Queen's University Computing

Computer Assisted Medial Patellofemoral Ligament (MPFL) Reconstruction

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1. Introduction

This report presents an enhanced computational model for simulating knee motion during medial patellofemoral ligament (MPFL) reconstruction. The model builds on an existing knee joint motion framework by incorporating tendon forces, particularly from the quadriceps muscle and the patellar tendon, which are essential for accurate patellar tracking. By using a spring and damper system to represent these tendons, the model calculates the forces acting on the patella during knee flexion, providing a more dynamic and realistic simulation. This is achieved through incremental advances in the patella's position and rotation, with a focus on ensuring the optimal alignment of the patella within the femoral groove. The enhanced model also integrates a repulsive force from the cartilage separator to prevent collision, further improving the realism of the simulation. This approach allows for more precise optimization of tendon length and graft insertion points, potentially reducing complications such as graft impingement or non-isometric graft tension. The results of this model can help refine surgical planning, optimize graft placement, and ultimately lead to more effective and individualized MPFL reconstruction procedures, improving patient recovery and long-term outcomes.

2. Motivation

The medial patellofemoral ligament (MPFL) is a critical stabilizer of the patella. It originates along the upper two-thirds of the inner edge of the patella and attaches to the femur near the medial epicondyle, blending into the surrounding soft tissue structures [1]. The MPFL is part of a larger complex on the inner side of the knee that includes the medial collateral ligament (MCL), patellotibial, and patellomeniscal ligaments, all of which contribute to patellar tracking and joint stability.

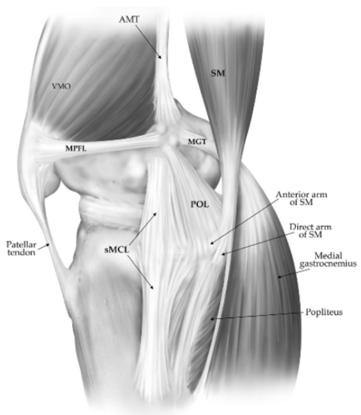


Figure 1. Illustration of the main medial knee structures from [1]. VMO = vas- tus medialis obliquus muscle, MPFL = medial patellofemoral ligament, POL = posterior oblique ligament, sMCL = superficial medial collateral ligament, SM = semimembranosus muscle, MGT = medial gastrocne- mius tendon, and AMT = adductor magnus tendon

Anatomically, the patella sits within the trochlear groove of the femur, guided by passive constraints like ligaments and active forces from the quadriceps. When the MPFL is intact, it prevents the patella from shifting too far outward during movement. However, in individuals, often young athletes, who experience sudden directional changes or direct impact to the medial knee, the MPFL is prone to tearing. Lateral patellar dislocation is typically the result of these high-stress movements, and initial dislocations often involve damage to the MPFL near its femoral attachment [7]. Once torn, the MPFL rarely heals in a way that restores full stability, making recurrent dislocations more likely.

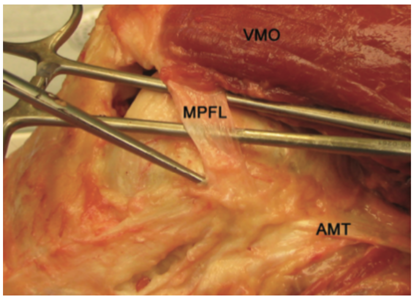


Figure 2. Photo from [2] of the isolated medial patellofemoral ligament (medial view, right knee).

MPFL reconstruction has become the standard surgical approach for treating chronic patellar instability following a tear. The procedure typically involves using a tendon graft, often harvested from the hamstrings, to recreate the function of the original ligament. Accurate positioning of the graft, particularly its attachment to the femur, is crucial for restoring natural patellar mechanics. One of the most widely accepted methods for identifying this location is Schöttle's technique, which uses radiographic landmarks to approximate the insertion point on lateral fluoroscopy images [2]. This point, commonly referred to as "Schöttle's point," is situated just forward of the posterior femoral cortex and below the beginning of the medial femoral condyle.

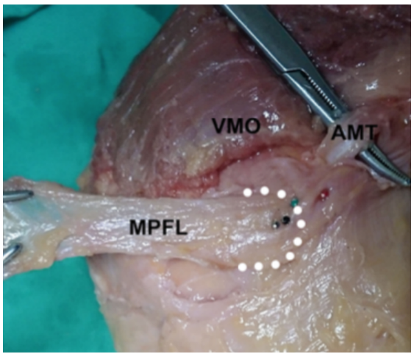


Figure 3. Photo from [2] showing the medial aspect of the right cadaveric knee. The white circles depict the medial patellofemoral ligament (MPFL) femoral attachment and the grey pin marks the center of the MPFL femoral attachment. The green, red, and black pins represent the femoral tunnel entry points established using the midpoint, fluoroscopic, and sulcus localization methods, respectively.

Despite its broad adoption, using Schöttle's point as a universal reference poses challenges. Even small deviations of just a few millimeters from the ideal insertion site can significantly alter graft behavior. Misplacement may lead to non-isometric grafts that become overtensioned during knee flexion or too slack in extension [5]. These mechanical mismatches can cause a range of postoperative complications, including limited range of motion, excessive pressure on the medial joint structures, or eventual graft failure. The method also relies on interpreting 2D imaging to guide 3D anatomical placement, introducing variability based on image quality and surgical judgment.

Overall, while MPFL reconstruction offers effective restoration of patellar stability, its success depends heavily on precise anatomical knowledge and surgical execution. Inaccurate femoral tunnel placement remains a major source of postoperative complications. As a result, there is a growing interest in using computational tools and patient-specific modeling to guide surgical planning, with the goal of improving isometry and restoring more natural patellar motion across a diverse patient population.

3. Background

As surgical techniques for medial patellofemoral ligament reconstruction continue to evolve, the integration of computational modeling into clinical workflows has opened promising new avenues for improving surgical accuracy and patient-specific outcomes. Traditional reconstruction methods rely on general anatomical landmarks and surgeon expertise to guide graft placement, yet such methods often fail to account for individual anatomical variability and the dynamic behavior of the joint under load. To address these limitations, researchers have increasingly turned to simulation-based approaches that model knee function with high fidelity, offering both predictive insight and surgical guidance.

One avenue of investigation has focused on dynamic multibody simulations of the knee joint to understand how anatomical differences affect patellar tracking after MPFL reconstruction. In a study by Elias et al., a patient-specific simulation framework was developed using MRI-derived 3D models of the knee. These models captured detailed anatomical structures including bones, cartilage, ligaments, and muscle attachment points, allowing for subject-specific analysis across a sample of nine individuals. By modeling the reconstructed MPFL graft as a tension spring fixed to the femur near the commonly used Schöttle point, the study evaluated the effect of different graft tensions and placements during activities such as knee extension and squatting.

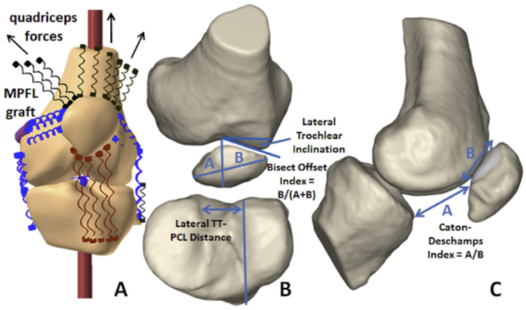


Figure 4. Diagram from [7]. Computational model for multibody dynamic simulation for one knee.

Crucially, the simulations did more than just track anatomical motion. Muscle forces from the quadriceps and hamstrings were incorporated, and ligament properties were modeled with spring elements to reflect real biomechanical behavior. Contact between joint surfaces was also approximated using contact mechanics. These elements allowed the researchers to simulate knee motion under realistic conditions, revealing that subtle anatomical differences such as femoral trochlear shape or patellar height can significantly alter post-reconstruction patellar tracking. Even reconstructions performed according to standard guidelines sometimes resulted in lateral patellar shift, highlighting the value of incorporating individual biomechanics into surgical planning. The study suggests that simulations like this could eventually help predict how a given surgical configuration would behave before the procedure is performed, potentially reducing the likelihood of post-operative instability or graft overconstraint.

While dynamic simulations help evaluate functional outcomes, other researchers have focused on refining graft placement through precise anatomical modeling. In work by Blatter et al., 3D knee models were developed from CT scans to determine the most isometric femoral insertion point for the MPFL graft, ie. where the ligament would experience the least length change throughout the range of motion. Their study captured knee geometry at five different flexion angles under weight-bearing conditions, creating a more physiologically accurate representation of how the joint behaves during real-life motion.

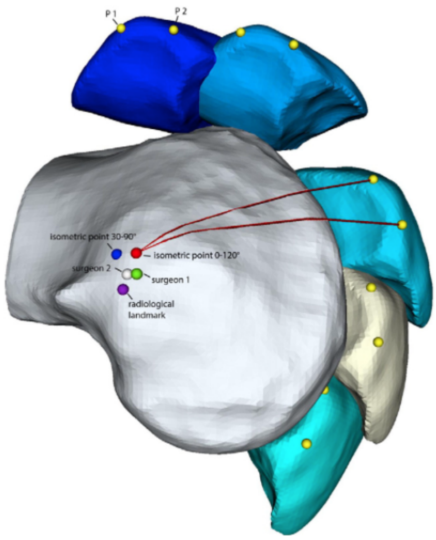


Figure 5. Diagram from [5]. 3D image of a knee with distribution of the different femoral insertion points and the two defined patellar points P1 and P2. The two red lines (strings I and II) show the exemplary distance between P1 and P2 in the 60° patellar position and the computed isometric point 0 to 120°

Using this data, the researchers employed computational techniques to register femoral motion and measure the length of virtual grafts placed at both radiographic landmarks and surgeon-defined points. An isometry score was calculated for each insertion site, quantifying the degree to which graft length changed with flexion. The results revealed substantial variation across individuals and highlighted that standard landmarks, such as the Schöttle point, often did not correspond to the optimal isometric position. This underscores the need for patient-specific planning in MPFL reconstruction, as even small deviations in femoral tunnel placement can lead to abnormal tensioning, restricted range of motion, or increased stress on surrounding tissues.

Together, these studies illustrate how computational modeling can enhance both the planning and evaluation of MPFL reconstruction by accounting for individual variation in knee anatomy and biomechanics. Whether through dynamic simulations that replicate knee movement under load, or static models that quantify isometry across the joint's range of motion, these tools offer a level of predictive power that traditional surgical planning methods cannot match.

4. Methods

4.1. Original Model

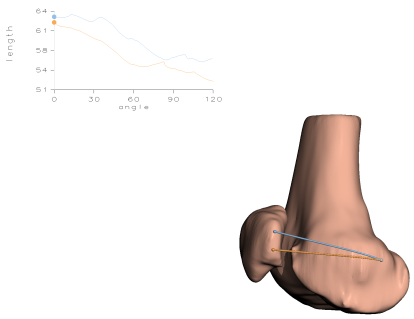


Figure 6. Screenshot of original model rendering before the addition of the femoral and patellar tendons.

The original knee joint motion model is designed to simulate patellofemoral kinematics, particularly focusing on the motion of the patella as it tracks along the femoral groove during knee flexion. This simulation is implemented using OpenGL to visually represent the 3D anatomy of the knee, providing an interactive model for visualizing the movement of the patella relative to the femur. The model primarily relies on geometric calculations, specifically the computation of curvatures and transformations, to determine the patella's position and trajectory. However, it does not account for the forces generated by the quadriceps muscle and patellar tendon, which are essential for a more biomechanically accurate simulation.

The simulation operates by calculating the principal curvatures at multiple points between the patella and femoral groove. These curvatures are essential for simulating how the patella moves along the femoral groove, as the patella follows the contours of the femoral condyle during knee flexion. The model approximates this motion by computing a series of transformations that move the patella incrementally along the groove based on curvature data. The movement is controlled by the distance parameter, which drives how far the patella is displaced between computational steps.

The model's core calculation method involves updating the patella's position using a transformation matrix that is computed at each simulation step. This matrix incorporates both rotation and translation to ensure the patella's movement is aligned with the femoral groove. The transformation is derived using Wahba's algorithm, a least-squares optimization technique that computes the optimal rotation and translation between two sets of points.

While the model is successful in simulating patellar motion based on curvature, it does not incorporate the biomechanical forces that govern real knee motion, such as the force exerted by the quadriceps muscle and transmitted through the patellar tendon. These forces are crucial for accurately simulating the dynamic interaction between the patella, femur, and surrounding tissues. Without this integration, the model is limited to a purely kinematic simulation that lacks the complex biomechanical behavior seen in real-world knee movements. The current project seeks to extend this model by incorporating these forces to create a more realistic and comprehensive simulation of patellofemoral motion.

4.2. New Model

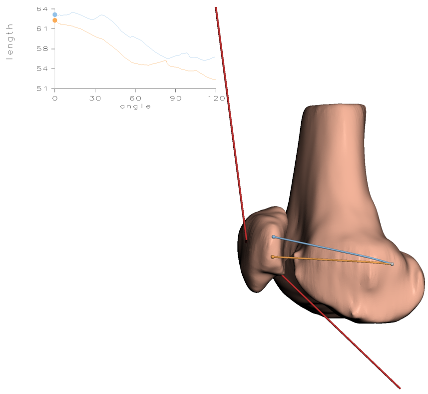


Figure 7. Screenshot of new model rendering after the addition of the femoral and patellar tendons.

To extend the capabilities of the original curvature-based simulation, this project entails a new physics-and-kinematics model to better represent the biomechanical forces acting on the patella during knee motion. This implementation introduces simplified tendon mechanics and cartilage interaction, improving anatomical realism while maintaining computational efficiency to produce a visually realistic simulation. Unlike the original model, which simulated patellar movement purely through geometric transformations, the updated version integrates external forces through spring-based tendon modeling and contact prevention forces, providing a more functional and responsive simulation environment for evaluating medial patellofemoral ligament reconstruction scenarios.

The primary addition is a tendon force model that simulates the effect of the quadriceps and patellar tendons. These are represented as idealized spring and damper systems, where the elastic component models tensile behavior according to Hooke's Law, and the damping component provides resistance based on relative velocity between endpoints. This formulation mirrors the tendon modeling approach used in the dynamic simulation study by Elias et al. [6], which successfully captured the influence of graft fixation error on patellar tracking by treating tendons as tension springs. In this project, spring constants, damping coefficients, and rest lengths are exposed as hyperparameters to allow for case-by-case customization and tuning.

These tendon forces are incorporated into a stepwise physics-and-kinematics simulation. At each simulation step, the resultant forces on the patella are calculated, including contributions from all tendons and soft tissue constraints, after which the patella is incrementally advanced in position and orientation. The simulation proceeds until the patellar velocity and acceleration converge to near-zero minimal values, indicating equilibrium. The final transformation matrices from this state are then used to update the patella's 3D position and alignment.

In addition to modeling active tissue forces, the new implementation refines how the patella interacts with the femur. The original model computed a cartilage separator using principal curvature values along the trochlear groove, but did not assign any physical force to this geometry. In the new model, this separator is repurposed as a contact surface that generates a repulsive force between the patella and femur. It is represented by a series of points, each paired with a normal vector derived from curvature-based calculations. When the patella nears this surface, a small corrective force is applied outward along the corresponding normal, simulating the mechanical effect of cartilage in preventing contact with the bone.

Given the project's scope, the patella's rotation is approximated about its centroid rather than using precise torque and inertia calculations. Although tendon endpoints are not necessarily perfectly located, the rotational matrix sufficiently represents movement for demonstration purposes. This simplified approach balances computational efficiency with model realism, making the simulation flexible enough for experimental tendon configurations while retaining anatomically plausible motion. The interface also features keyboard shortcuts and zoom capabilities to facilitate quick selection of tendon endpoints, further improving usability for interactive testing.

4.3. Implementation Details

The core functionality of the updated simulation is implemented with C++ and OpenGL, enabling both computational modeling and real-time visual feedback. The program simulates patellar motion during knee flexion using a physics-informed system of spring-damper forces that approximate the behavior of key anatomical structures, such as the quadriceps tendon, patellar tendon, and soft tissue constraints. These forces are integrated into a simplified biomechanical simulation, driving the translation and rotation of the patella within a 3D scene.

The primary technical implementation is distributed across two custom C++ classes: `Spring` and `PatellaSimulation`. These classes form the computational and visual backbone of the simulation. `PatellaSimulation` is responsible for computing and aggregating all external forces acting on the patella, including elastic tendon tension, velocity-based damping, and cartilage repulsion from the femoral groove. It is designed to be modular, supporting multiple tendons and customizable physical parameters such as spring stiffness and damping coefficients. `Spring` encapsulates each tendon's state at any point of movement. This class stores the tendon's individual velocity and force which is then applied onto the 3D patella object.

Both classes operate within the simulation loop where forces are recalculated at each timestep, and the patella is iteratively repositioned until reaching equilibrium; defined as a state of minimal acceleration and negligible movement. This loop mimics the dynamic settling process observed in physical systems under soft tissue tension. The result is a responsive and anatomically plausible animation that reflects how the patella would behave during knee motion.

The `Spring` class captures the behavior of soft tissue structures such as tendons and ligaments by modeling them as damped linear springs. Each instance represents a single anatomical connection (e.g., quadriceps tendon or patellar tendon) with defined attachment points on the patella (in the patella's local coordinate system for stability during simulations) and the surrounding muscular area. It is responsible for calculating elastic and damping forces according to Hooke's law and velocity damping, and for applying these forces to influence patellar motion. The `update()` method is the core of the class, called each simulation frame to compute the current spring force based on displacement and damping, and to scale the force based on anatomical weighting.

```
Class Spring:
    Initialize with:
        - stiffness (k), damping, anchor points (patella,
  ↪  tendon), and weight
        - compute initial rest length

    Method: calculateRestLength()
        return Euclidean distance between patella and
  ↪ tendon anchor points

    Method: setAnchorPoints()
        update positions of patella and tendon
        recalculate rest length

    Method: update(deltaTime, updatedLength)
        displacement = updatedLength - restLength
        springVelocity = (updatedLength - previousLength
  ↪ ) / deltaTime
        clamp springVelocity to max range
        direction = normalized vector from tendon to
  ↪ patella

        springForce = -k * displacement * direction
        dampingForce = -damping * springVelocity *
  ↪ direction
        totalForce = (springForce + dampingForce) *
  ↪ weight

        store totalForce and update previousLength

    Method: drawSpring()
        visualize the spring as a cylinder in OpenGL
```

Code 1. Pseudo code of the Spring class

The `PatellaSimulation` class is central to the simulation of patellar motion, responsible for computing the forces acting on the patella and driving its movement within the 3D environment. It operates by calculating the combined forces from various sources, including tendon tension modeled by instances of the `Spring` class, repulsion from skeletal points, and damping effects. At each timestep, `PatellaSimulation` aggregates forces from all the springs, and iteratively updates the patella's velocity, acceleration, and position until equilibrium is reached. This is achieved by incrementally applying the calculated forces in a stepwise manner, ensuring that the patella's motion mimics realistic physical behavior, including both translational and rotational transformations. The modular design allows the simulation to incorporate multiple springs, making it adaptable to various configurations and physical parameters.

```
Class PatellaSimulation:
    Initialize with:
        - patellaObj (3D patella object), mass,
  ↪ currentPosition, velocity, acceleration, and
  ↪ totalForce

    Method: simulate(separatorPoints, separatorNormals,
  ↪ correctionAmount, rotationAxis):
        Initialize:
            - minVelocity (threshold for velocity)
            - minAcceleration (threshold for
  ↪ acceleration)
            - timestep (incremental time step)

        while velocity > minVelocity or acceleration >
  ↪ minAcceleration:
            step(timestep, separatorPoints,
  ↪ separatorNormals, correctionAmount)

    Method: step(timeStep, separatorPoints,
  ↪ separatorNormals, correctionAmount):
        Clear totalForce & totalTorque

        for each spring:
            springForce = calculateSpringForce(spring,
  ↪ timeStep)
            totalForce = totalForce + springForce

            r = tendonPoint - patellaSurfacePoint
            springTorque = r cross springForce
            totalTorque = totalTorque + springTorque

        skeletalForce = getSkeletalForce(separatorPoints,
  ↪  separatorNormals, correctionAmount)
        totalForce = totalForce + skeletalForce

        acceleration = totalForce / mass
        velocity = velocity + (acceleration * timeStep)
        currentPosition = currentPosition + (velocity *
  ↪ timeStep)

        Update rotationAxis based on torque

    Method: getSkeletalForce(separatorPoints,
  ↪ separatorNormals, correctionAmount):
        Initialize totalForce to zero

        for each separator point and normal:
            Calculate repulsion force if point is within
```

```
        range
            Scale and add the force to totalForce

    Method: getNewPosition():
        Calculate updated transformation matrix based on current position and rotation
        Return the new matrix including rotation and translation
```

Code 2. Pseudo code of the PatellaSimulation class

5. Results

The enhanced knee simulation successfully integrates the biomechanical effects of tendon and cartilage forces to generate a more anatomically realistic rendering of patellar motion during knee flexion. Following the incorporation of spring-damper models to represent the quadriceps and patellar tendons, the patella's movement now responds to calculated translational and rotational forces. These forces are updated iteratively throughout the simulation loop until a stable equilibrium is reached, defined by minimal patellar acceleration and velocity.

Figures 9 and 10 illustrate the patellar placement before and after the simulation is run, demonstrating the improvement in anatomical realism achieved by the updated model. Before the simulation is executed, the patella resides in a neutral, geometrically aligned position within the femoral groove. After the simulation progresses through force iterations, the patella is displaced to a new position that more accurately reflects the combined influence of muscular tension and soft tissue resistance.

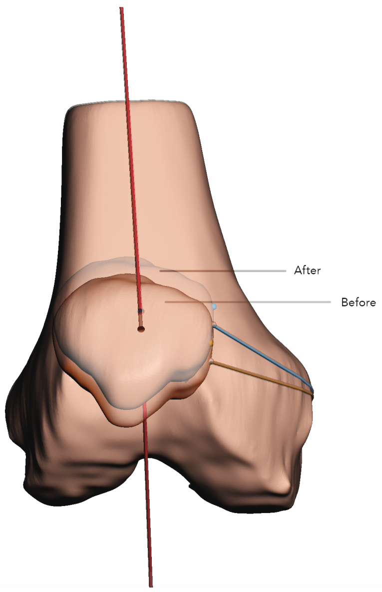


Figure 8. Overlay of patella placement before and after one simulation step

Furthermore, the cartilage repulsion mechanism introduced in the new model effectively prevents unrealistic overlap between the patella and femoral condyle. The separator, previously a static curvature-based guide, now exerts a repulsive force proportional to patella proximity. This force not only preserves anatomical boundaries but also contributes to maintaining proper patellar alignment within the trochlear groove.

Overall, the simulation advances the realism of the knee model by enabling responsive, physics-informed patellar behavior. The successful integration of soft tissue forces represents a significant improvement over the original curvature-only model and demonstrates the potential of this tool for preoperative evaluation and optimization of MPFL reconstruction parameters.

```
Patella Obj to World Transform: 0.967339 -0.16016 0.196471 -127.382
0.119368 0.971601 0.20432 -7.10854
-0.223615 -0.174195 0.958983 -0.325717
0 0 0 1

Patella Before: -127.382 -7.10854 -0.325717
Patella After: -127.339 -7.18289 -0.186295
Rotation Angle: 2.18812e-11
Rotation Axis: -0.689001 -0.240253 -0.683781
Distance Moved: 0.163882

Patella Obj to World Transform: 0.969324 -0.151437 0.193583 -127.207
0.114506 0.975181 0.189508 -7.33265
-0.217476 -0.161528 0.962605 0.626619
0 0 0 1
```

Code 3. Output of one simulation step

6. Next Steps

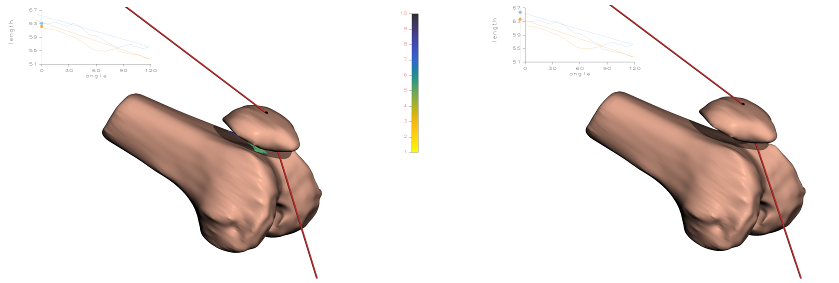
Future work on this project could focus on refining both the internal parameters of the simulation model and its external validation to enhance the accuracy and clinical applicability of the tool. One critical area for further development is the fine-tuning of the spring and damper system hyperparameters. Specifically, the stiffness coefficients, damping ratios, and rest lengths of the tendons. These parameters govern the behavior of the patellar and quadriceps tendons in the simulation, and their calibration is vital to replicating realistic patellofemoral mechanics. Accurate tuning of these variables is crucial, as even small discrepancies can lead to significant differences in the simulated forces acting on the patella. Employing optimization techniques or using patient-specific data could be explored as methods to refine these hyperparameters. The use of patient-specific data may involve leveraging imaging data, such as MRIs or CT scans, to inform tendon parameters tailored to the anatomical characteristics of individual patients. This would allow the model to more closely align with in vivo tendon behavior and provide a more accurate representation of patellofemoral kinematics, ultimately improving its predictive power.

Another important next step in advancing the model is the empirical validation of its outputs against cadaveric data. This validation process could involve measuring the position and rotation of the patella during controlled flexion-extension cycles on cadaveric knee specimens. Techniques such as motion capture or fluoroscopy could be used to capture detailed movement data of the patella during these cycles. By comparing these experimental results to the simulation's outputs under similar boundary conditions, the model's anatomical and biomechanical accuracy can be assessed. Discrepancies between the modeled and observed behaviors would offer valuable insight into areas of the model that require adjustment, ensuring that the simulation is grounded in real-world data.

7. Conclusion

This project presented an enhanced computational model for simulating patellar motion during medial patellofemoral ligament (MPFL) reconstruction, addressing limitations in a prior model that relied solely on geometric transformations. The goal was to better approximate the biomechanical environment of the patellofemoral joint by incorporating soft tissue forces that play a critical role in patellar tracking. Through the integration of a spring-damper system to represent the quadriceps and patellar tendons, and the introduction of a cartilage-based repulsive force, the simulation evolved into a physics-informed framework capable of more accurately modeling knee joint mechanics during flexion.

The research began by establishing the anatomical and clinical motivations for improving MPFL reconstruction planning. Given the



(a) Before **(b)** After

Figure 9. Positioning of the patella before and after effect of muscular and skeletal forces. Separator can be seen between the two bones.

(a) Before **(b)** After

Figure 10. Positioning of the patella before and after effect of muscular and skeletal forces from a top down view.

sensitivity of graft placement and the biomechanical variability across patients, traditional landmark-based surgical techniques can lead to suboptimal outcomes. Prior computational studies demonstrated the value of modeling soft tissue dynamics and joint contact mechanics for evaluating surgical configurations, guiding the direction of this project's simulation approach.

Building upon an existing curvature-based simulation, the new model incorporated tendon forces using idealized spring and damping elements. These were applied incrementally during the simulation, allowing the patella to settle into an anatomically plausible position of equilibrium under the influence of muscle and ligament tension. Additionally, a contact response mechanism was implemented using curvature-derived normals to simulate cartilage repulsion and prevent unrealistic interpenetration of the patella and femur.

Technically, the model was implemented in C++ and structured through modular classes (`Spring`, `PatellaSimulation`) that manage the force calculations and 3D rendering. The resulting simulation updates the patella's position and orientation iteratively based on force feedback, producing realistic motion that reflects the mechanical interplay between bone, tendon, and cartilage.

The final deliverable is a visually and biomechanically responsive knee simulation that enables interactive testing of tendon placements and their effects on patellar alignment. With further refinement, particularly through the tuning of hyperparameters and incorporation of subject-specific anatomical data, this tool could serve as a powerful aid for surgeons aiming to restore stable and natural patellar motion through MPFL reconstruction.

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