that contained the top of the femur. The angle that the femoral condyles formed with the horizontal was then calculated using the knee MRI slice that contained the bottom of the femur (Figure 3). The degree of hip anteversion was taken for each lower extremity of the patient by subtracting the angle of the femoral condyles from its respective femoral neck angle (Equation 1).[11]

$$\text{Hip Anteversion}^o = \angle\text{Hip} - \angle\text{Knee} \qquad [1]$$
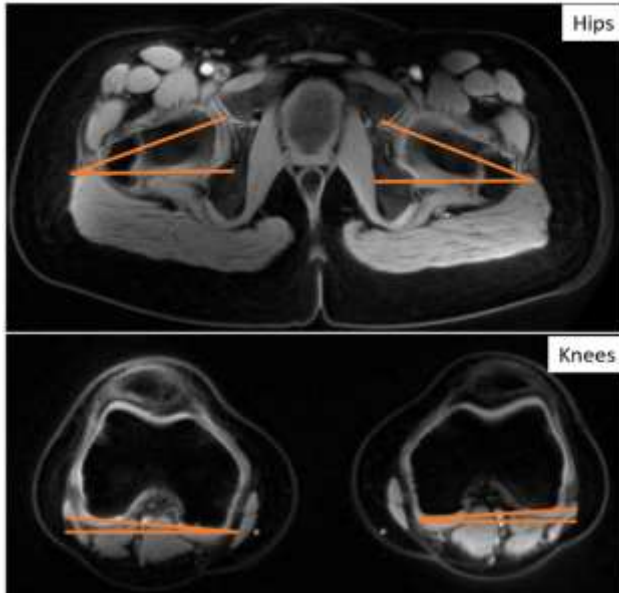


**Figure 3:** *Determined angles for the calculation of patient hip/femoral anteversion. Patient MRI scans were analyzed to determine the hip anteversion parameter.*

## Discussion

### Accomplished

The objective of this capstone project was to create a patient-specific computational model to optimize surgical planning for patellar instability. To accomplish this, we used patient MRI scans to make a representative musculoskeletal model and imported that into OpenSim for further analysis. With that, our group successfully modeled the force vector acting on the patella from 0 to 30 degrees of flexion. The analysis showed that the patellar force acting on a pathological patient differs from that seen in a healthy patient. Additionally, the lateral force vector that was being estimated by the model matched what was expected to be seen in a patient experiencing patellar instability. This finding seems to be an indication that the computational model was able to correctly predict the magnitude and direction of the force vector.

### Limitations

Limitations to the computational model produced include having access to limited healthy and pathological patient scans. This limited data led to only being able to model one healthy patient and one pathological patient for model analysis. Only analyzing two patient models made it difficult to collect the number of force values required for making generalizable conclusions, and validate that the model is accurate. Furthermore, the current resolution of MRI scans made it difficult to obtain necessary muscle architecture metrics, such as fiber length, orientation, and activation, needed to create a more complex musculoskeletal model. Additionally, the MRI resolution makes it harder to define the boundaries of the musculature, specifically with regards to the tendons. This is because the tendons are relatively small compared to muscles which makes it difficult to segment them. Despite these limitations, we were able to create a representation computation musculoskeletal model that could be used to estimate the patellar force vector. Importantly, this model has the potential to be used to optimize surgical planning and outcomes for patients that are undergoing surgical intervention for patellar instability.

### Future Directions

The future direction for this project centers around analyzing more patient scans. Having access to, and analyzing more scans, will allow for the determination and comparison of the resulting patellar force values that the model estimates. These analyses are integral to the ultimate success

of this project because it will provide a means of model validation. Following this, simulations can be performed on the pathological patient models in OpenSim to simulate surgical intervention. Our current computational model does not have the capability to alter the position of the tibial tubercle insertion. With further manipulation of the software, researchers could observe how the force vector acting on the patella for a pathological patient varies with different surgical intervention approaches. Finally, long term goals for this project include using large-scale clinical trials to validate our model's implementation in a medical setting. This validation can be done by using the project to model the surgeon's procedure and estimating how successful the surgery will be based on how the model predicts the force will change with the given surgery. Then the predicted results can be compared with the actuality that a patient will experience recurrent patellar instability and require additional surgery.

## Materials & Methods

### *MRI Acquisition and Segmentation*
Patient MRI data, and the accompanying musculoskeletal segmentation data, were provided by Springbok Analytics, Inc. The four quadricep muscles: the vastus medialis, vastus intermedius, vastus lateralis, and rectus femoris, in addition to key bones including the pelvis, femur, patella, and tibia were successfully segmented. Additionally, the patellar tendon and MPFL were segmented. The MRI data consisted of axial slices that were obtained every 5 mm starting at the top of the iliac crest and ending at the patient's ankle.

### *Model Creation*
Geometries and volumes from the segmented muscles, tendon, and bones were imported into nmsBuilder via STL files. Importing these files allowed for the generation of a static 3D model of the patient's musculature, bones, and tendons. These 3D surfaces then had appropriate landmarks placed on them which included landmarks that label the origin, insertion, and via points for both muscles and tendons, and tubercles for bones. The patellar tendon was represented by three actuators in order to best represent the wide surface area along which it attaches to the patella and tibial tuberosity. These 3D surfaces and landmarks were then imported into OpenSim for force quantification (Figure 4). Within nmsBuilder, specific joints were created around the knee, including a pin joint between the femur and tibia, and a custom joint was created around the patella. This process was done for one healthy patient scan and one pathological patient scan.

## Data Analysis in OpenSim
Data acquisition and analysis was done separately for each model. Within OpenSim, it was first confirmed that the defined joints were properly represented and functioned as would be expected in the human body. Following this, the coordinates of the bodies were adjusted to position the model in an upright position. The plot tool embedded in the software was utilized in order to find the relationship between knee flexion angle and the moment acting on the patella in the coronal
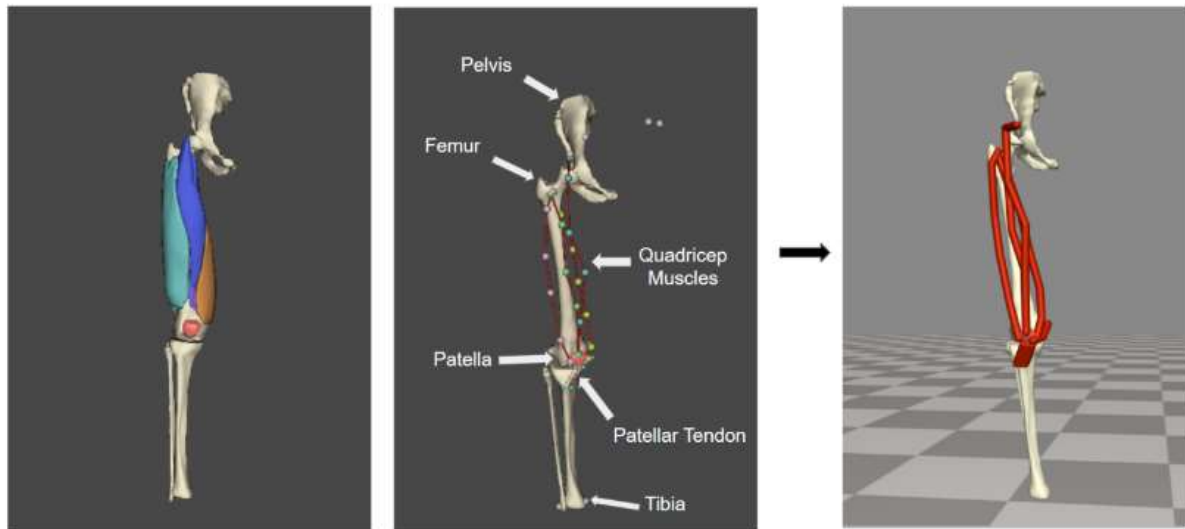


**Figure 4:** *Creation of the patient-specific model in nmsBuilder and OpenSim. The segmented bone and muscle architecture data was imported into nmsBuilder which allowed for the creation of a static 3D model.*

plane. The same tool was then used to find the relationship between knee flexion angle and the moment arm of the bodies acting on the patella. The moment and moment arm values were found for a full range of knee motion, 180 degrees flexion to full extension, but the range of 30 degrees flexion to full extension was of the most interest. All of the data was exported and formatted in a text editor in order to make it more compatible with Matlab software.

## Data Analysis in Matlab
Knee flexion angle, moment, and moment arm data sets were imported into Matlab for both the healthy patient and pathological patient models. A script was written in order to perform further analysis and generate a plot of the results. The moment (*M*) and moment arms (*ma*) values were used to calculate force values (*F*) (Equation 2).

$$F = \frac{M}{ma} \qquad\qquad [2]$$

As the moment and moment arm data was taken specifically in the coronal plane, the calculated force values were representative of the force vector acting on the patella in the coronal plane. In order to compare the two models, a plot was generated that depicted the knee flexion angle and

force relationship for both patients. Positive y-axis values corresponded with medially acting force while negative values signified laterally acting force. Additionally, markers were added to the graph to denote the flexion range of interest and the point at which the force changed from acting medially to laterally.

## End Matter

*Author Contributions and Notes*
A.C.K, K.E.D, and V.E.P performed all background literature research, contributed to model creation, and wrote the paper. S.S.B and D.R.D oversaw all research progress and actions.

The authors declare no conflict of interest.

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