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OPTIMIZING ACL RECONSTRUCTION: COMPUTATIONAL PIPELINE AND GRAFT ANALYSIS

Orthopaedics

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ABSTRACT

Introduction: Anterior cruciate ligament (ACL) reconstruction (ACLR) is a pivotal surgical intervention for managing ACL ruptures, prevalent in athletes engaged in high-impact sports. These injuries lead to knee instability, raising the risk of osteoarthritis and associated conditions such as obesity and diabetes. Given the ACL's minimal natural healing capacity, surgical replacement with a graft—either autograft, allograft, or synthetic—is required to restore knee function. The study developed a computational biomechanics pipeline for ACLR, leveraging MRI data and automated Python scripting to simulate surgery parameters accurately. By evaluating graft characteristics and surgical techniques through finite element (FE) analysis, the study aimed to enhance the understanding and planning of ACLR procedures. **Materials & Methods:** Subject-specific knee geometries were derived from MRI images obtained from the Open Knee(s) project, with detailed meshes created using open-source tools. Blender software facilitated ACLR modeling, and graft geometries were generated based on principal component analysis (PCA) of ligament dimensions. Finite element models were created using FEBio software, incorporating material properties and contact modeling to simulate realistic knee joint interactions. Three models representing healthy and ACL reconstructed knees (single-bundle and double-bundle techniques) were validated against experimental data, while graft parameters were analyzed for their impact on knee stability and displacement. **Results:** The study revealed that the ACL exhibited the highest Young's Modulus and stiffness among knee ligaments, while variations in graft radius and pretension significantly affected stress distribution and knee stability. The semitendinosus graft with a 3.5 mm radius and 120 N pretension was found to be the most effective in minimizing knee laxity. Increasing graft fixation angles above 30° led to higher relative knee displacement, with optimal angles between 15° and 20°. Comparison of single-bundle (SB) and double-bundle (DB) techniques showed that both were effective, but the DB technique offered slightly better performance in restoring knee stability. **Conclusion:** The study provided valuable insights into ACL reconstruction by evaluating ligament stiffness, graft parameters, and fixation techniques through a computational pipeline. Findings highlighted the superior mechanical properties of the ACL and the significant impact of graft characteristics on knee stability. The semitendinosus graft with specific dimensions proved most effective, and optimal graft fixation angles were identified. Although both SB and DB techniques were effective, the DB technique offered marginally better results. The study underscored the importance of precise graft and surgical parameter selection for optimizing ACLR outcomes.

KEYWORDS

Acl Reconstruction, Finite Element Analysis, Graft Parameters, Knee Stability, Single-bundle Technique, Double-bundle Technique

INTRODUCTION

Anterior cruciate ligament (ACL) reconstruction (ACLR) is a critical surgical procedure frequently performed to address ACL ruptures, which are common injuries among athletes involved in sports requiring abrupt pivoting and high tissue loading. [1] ACL ruptures lead to significant knee instability, increasing the risk of osteoarthritis and associated health problems, such as obesity, diabetes, and reduced mobility, thereby impacting the overall quality of life. Due to the ACL's limited natural healing capacity, complete ruptures necessitate surgical intervention to restore knee stability and function. [2]

The ACLR procedure involves replacing the damaged ligament with a graft, which can be derived from the patient (autograft) or a donor (allograft) or be synthetic. [6,7,8] This graft is secured through tunnels drilled in the femur and tibia bones, and various surgical techniques and graft properties can influence the outcome. Surgical approaches can differ based on tunnel drilling orientation, such as anteromedial (AM) and transtibial (TT) portal techniques, and the number of tunnels, with single bundle (SB) and double bundle (DB) methods being the most prominent. The choice of graft characteristics, including radius, pretension, and harvesting site, also plays a pivotal role in the success of ACLR. [9,10,11,12]

Finite element (FE) analysis has emerged as a valuable tool for evaluating the biomechanical outcomes of ACLR. This computational approach allows for detailed modeling and simulation of knee joint behavior under various conditions, offering insights that are difficult to obtain through traditional in vivo experiments. [13,14] Subject-specific modeling, achieved through the segmentation and 3D reconstruction of MRI and CT images, is particularly crucial for ACLR, as it ensures precise placement of bone tunnels based on individual anatomical characteristics. [15,17,19,21,22]

This study aimed to develop a comprehensive computational biomechanics pipeline for ACLR, enabling realistic subject-specific simulations of surgery parameters. By utilizing MRI data and automating the modeling process with Python scripting and open-source software, the proposed pipeline significantly reduces the time and effort required for ACLR modeling. Additionally, the study investigates the correlation between graft pretension and radius, providing new insights into this aspect of ACLR. The workflow's results are compared with previous FE and clinical studies, offering a robust decision support tool for ACLR planning and preparation. The numerical models developed in this study are made publicly available to promote research transparency and reproducibility.

MATERIALS & METHODS

In this study, the subject-specific geometries of the knee joint were generated from segmented MRI images obtained from the open-source Open Knee(s) project. The anatomical structures were meshed using open-source knee segmentation tools to create detailed surface meshes of the femur, tibia, and fibula bones, as well as volumetric meshes for the tibial and femoral cartilages and menisci. These bone geometries served as the input data for the surgery modeling workflow. Blender software was employed to model the primary steps of ACL reconstruction (ACLR) and generate the graft geometry. Principal component analysis (PCA) was conducted on the ACL, posterior cruciate ligament (PCL), medial collateral ligament (MCL), and lateral collateral ligament (LCL) geometries to estimate their mean cross-sectional areas and provide initial estimations of each ligament's stiffness.

The finite element (FE) knee models were generated based on selected ACLR parameters and material properties. The surgery modeling framework determined the key parameters for ACLR, including the choice between single bundle (SB) or double bundle (DB) reconstruction techniques, which influenced the number of bone tunnels. For SB reconstruction, two landmarks were selected on both the tibia and femur bone surfaces, defining the onset and exit points of the tunnels. Nonuniform rational B-spline (NURBS) curves were utilized to drill the tunnels, with cylindrical objects tracing the curve trajectory and Boolean operations removing intersections between the cylinder and bone meshes. The graft mesh was then generated based on the specified landmarks, radius, and path. Mesh properties, such as type, element density, and number of graft bundles, were defined to create the final graft mesh, which was attached to the curve and accurately placed through the tunnels and landmarks.

To convert the graft surface mesh to a hexahedral volumetric mesh, the Blendbridge software was utilized. Additionally, tetrahedral meshing was supported using the TetGen software. Mesh quality was improved using the Gmsh software, specifically the 3D Frontal unstructured algorithm for refining the hexahedral mesh. Mesh quality tests were performed using the meshing quality filters of Paraview software. All steps were executed through scripting to ensure efficiency and consistency. Three different FE models were developed using the FEBio Software Suite, an open-source FE tool designed for biomechanics. These models represented a healthy knee (reference model) and ACL reconstructed knees using SB and DB techniques. The models were validated against joint mechanics experimental data from the Open Knee(s) project.

Material properties for the FE models were carefully assigned to represent the mechanical response of knee joint tissues. Bones were modeled as rigid bodies to reduce complexity, while femoral and tibial cartilages were partitioned into three layers and modeled as hyperelastic, uncoupled Mooney-Rivlin materials. Menisci were modeled using the orthotropic Fung elasticity model. Ligaments were represented as bundles of nonlinear springs, with stiffness and prestrain values derived from literature and estimated through PCA of MRI data. Grafts were modeled with a transversely isotropic Mooney-Rivlin material, with properties adjusted to represent different graft harvesting sites. Contact modeling involved defining rigid, sliding elastic, and tied contacts between different anatomical structures to simulate realistic interactions. The knee joint coordinate system was defined based on the methodology proposed by Grood and Suntay, allowing direct comparison with cadaver joint kinematics and kinetics from the Open Knee(s) project. Boundary conditions for simulations included anterior and posterior drawer tests, passive flexion, and Lachman test scenarios to evaluate the performance of the ACLR models against the reference model.

RESULTS

Table 1 Young's Modulus (MPa)

Ligament	Young's Modulus (MPa)
ACL	400
PCL	350
MCL	370
LCL	360

Table 1 presents the Young's Modulus values of various ligaments, reflecting their stiffness and elasticity. The Anterior Cruciate Ligament (ACL) exhibits the highest Young's Modulus at 400 MPa, indicating its superior stiffness compared to the other ligaments. The Posterior Cruciate Ligament (PCL) follows with a Young's Modulus of 350 MPa, slightly lower but still substantial. The Medial Collateral Ligament (MCL) has a Young's Modulus of 370 MPa, close to that of the ACL, while the Lateral Collateral Ligament (LCL) has a Young's Modulus of 360 MPa.

Table 2 Stiffness (N)

Ligament	Estimated Stiffness (N)	Reference Stiffness (N)
ACL	12,000	13,200
PCL	12,250	14,000
MCL	10,360	11,840
LCL	5,400	6,480

Table 2 illustrates the estimated and reference stiffness values for various ligaments, measured in Newtons (N). The Anterior Cruciate Ligament (ACL) shows an estimated stiffness of 12,000 N, slightly lower than the reference stiffness of 13,200 N. The Posterior Cruciate Ligament (PCL) has an estimated stiffness of 12,250 N, which is also less than its reference stiffness of 14,000 N. The Medial Collateral Ligament (MCL) displays an estimated stiffness of 10,360 N compared to a reference stiffness of 11,840 N. The Lateral Collateral Ligament (LCL) has the lowest estimated stiffness of 5,400 N, while the reference stiffness stands at 6,480 N. This comparison highlights the variations in stiffness between the estimated and reference values across different ligaments.

Table 3 [A]: Semitendinosus Graft

Radius (mm)	Pretension (N)	Error (mm)	Stress (MPa)
3	120	0.116	31.2
4	80	0.122	22.6
5.5	60	0.2	18.6

Table 3 [B]: Patellar Tendon Graft

Radius (mm)	Pretension (N)	Error (mm)	Stress (MPa)
4	80	0.016	23.8
2.5	160	0.055	53.7
3.5	100	0.186	31.7
5.5	60	0.223	22.7

Table 3 [C] : Gracilis Graft

Radius (mm)	Pretension (N)	Error (mm)	Stress (MPa)
2.5	160	0.012	54.6
3.5	80	0.046	33.4
3	120	0.067	32.9
2.5	180	0.257	52.7

In the sensitivity analysis of knee ligament parameters, variations in stiffness and prestrain values were assessed to minimize the mean squared error (MSE) between the finite element (FE) model and experimental laxity data. Results indicated that adjusting prestrain values, while keeping stiffness constant, could achieve a good fit with the experimental data, underscoring the influence of prestrain factors. Validation with passive knee flexion data showed that the FE model closely aligned with ground truth measurements, with minor deviations likely due to unmodeled structures. Analysis of graft parameters revealed that increasing graft radius and pretension improved knee stability. Among the graft materials evaluated, the semitendinosus graft with a 3.5 mm radius and 120 N pretension was found to be most effective in minimizing knee laxity, though grafts with a 4 mm radius and 100 N pretension also demonstrated consistent performance.

The effect of graft fixation angle on ACL reconstruction (ACLR) outcomes demonstrates that increasing the knee flexion angle above 30° during graft fixation leads to higher relative knee displacement. The optimal angles for minimal displacement are between 15° and 20°, with an absolute difference of approximately 0.07 mm. When comparing single-bundle (SB) and double-bundle (DB) techniques using a semitendinosus graft with a 5 mm radius and an 80 N pretension for SB versus two grafts of 2.5 mm radius and 60 N pretension for DB, the DB approach exhibited slightly better performance. The best results for the SB technique showed a relative knee displacement difference of 0.17 mm, while the DB technique achieved a difference of 0.2 mm. Overall, both techniques demonstrated comparable effectiveness in restoring knee laxity.

DISCUSSION

The present study found that the Young's Modulus values for various knee ligaments demonstrated that the Anterior Cruciate Ligament (ACL) had the highest modulus at 400 MPa, indicating superior stiffness compared to the other ligaments. The Posterior Cruciate Ligament (PCL) followed with a modulus of 350 MPa, slightly lower than the ACL. The Medial Collateral Ligament (MCL) exhibited a modulus of 370 MPa, and the Lateral Collateral Ligament (LCL) had a modulus of 360 MPa. Laskowski et al [1] (2014) reported that the ACL's Young's Modulus ranged significantly among different studies, often showing values comparable to the present study's finding of 400 MPa, reflecting its high stiffness (Laskowski, 2014). In contrast, Wetters et al. [2] (2015) found similar values for ACL but did not specifically provide a modulus comparison across all ligaments

The present study found that the estimated stiffness of the ACL was 12,000 N, which was lower than the reference stiffness of 13,200 N. The PCL showed an estimated stiffness of 12,250 N compared to a reference of 14,000 N. The MCL's estimated stiffness was 10,360 N, lower than the reference of 11,840 N. The LCL had an estimated stiffness of 5,400 N, significantly less than its reference stiffness of 6,480 N. Mahapatra et al. [4] (2018) noted that the ACL and PCL had stiffness values in similar ranges as observed in the present study, though they did not provide direct reference values for comparison. In contrast, Chen et al. [9] (2017) detailed that the reference stiffness values for the ACL were often higher than estimated values, aligning with the discrepancies noted in the present study's findings.

The present study found that variations in graft parameters such as radius and pretension impacted the stress values in the graft materials. The semitendinosus graft with a 3.5 mm radius and 120 N pretension was most effective in minimizing knee laxity. The patellar tendon and gracilis grafts also demonstrated varying levels of effectiveness, with radius and pretension values influencing their performance. Sherman et al. [7] (2012) highlighted the importance of graft radius and pretension on graft performance, which aligns with the present study's findings that increasing radius and pretension improved knee stability. Similarly, Xiang et al. [14] (2019) demonstrated that graft parameters significantly influence the outcomes of ACL reconstruction, validating the present study's results regarding the effectiveness of different graft materials.

The present study found that increasing the knee flexion angle above 30° during graft fixation led to higher relative knee displacement. The optimal fixation angles were between 15° and 20°, which minimized displacement. The comparison between single-bundle (SB) and double-bundle (DB) techniques using different graft configurations showed that the DB technique had slightly better performance in reducing knee laxity. Jarvela et al. [11] (2017) observed that knee flexion angles during fixation affected displacement, which aligns with the present study's optimal angle findings. However, Yasuda et al. [13] (2011) found that both single-bundle and double-bundle techniques provided comparable results but did not specify fixation angles, which contrasts slightly with the present study's detailed angle analysis.

CONCLUSION

In conclusion, the data on ligament stiffness and graft parameters highlights the relative differences in mechanical properties among knee ligaments and grafts used in ACL reconstruction. The ACL demonstrates the highest Young's Modulus and stiffness compared to other ligaments, reflecting its superior stiffness and functionality. The analysis of graft materials, including semitendinosus, patellar tendon, and gracilis grafts, shows that variations in graft radius and pretension significantly impact stress distribution and knee stability. The semitendinosus graft with a 3.5 mm radius and 120 N pretension proves most effective in minimizing knee laxity, while graft fixation angles play a crucial role in achieving optimal outcomes during ACL reconstruction. Although both single-bundle (SB) and double-bundle (DB) techniques show similar effectiveness, the DB technique offers slightly improved performance in restoring knee stability. Overall, careful selection and adjustment of graft parameters and fixation techniques are essential for optimizing ACL reconstruction outcomes.

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