Optimizing Surgical Planning for Patellar Instability Pathologies using Computational Modeling

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Abstract

Patellar instability is a relatively common orthopedic condition characterized by a patellar dislocation event followed by immediate relocation, while all joint surfaces remain in contact. Several pathologies can lead to patellar instability, with the most prominent being an excessive tibial tubercle-trochlear groove measurement. Current treatments focus on surgical interventions which rely almost solely on the expertise of the acting physician, promoting a subjective surgical planning process and contributing to a high redislocation incidence. With recent advances in technology, biomechanical computational modeling demonstrates the potential to objectively determine the optimal surgical plan on a clinical timeline. Our group sought to create a patient-personalized model capable of simulating possible surgeries to determine the best plan of action, optimizing surgical outcomes and reducing redislocation rates. This report describes the creation of a computational model of a healthy, baseline patient in order to run kinematic simulations, the first step towards demonstrating proof of this concept and inserting computational biomechanical modeling into orthopedic clinics.

Keywords: Biomechanics; Musculoskeletal Modeling; OpenSim; Patellar Instability; Orthopedic Surgery

Introduction

Patellar instability/subluxation is a musculoskeletal condition characterized by patellar dislocation followed by an immediate relocation with joint surfaces remaining in contact. The initial patellar dislocation ruptures the medial patellofemoral ligament (MPFL), promoting maltracking of the patella, especially during the first 30 degrees of knee flexion and internal rotation. Patellar instability is viewed as a fairly common condition by orthopedic standards, as it is observed in six out of every 100,000; this injury most commonly affects adolescent athletes, increasing this statistic to an estimated 29 per 100,000 [1], [2]. Despite surgical treatment, redislocation rates in adolescents and adults is nearly 50%. Researchers and orthopedic clinicians believe the cause of the dislocation problem is multifaceted, and likely due to a combination of multiple complex pathologies, patient susceptibility, or inadequate surgical planning/intervention. On top of the long recovery and expensive procedures, approximately half of the aforementioned young athletes that suffer from patellar instability are unable to ever return to the same sports performance level [2]. Thus, it is imperative that the process of addressing patellar instability be altered to optimize patient outcomes.

A patient's patella will almost always dislocate laterally due to the nature of the human anatomy. Humans more often than not have a larger vastus lateralis muscle when compared to their vastus medialis muscle, increasing net valgus directed force vectors. As previously discussed, various pathologies can contribute to a dislocation event and ultimately lead to patellar instability. These pathologies include trochlear dysplasia, patella alta, patellar tilt, and increased tibial tubercle-trochlear groove (TT-TG) measurement. Trochlear dysplasia is an abnormal shape of the one or both of the femoral trochlea causing the osseous of patella tracking to be lost. Common types of dysplasia are: shallow, flat, lateral convexity, and cliff [3]. Similarly, patella alta delays patellar tracking into the trochlear groove until a higher degree of knee flexion because the patella rests abnormally high, predisposing the patient to instability. Patellar tilt is characterized by the lateral facet of the patella having an abnormal position relative to the anterior tibial crest [3]. In severe cases the lateral facet will sit behind the crest, creating a higher risk for a dislocation event.

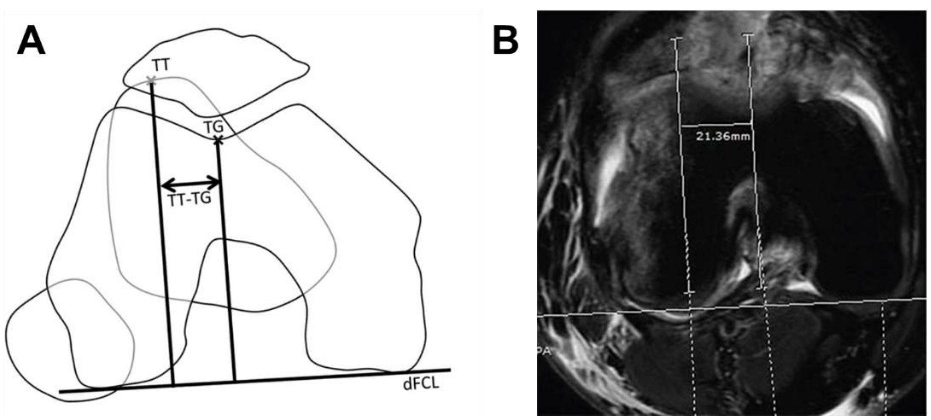

Figure 1. Visual of the tibial tubercle-trochlear groove (TT-TG) measurement. A: Visual depiction of the TT-TG measurement from the deepest part of the trochlear groove (TG) to the most prominent part of the tibial tubercle (TT) B: TT-TG measurement taken on patient MRI.

Lastly, one of the more common contributors to patellar instability is an increased TT-TG. This measurement is the distance between the deepest point of the trochlear groove and the most prominent point of the insertion point of the patellar tendon, known as the tibial tuberosity. The TT-TG measurement is the most commonly used tool for orthopedic doctors to diagnose a patellar dislocation, and it is obtained by superimposing two axial magnetic resonance (MR) images and estimating a distance using the spatial resolution of the scan (Figure 1) [4], [5]. A normal TT-TG value is between 10-13 millimeters (mm) and is considered pathological when greater than 20mm [3]. Rupturing of the MPFL causes an escalation of the TT-TG value because the patella loses a medially-directed stabilizing force. An increased TT-TG will then lead to abnormal alignment of the extensor mechanism and a consequential valgus displacing vector to act on the patella.

The standard of care for treating patellar instability is subjective, almost solely relying on the expertise of the attending orthopedic surgeon (Figure 2). No quantitative data is currently collected to provide insight for proper surgical planning. Currently, MR and computed tomography (CT) imaging methods are the most commonly used medical tools to diagnose a dislocation event and to unveil possible intervention plans. Conservative treatments, such as physical therapy, are often the first treatment plan. If conservative methods fail, surgical intervention is necessary. Since a true dislocation will coincide with a rupture of the MPFL, a MPFL reconstruction will always be performed, using the gracilis tendon as a graft [3]. Each pathology may require further surgical intervention if deemed necessary. Trochlear dysplasia can be treated by a trochleoplasty, depending on the pathological anatomy of the patient. Patella alta can be treated with a tibial tubercle distalization, while patella tilt can be treated with a proximal vastus medialis realignment [3]. Finally, an exaggerated TT-TG can be redacted with a tubercle medialization transfer surgery. This surgery requires the doctor to detach the tubercle and refasten it to the tibia in a more medial and/or proximal position. The purpose of this is to reduce the valgus forces acting on the patella to prevent a redislocation event.

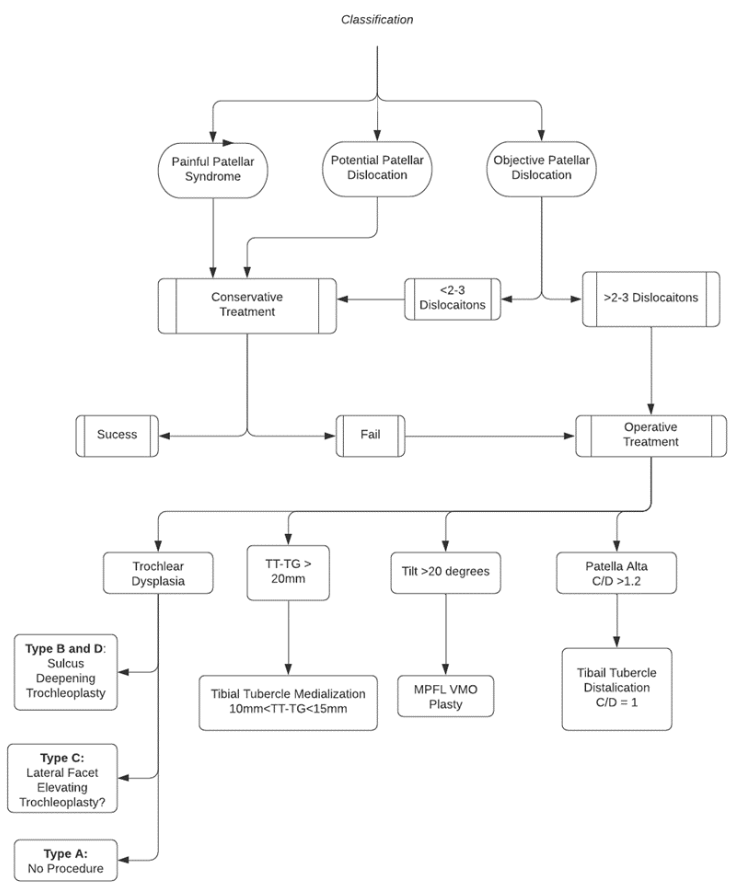

Figure 2. Flow chart used by physicians to help determine treatment options for patellar subluxation and/or dislocations [3].

In this project, our group aims to resolve the issue of subjectivity in patellar instability surgical planning by creating patient-specific, biomechanical computational models quantifying forces acting on the patella, simulating potential surgeries, and optimizing surgical outcomes. Due to the nature and realistic time frame of this capstone project, our group set out to create a model framework to address one of the patellar instability pathologies. We decided that this pathology to be the increased TT-TG because of its higher incidence and impact. Therefore, we sought to predict whether a tubercle transfer surgery would be necessary in addition to an MPFL reconstruction surgery, a question that is currently up to the discretion of the orthopedic surgeon. The surgeon would also know how far medially and/or proximally to move the tubercle (on the mm scale). This modeling framework would have the potential to simultaneously minimize invasiveness while optimizing surgical outcomes.

Materials and Methods

MR Image Acquisition and Processing

The first objective was to create an easily-visualized computational model of a healthy subject's knee, providing a baseline to compare against future models based on patients with patellar instability. MR images and the accompanying musculoskeletal segmentation data of 24 active, healthy subjects without a history of lower limb injury were made available to create these baseline healthy models. This data was provided to the researchers by Springbok Analytics, Inc, a company co-founded by two of the project advisors which uses artificial intelligence to perform volumetric segmentation of lower extremity musculoskeletal tissue found in MR scans. The Springbok Analytics segmentation process is graphically depicted in Figure 3.

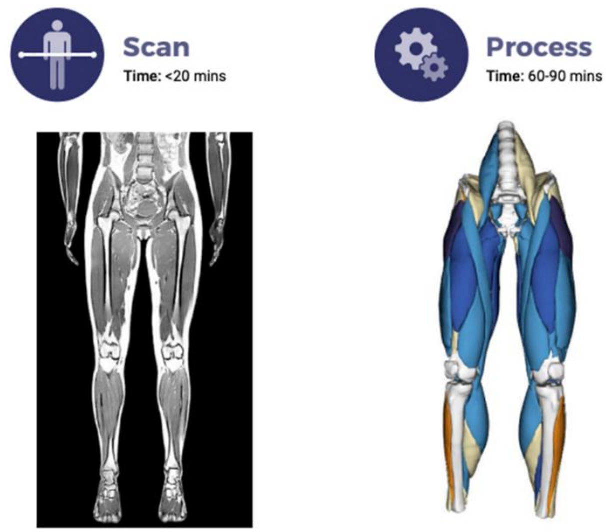

Figure 3. Depiction of the MR image processing performed by Springbok Analytics, Inc. For conceptualization purposes, coronal MR images are shown on the left; however, axial MR images are used for segmentation. The muscle and bone OBJ files resulting from segmentation are depicted on the right. This figure was provided by Springbok Analytics, Inc.

Briefly, the subjects were scanned on a "3T Siemens Trio (Munich, Germany) MRI Scanner using a 2D multi-slice sequence utilizing spiral gradient echo" [6]. The field of view for the scans were 400mm x 400mm. Axial slices were obtained every 5mm starting at the iliac crest and ending at the ankle joint, capturing the entirety of the four quadriceps muscles at the focus of the proposed computational model for this project. All 35 pairs of lower limb muscles were segmented for each of the subjects in addition to the pelvis, femur, patella, tibia, and fibula [7], [8]. The researchers therefore obtained de-identified MR images, in accordance with the health insurance portability and accountability act (HIPAA), bone and muscle geometries in the form of Wavefront 3D geometric object (OBJ) files, and the volumes of the segmented bones and muscles in milliliters (mL).

Model Software Determination

An extensive search was conducted to gather information on possible methods that could be used to convert the aforementioned outputs of musculoskeletal segmentation to a functional model computing biomechanics during motion. When comparing possible methods, it was important to consider the tradeoff between model complexity and computational efficiency. Some biomechanical models such as torque-driven models excel in computational speed, but severely lack in biological fidelity. Contrarily, biological finite element modeling softwares, such as FEBio, often run into the opposite problem; the models are too computationally expensive due to intricacy

[9]. It was concluded that OpenSim was the optimal software for kinematic biomechanical model analysis within the context of this project.

OpenSim is an open-source software created by Stanford University specifically designed to automate the calculation of biomechanical measurements for human motion. The software contains a multitude of analysis plug-ins that allow for rapid calculation of joint forces, muscle-induced acceleration, and other variables. Furthermore, model frameworks can be exchanged between research universities for validation and future exploration [10].

However, subject-specific personalization of an OpenSim model requires extensive knowledge of the OpenSim source code. Learning how to personalize OpenSim models using back-end code would require more time than the scope of a two-semester capstone project. Thus, NMSBuilder was used for pre-OpenSim model creation and personalization in lieu of coding. NMSBuilder enables the "processing of image-based data and creation of subject-specific musculoskeletal models for OpenSim" [11]. In other words, the software simultaneously standardizes musculoskeletal modeling creation from imaging-based data and reduces the time required for us to create biomechanical models for OpenSim. This research culminated in the decision to use a combination of NMSBuilder and OpenSim for the respective construction and analysis of our personalized patellar instability model (Figure 4).

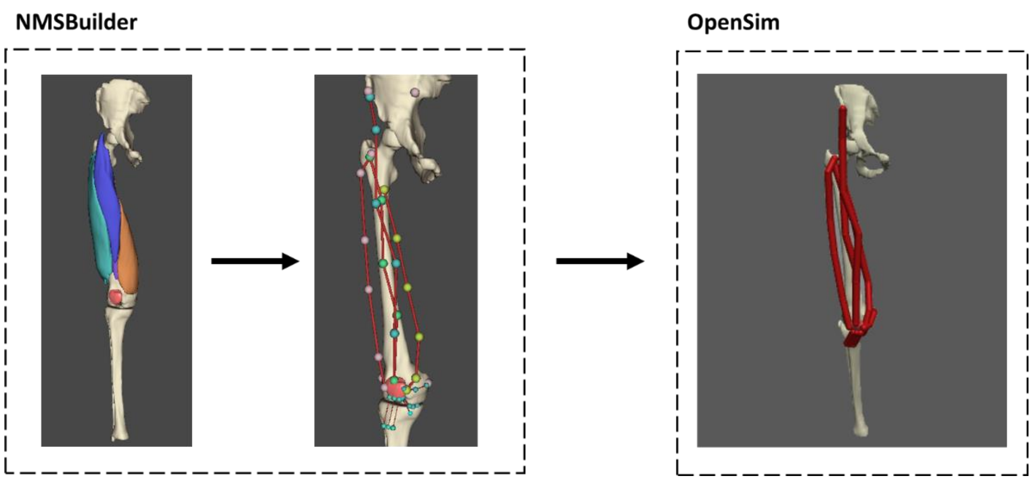

Figure 4. Diagram demonstrating the model creation workflow. The OBJ files resulting from musculoskeletal segmentation are imported into NMSBuilder. The centroids of the muscles are then used as guidance to place landmarks for the muscle actuators while the MR images are used for guidance to place the patellar tendon and other ligaments. The NMSBuilder model is then exported to OpenSim for analysis.

Results

MRI Acquisition

De-identified MR images and their associated segmentation data was supplied by Springbok Analytics, Inc. MR images were taken at 5mm increments of the full bilateral lower extremities. A full lower extremity MR scan is necessary in order to visualize the proximal bony anatomy, visualize the attachment points of the all four quadriceps muscles and calculate their associated volumes. Our original model was created from a healthy patient to establish a baseline to compare to a pathological scan once obtained. Following segmentation, musculoskeletal tissue geometric data and volumetric data was obtained in the form of OBJ files and comma-separated values (CSV) file, respectively.

Healthy Patient Model

The OBJ files were converted to stereolithography (STL) files, and then imported into the NMSBuilder software as surfaces. To appropriately model patellar instability, STL files of the ipsilateral femur, patella, tibia, fibula, vastus medialis, vastus lateralis, vastus intermedius, and rectus femoris were used. Both the left and right pelvis geometries were also required. Once all bony and soft tissue anatomy were imported into NMSBuilder, we created an anatomical reference system in preparation for defining the right knee and right hip joints [11]. The reference system was established using an anatomical landmark cloud, a set of predefined common bony anatomical markers (Figure 3Figure 5).

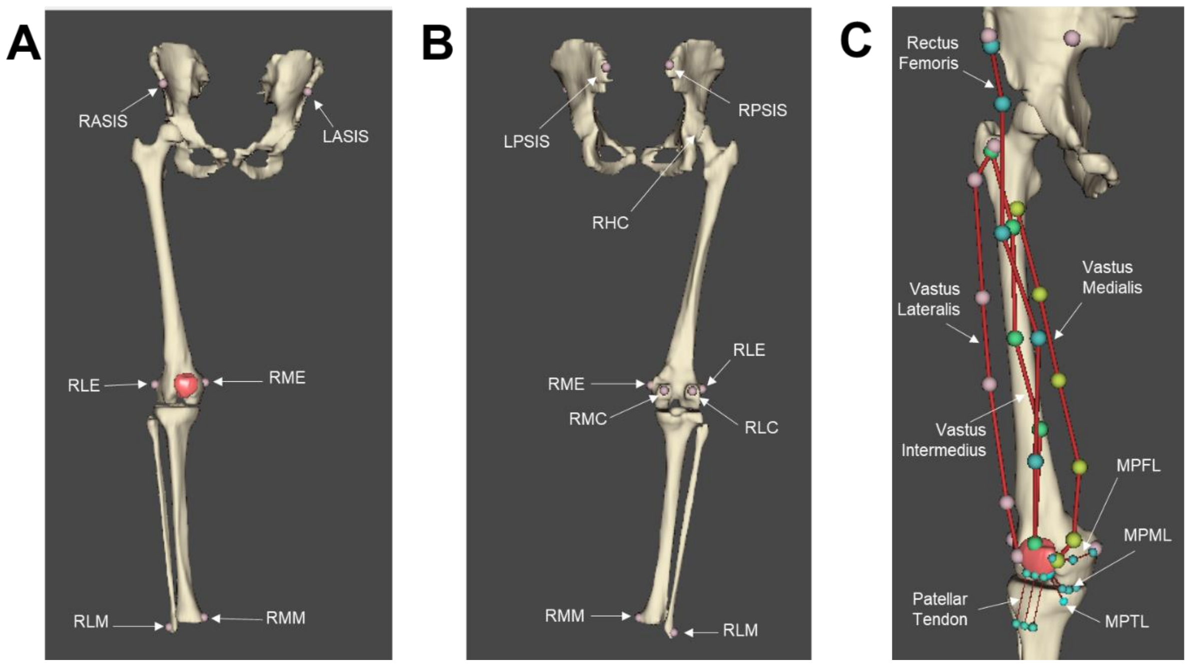

Figure 5. A: Anterior labeled view of the anatomical landmark system composing the reference system for joints. RASIS, right anterior superior iliac spine; LASIS, left anterior superior iliac spine; RLE, right lateral epicondyle; RME, right medial epicondyle; RLM, right lateral malleolus; RMM, right medial malleolus. B: Posterior labeled view of the anatomical landmark system composing the reference system for joints. RPSIS, right posterior superior iliac spine; LPSIS, left posterior superior iliac spine; RHC, right humeral head; RMC, right medial condyle; RLC, right lateral condyle. C: Detailed view of the baseline healthy patient model with soft tissue labeling and actuator landmark pathways. The patellar tendon refers to all three actuators originating on the patella and inserting onto the tibia. MPFL, medial patellofemoral ligament; MPML, medial patellomeniscal Ligament; MPTL, medial patellotibial ligament.

Similarly, we created muscle landmarks for each of the four quadriceps muscles. A chain of landmarks was added along the centroid of each muscle (Figure 5). The centroid of each muscle was approximated using the STL file acquired via MR segmentation. The landmarks for each muscle were added and specifically labeled in order starting at the muscle origin, labeled “muscle orig”, and ending at the muscle insertion, labeled “muscle ins”, on the patella. The intermediate landmarks were labeled in numerical order along the pathway of the muscle. The NMSBuilder software requires this specific labeling for proper muscle actuator export to OpenSim. The same process was used for creation of the patellar tendon, medial patellotibial ligament (MPTL), medial patellomeniscal ligament (MPML), and MPFL. Because ligaments and tendons were not segmented from MR images, there was no geometry file to aid in placing these landmarks. Instead, primary literature was used as a reference in combination with the patient's MR images to accurately place the origin, insertion, and pathway landmarks (Figure 5). The anatomical accuracy of the baseline model was approved by an orthopedic surgeon before proceeding to OpenSim.

Once all landmark clouds and reference systems were established, the NMSBuilder model was prepared for OpenSim format. OpenSim bodies and muscle actuators were automatically created using the bony anatomy surfaces and muscle landmarks previously established. The next step in model creation was to establish the OpenSim joints, which will determine body movement during OpenSim simulations. Each body requires one joint, defining how the movement is physiologically constrained relative to another bone. For example, a pin joint was created between the femur and the tibia, constraining the joint to one degree of rotational freedom. Meanwhile, a ball joint was appropriate for the femur relative to the pelvis, providing three rotational degrees of freedom. A custom joint with six degrees of freedom was created between the patella and the tibia because the muscle, ligament, and tendon actuators would stabilize movement and rotation.

$$F_O^M = \frac{V}{l_O^M}\,\sigma_O^M \qquad [1]$$

The peak isometric forces were implemented for the individual OpenSim muscle, ligament, and tendon actuators in the healthy baseline model. These forces vary between patients and are integral to accurately representing patellar motion. Patient-specific muscle volumes and human average optimal fiber lengths were used for the calculations of the peak isometric forces for the four quadricep muscles. Optimal fiber length values could not be personalized to each patient because no diffusion tensor imaging tractography was performed on the patients. Instead, optimal fiber length values were obtained from a muscle modeling paper cited by a multitude of subsequent OpenSim models [12]. Peak isometric forces (F_O^M) were obtained by dividing the muscle volume (*V*) by its respective optimal fiber length (l_O^M), and then multiplying by the specific tension coefficient (σ_O^M) (*Equation 1*).

The patella tendon was split into three actuators in order to more accurately represent a physiological tendon. The insertion of the tendon covers a wide area on the tibial tuberosity, and one segment on the model would not properly simulate knee mechanics. The isometric force of this tendon is equivalent to the summation of the muscles it is attached to, therefore we used the isometric force of the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius, and divided it evenly among the three segments [13], [14]. Other published models of the knee and cadaveric-based literature values were used to approximate the peak isometric forces of the MPTL, MPML, and MPTL. Following peak isometric force definition, the model was exported to OpenSim for dynamic simulations and analysis [13], [14].

In OpenSim, not all kinematic tests were able to be run due to troubleshooting issues within the model. Tests were performed to validate that the model was reflecting physiologically accurate muscle function and movement. Data of the fiber length of each quadriceps muscle was collected and analyzed during the first 30 degrees of flexion to extension (Figure 6). Each of the four quadriceps muscles (rectus femoris, vastus intermedius, vastus lateralis, and vastus medialis) behaved in a predictable manner, with fiber length increasing with flexion. These tests have ultimately served as a proof of concept in order for further exploration of computational biomechanical modeling uses in a clinical setting. Overall, the model created was an interactive process that was aided with the guidance of orthopedic surgeons, biomedical engineers, and review of primarily literature.

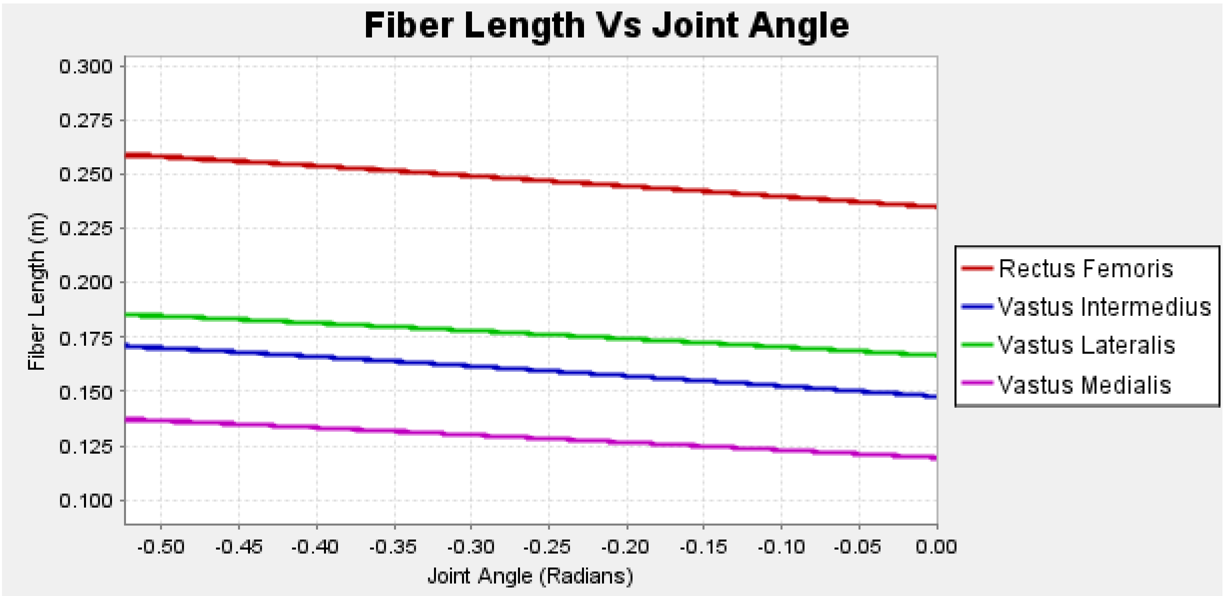

Figure 6. Graph demonstrating muscle fiber lengths throughout the first 30 degrees of knee flexion. Fiber length decreases with extension, reflecting proper muscle function.

Discussion

The objective of this capstone project was to create a patient-personalized computational biomechanical model to optimize patellar instability surgical planning. To accomplish this, we extensively researched biomechanical modeling software options and determined that a combination of NMSBuilder and OpenSim would enable efficient model personalization and creation while maintaining a high level of biofidelity. Our group successfully used NMSBuilder in combination with MR image-based musculoskeletal segmentation data to create a biomechanical model of a healthy, active, young adult. This model was exported to OpenSim for kinematic analysis.

It is worth noting that there are limitations to the model produced. The current model is unable to simulate proper knee motion, preventing the collection of joint-contact force and joint moment data required for validation that the model is accurate. Furthermore, the MR images used have an axial spatial resolution of 5mm. This spatial resolution drastically reduces the scan time of the extended MR that encompasses the entirety of the four quadriceps muscles, benefiting the patient. However, an MR scan with a higher axial resolution, such as 1mm, would increase the anatomical accuracy of muscle, ligament, and tendon actuator placement. A lack of clinical data also presents as a major limitation of this project. MR scans of patients suffering from patellar instability due to excessive TT-TG distance could not be obtained without institutional review board (IRB) approval because an extended MR scan is not covered under insurance. This meant that we were unable to create a true pathological model to compare to our healthy baseline model.

Despite these limitations, we successfully created a framework for a computational biomechanical model with the potential to optimize surgical planning and outcomes for patients presenting with excessive TT-TG measurements. Importantly, we established and documented a protocol for replicating our work for any given patient on a clinically relevant time frame. It takes approximately eight hours total following MR scan upload to perform musculoskeletal segmentation, model construction, and OpenSim analysis. That said, surgeons will be able to obtain a suggested "optimal surgical plan" approximately one business day following the MR scan, well before the pre-operative patient visit occurs.

Provided that our modeling framework is validated and proven effective, this concept has the potential to revolutionize orthopedic surgery. First and foremost, this modeling framework could easily be transferred to other patellar instability pathologies such as trochlear dysplasia, patellar tilt, and patella alta. Optimization of patellar instability surgical outcomes would notably reduce the 50% redislocation rate currently observed, consequently reducing the prevalence of subsequent knee surgeries. Many downstream effects might occur due to increased surgical success. Health systems may reduce wasted energy, finances, and material spent on any given patient, and patients would no longer spend double the amount of money on a fully avoidable surgery. Additionally, this project serves as the foundation for other patient-specific orthopedic surgical simulations; the necessary research performed and framework outlined in this project may be applied to orthopedic conditions similar to patellar instability.

The future direction of this project centers on pathological model comparison. IRB approval was recently obtained, enabling the research team to order extended MR scans for three patients with patellar instability due to an excessive TT-TG measurement. Pathological scans are integral to the ultimate success of this project because they provide a means of model validation. Using the established protocols, a biomechanical computational model can be created of the pathological patient pre-surgical intervention. Kinematic simulations can then be performed in OpenSim to observe dislocation *in situ* and compare biomechanical measurements, such as net lateral contact force acting on patella, to the healthy model. Following this, we could simulate an isolated MPFL reconstruction case as well as possible tubercle transfer surgeries in conjunction with the MPFL reconstruction and collect the same biomechanical measurements. We could then compare the "optimal surgical plan" according to these results against the expertise of the attending orthopedic surgeon. If this data proves valuable, it might serve as possible proof of concept to gain IRB approval for a large-scale clinical trial.

End Matter

Author Contributions and Notes

M.T.L. and L.C.S. performed all background literature research, contributed to model framework construction and documentation, debugged coding issues, and wrote the paper. J.M.H. and D.R.D. performed the actions necessary to obtain the institutional review board approval. S.S.B., J.M.H., and D.R.D. oversaw all research progress and actions. The authors declare no conflict of interest.

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