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THE RISK OF PATELLAR FRACTURE IN DIFFERENT MEDIAL PATELLOFEMORAL LIGAMENT TUNNEL TECHNIQUES: A FINITE ELEMENT ANALYSIS

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ABSTRACT

Objective: *Patellar fracture is a known complication of medial patellofemoral ligament (MPFL) reconstruction surgery. This study aims to evaluate the biomechanical impact of various patellar tunnel techniques in MPFL reconstruction with regard to risk of patellar fracture.*

Material and Method: *In this study, knee computed tomography (CT) images of 10 patients (5 males and 5 females, aged 18-50) were used. Exclusion criteria included patellar or trochlear dysplasia, previous patellar fracture, or knee surgery. Three-dimensional models of each patella were created from the CT images using Mechanical Finder 11 (RCCM Inc., Tokyo, Japan). Tunnels were then modeled to reflect the patellar tunnel techniques described in the literature. The distal patellar pole was fixed while tensile force was applied to the proximal pole using finite element method. The loads causing fractures in the models were recorded.*

Result: *Significant differences in patellar surface-to-volume ratios and fracture load reductions were observed among the models. The double transverse bicortical and double transverse unicortical tunnel techniques showed a statistically significant decrease in fracture load compared to the unmodified patella, indicating a higher risk of fracture. No significant differences were observed with the single transverse and single oblique tunnel techniques. The analysis suggests that the double tunnel techniques, particularly the unicortical variant, significantly weaken the patella's structural integrity, increasing the risk of fracture.*

Conclusion: *Quantitative CT-based finite element analysis revealed that single transverse and single oblique tunnel techniques do not significantly compromise patellar strength. In contrast, the double transverse bicortical and double transverse unicortical techniques pose a significantly higher risk of patellar fractures. It was shown that the double transverse unicortical tunnels, despite not causing more bone loss than the single bicortical tunnels, have a weakening effect similar to that of the double transverse bicortical tunnels. These findings suggest avoiding the double transverse tunnel technique to minimize the risk of patellar fractures.*

Keywords: *Biomechanics, finite element analysis, medial patellofemoral ligament reconstruction, patellar tunnel.*

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MEDİAL PATELLOFEMORAL LİGAMENT REKONSTRÜKSİYONU İÇİN FARKLI TÜNEL TEKNİKLERİNDE PATELLA KIRIĞI RİSKİ: SONLU ELEMAN ANALİZİ

ÖZET

Amaç: Patella kırığı, medial patellofemoral ligament (MPFL) rekonstrüksiyon cerrahisi sonrasında karşılaşılabilen bir komplikasyondur. Bu çalışma, MPFL rekonstrüksiyonunda çeşitli patellar tünel tekniklerinin biyomekanik etkisini, patellar kırık riski açısından değerlendirmeyi amaçlamaktadır.

Materyal ve Metod: Çalışmada 10 hastanın (5 erkek, 5 kadın, yaş aralığı 18-50) diz bilgisayarlı tomografi (BT) görüntüleri kullanılmıştır. Dışlama kriterleri patellar veya troklear displazi, geçirilmiş patella kırığı veya cerrahi olarak belirlenmiştir. Mechanical Finder 11 (RCCM Inc., Tokyo, Japan) kullanılarak her hastanın BT görüntülerinden üç boyutlu patella modelleri oluşturuldu. Literatürde tanımlanmış patellar tünel tekniklerini yansıtacak şekilde modeller üzerinde tüneller açıldı. Distal polden fikse edilen patella modellerine proksimal polden çekim kuvveti sonlu eleman analizi yöntemi ile uygulandı. Modellerde kırık oluşturan yük miktarları kaydedildi.

Bulgular: Modeller arasında yüzey-hacim oranları ve kırılma yükünde azalma konusunda önemli farklar bulundu. Çift transvers bikortikal ve çift transvers unikortikal tünel tekniklerinde, kırılma yükünde istatistiksel olarak anlamlı bir azalma olduğu görüldü. Tek transvers ve tek oblik tünel tekniklerinde önemli farklar gözlenmedi. Çift tünel tekniklerinde, özellikle çift transvers unikortikal teknikte, patellanın tensil kuvvetlere direncinin istatistiksel olarak azaldığı ve kırık riskinin arttığı görülmüştür.

Sonuç: Kantitatif bilgisayarlı tomografi tabanlı sonlu eleman analizi, tek transvers ve tek oblik tünel tekniklerinin patellar gücünü önemli ölçüde tehlikeye atmadığını gösterirken, çift transvers bikortikal ve çift transvers unikortikal tekniklerin patellayı anlamlı ölçüde zayıflattığını ortaya koymuştur. Çift transvers unikortikal teknikte, tek bikortikal tünellere göre daha fazla kemik kaybı olmamasına rağmen, tekniğin zayıflatıcı etkisinin çift transvers bikortikal tünele benzer olduğu gösterilmiştir. Bu bulgular, patellar kırık riskini en aza indirmek için çift transvers tünel tekniklerinden kaçınılması gerektiğini önermektedir.

Anahtar kelimeler: Biyomekanik, sonlu eleman analizi, medial patellofemoral ligaman rekonstrüksiyonu, patellar tünel.

INTRODUCTION

Lateral patellar dislocation is a common injury that typically occurs in the first two decades of life.[1] Recurrent dislocation of the patella that does not respond to conservative measures is usually treated with surgery. Techniques for restoring stability include tibial tubercle transfer, trochlea plasty, lateral retinacular release, and medial patellofemoral ligament reconstruction.[2-4]

The medial patellofemoral ligament (MPFL) is the primary soft-tissue restraint to lateral translation of the patella during the initial 20-30 degrees of flexion.[5] It is torn in up to 100% of these injuries.[6-8] There are various surgical techniques for reconstructing the MPFL. These techniques differ in graft types, number and placement of tunnels, bundles, as well as patellar and femoral fixation methods.[9-11]

Patellar fixation methods mainly include single or double tunnels – with or without screws, and suture anchors.[12] A well-known complication of patellar fixation techniques is patellar fracture.[13] These fractures have been reported to occur more than 2 months after the operation date, often with low-energy trauma. Despite being a major complication, clinical and experimental data on how to avoid patellar fractures are still limited.

Finite element analysis (FEA) is a computational technique employed to simulate how structures behave when subjected to various forces. This method simplifies a complicated issue by dividing it into smaller, more manageable elements, known as nodes, which together form a mesh that replicates the physical outline of the object or region being examined.[14] CT-based FEA (CT-FEA) converts Hounsfield unit values from CT scans it into Young's modulus values using different formulas, such as Keyak's conversion formula to accurately model the properties of the bone.[15] CT-FEA has been used extensively in the literature to study fractures.[16-18]

This study aims to investigate the effects of four different techniques (single transverse, single oblique, double transverse bicortical, and double transverse unicortical) on the weakening of patella to tensile forces, and to provide practicing surgeons with QCT-based finite element analysis insights for choosing the safest technique.

MATERIAL AND METHOD

Institutional Review Board approval was obtained prior to commencing the study. Patients who had knee CT scans previously for reasons unrelated to the study were included. Patients with patellar or trochlear dysplasia, a history of patellar fracture or surgery, or lesions that could affect the bone strength of the patella were excluded. Ultimately, CT scans of 10 patients between 18-50 years of age (5 males, 5 females) were included.

Mechanical Finder version 11.0 (Research Center for Computational Mechanics, Tokyo, Japan) was used to segment the CT scans and create the meshes. Mesh convergence test suggested 1.0 mm meshes to be an optimal value for this study (Figure 1). The outer surface of the mesh consisted of triangular elements, whereas the inside consisted of tetrahedral elements. A shell with a thickness of 0.3 mm was added on the surface. Poisson's ratio for each element was set to 0.4. The ash density for each bone element was determined based on the mean ash density of the voxels contained within that element.[19] The Young's modulus and yield stress for each isotropic tetrahedral element were derived using the formulas suggested by Keyak *et al*.[20]

After creating the native (unmodified) patella models, four additional models were created for each patient, consisting of a single transverse tunnel, single oblique tunnel, double transverse bicortical tunnels, and double transverse unicortical tunnels (Figure 2). Each model had tunnels that were 4.5 mm wide. A total of 50 models were created. Loading and boundary conditions were set by fixing the model at the patellar tendon insertion and applying tensile force to the proximal pole, at the quadriceps tendon attachment site. Tensile forces were applied at 50N intervals, until more than one cracked elements were encountered.[21]

The Drucker-Prager equivalent criterion was adopted for the yield of the elements.[22] Statistical analysis was performed using SPSS for Windows (version 22; IBM SPSS Inc., Chicago IL). One-way ANOVA, Mann-Whitney U, and Tukey's HSD post hoc tests were used to compare the models with each other. A *p*-value of less than 0.05 was considered significant.

RESULTS

3D model node counts, surface areas, volumes, surface-to-volume ratios, and fracture loads are summarized in Table. Surface-to-volume ratios for each model are shown in (Figure 3). ANOVA revealed a statistically significant difference in surface-to-volume ratios among different model types ($p<0.05$). Pairwise comparisons using Tukey's HSD post hoc test revealed that the surface-to-volume ratios of the native patella were significantly lower than those of the other models ($p<0.001$), while the double transverse bicortical models' surface-to-volume ratios were significantly higher than those of the other models ($p<0.001$). In contrast, no statistically significant differences were found between the surface-to-volume ratios of single transverse, double transverse unicortical, and single oblique tunnel models ($p>0.05$). The average decrease in fracture load with different models was calculated for each patient, using native patella as the baseline (Figure 4).

Table. Summary of Average Measurements by Model Type

ID/Model	No. of nodes	Surface Area (mm^2)	Volume (mm^3)	Surface / Volume Ratio	Fracture Load (N)
Native	10331	3637	16227	0.228	2830
Single Transverse	10710	4052	15709	0.263	2800
Double Transverse Bicortical	10894	4458	15192	0.299	2700
Double Transverse Unicortical	10703	4060	15721	0.263	2660
Single Oblique	10713	4068	15702	0.264	2775

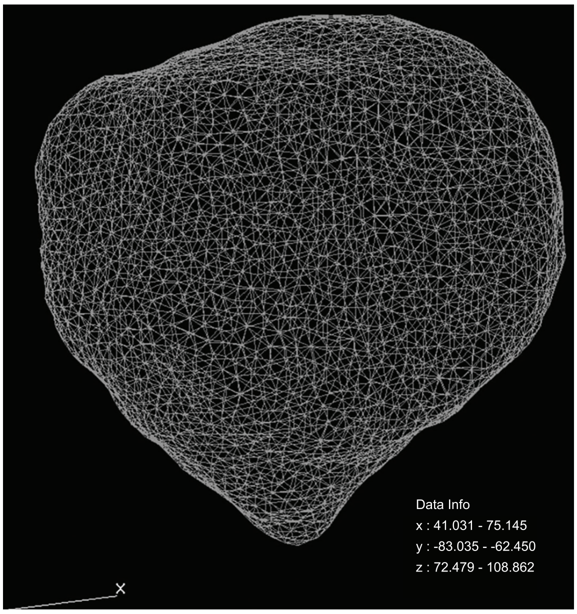

Figure 1. 1.0 mm mesh model of the native patella.

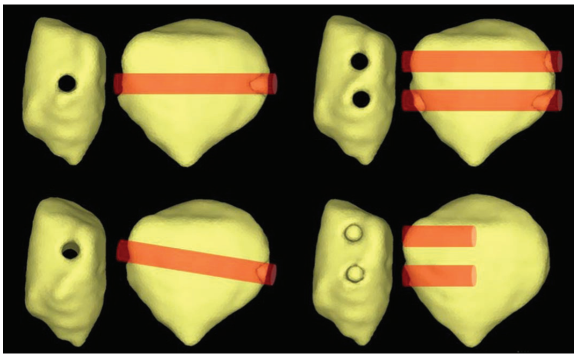

Figure 2. Patellar tunnel techniques are shown.

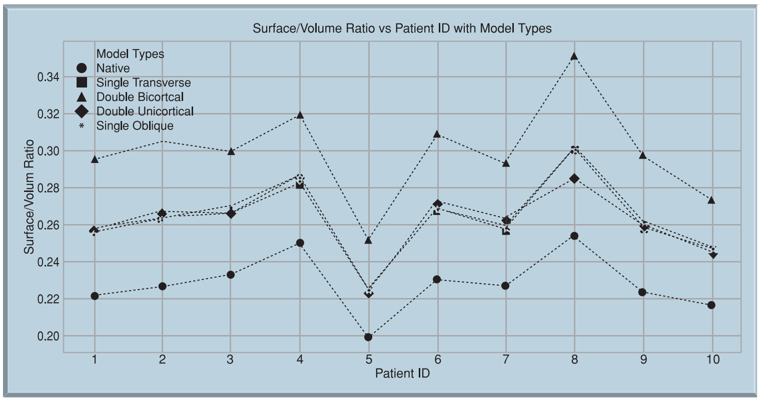

Figure 3. Surface-to-volume ratios of different models for each patients are shown.

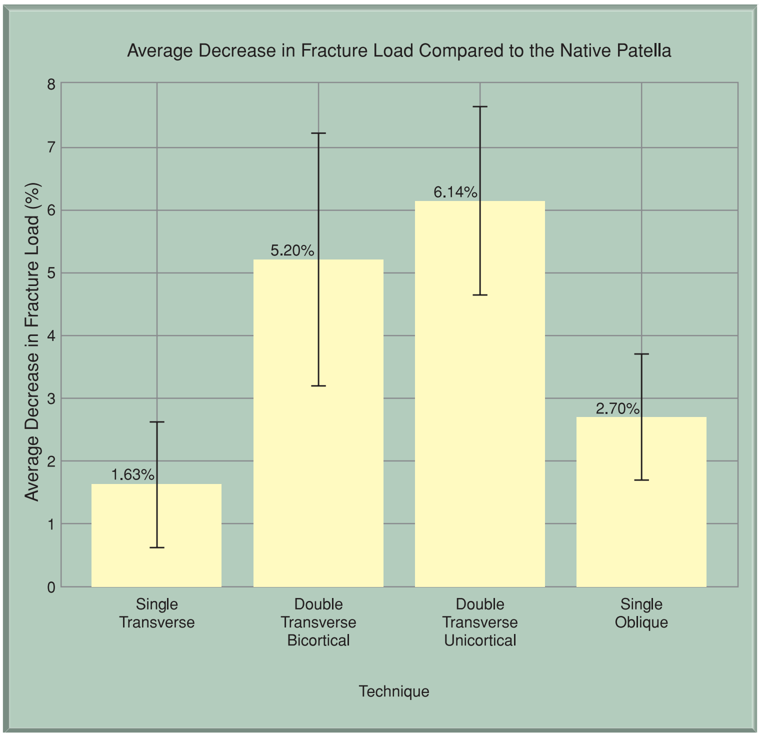

Figure 4. Average decrease in fracture load compared to the native patella is shown for each model.

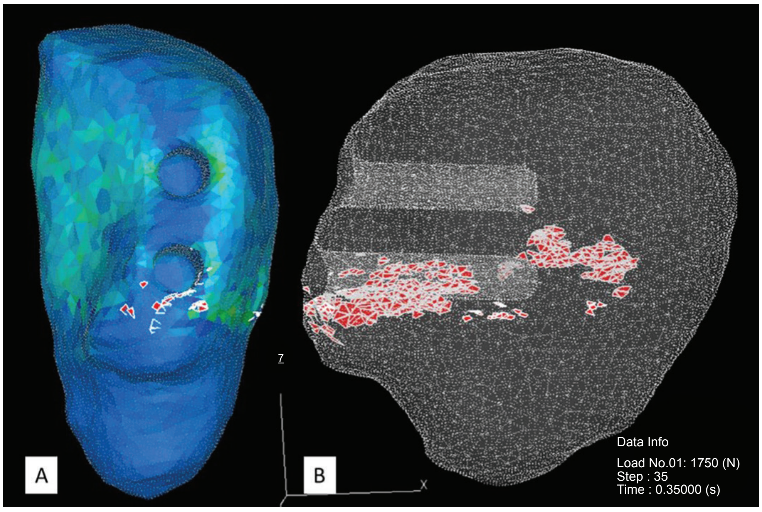

Figure 5. A. Surface yield stress of a double transverse unicortical model B. Crack propagation of the same model

Among the different MPFL tunnel techniques analyzed, the results indicate that the double transverse bicortical technique exhibits a statistically significant decrease in fracture load compared to the native patella, with an average reduction of approximately 5.20% (*p*=0.02), and the double transverse unicortical technique exhibits a statistically significant decrease in fracture load compared to the native patella, with an average reduction of approximately 6.14% (*p*=0.01). In contrast, no statistically significant differences were observed for the single transverse tunnel technique (*p*=0.37) and single oblique tunnel technique (*p*=0.12).

DISCUSSION

MPFL reconstruction can be done using different techniques. Patellar fixation of the graft may be achieved through the use of patellar tunnels in different configurations, suture anchors, or other methods not involving any bony procedure in patella.[23] Any bony procedure can cause weakness in the patella, which is subject to a wide range of tensile forces during daily activities, and as such, can increase the risk of a patellar fracture.[24] The optimal and safest tunnel configuration is contested in the literature, and the safety of the tunnel in terms of patellar fracture depends on the width, number, coronal and axial placement, and the method of fixation. Russo *et al*. studied unicortical tunnel models with different fixation techniques.[25] In their study, interference screw and suture anchor techniques failed due to either tendon slippage or pull-out, whereas two-tunnel and converging single tunnel techniques failed through fracture. Placella *et al*. compared single tunnel and converging tunnel techniques and concluded that while both methods achieve safe fixation, the single tunnel method in their study had 11% patellar fracture rate.[26] It is important to note that they used an 8x20 mm interference screw in the patella for this study.

A finite element analysis study by Wierer *et al*. in 2022 included a survey of surgeons performing MPFL reconstructions.[27] Participants were asked detailed questions that focused on the technical aspects of the surgery, such as the use and number of drill holes in the patella, the size and orientation of these drill holes, anterior or lateral perforations, and their specific locations on the patella (proximal, mid, or distal third). Regarding technique, 63% of the participants reported using drill holes in the patella, 24% never did, and 12% sometimes did. Most (87%) reported using two drill holes, with the majority (56%) of these holes being 4-5 mm in size. The proximal drill hole was typically located in the proximal third of the patella (89%), while the distal hole was most commonly in the mid third (59%). The orientation of these holes varies, with a majority favoring a horizontal orientation for both proximal (56%) and distal (67%) holes. 67% of respondents reported that they did not perforate the cortex other than at the medial entry point, while the rest did, either with a K-wire (11%) or a drill bit (22%).

In this study, the models closely mirror the current approaches in medial patellofemoral ligament (MPFL) reconstructions as indicated by presented survey data. While the majority of practitioners (87%) prefer using two drill holes, this study also incorporates the less common but clinically relevant single-hole techniques. This approach in our experimental design ensures that our findings are practically applicable and provide valuable insights into different surgical techniques currently in practice for MPFL reconstruction.

The most significant result of the study appears to be the weakness caused by the double transverse unicortical technique. Although the surface-to-volume ratio of this model is statistically similar to single transverse and single oblique models, indicating a similar bone loss in patella, it is as weakening as the double transverse bicortical tunnel technique. Figures 5A and 5B show the surface yield stress and crack propagation in a double transverse unicortical model, respectively. One explanation could be that although a similar amount of bone is removed in this technique as in a single bicortical tunnel, the concentration of holes on one side may create a significant biomechanical disadvantage. Although not specifically included in this study, this result can be possibly extended to converging holes technique, as it also creates two tunnels on the medial side. As such, our results discourage the use of both double transverse bicortical and double transverse unicortical tunnel techniques to avoid patellar fractures.

There are several key limitations to our study. First, we did not explore anterior breaching tunnel techniques, which can significantly impact biomechanical outcomes due to their distinct placement and trajectories. Additionally, our analysis did not consider the effects of varying loading angles, which might be significant, especially with anterior breaching techniques due to concentration of tensile forces in deep flexion, for instance. Another limitation is the exclusion of different drill sizes; varying drill diameters could offer a broader understanding of structural integrity and stress distribution. Lastly, our study did not investigate cyclic loading conditions, which are crucial for understanding the fatigue behavior of the structure under repetitive stress. These limitations suggest areas for future research to provide a more comprehensive understanding of the subject. Furthermore, patellar fracture is not the only determinant in choosing a tunnel or fixation technique. The size of the patient's patella, available instruments to the surgeon, previous experience, and the quality of the graft may all affect the technique chosen by the surgeon.

CONCLUSION

In conclusion, this study provides insights into the biomechanical implications of patellar tunnel configurations in MPFL reconstruction and their susceptibility to fracture under tensile forces. Our quantitative CT-based finite element analysis demonstrates that while single transverse and single oblique techniques do not significantly weaken the patella, both double transverse bicortical and double transverse unicortical techniques significantly increase the risk of patellar fractures. Notably, the double transverse unicortical technique, despite having no more bone loss compared to single bicortical tunnels, exhibits a weakening effect similar to that of the double transverse bicortical tunnel technique. This finding is particularly significant given the popularity of using two drill holes in MPFL reconstruction. Overall, our results aim to guide surgeons in selecting safer MPFL reconstruction techniques, thereby potentially reducing the risk of postoperative complications such as patellar fractures.

*The authors declare that there are no conflicts of interest.

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