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Original Research Article

Biomechanical effects of the tibial slope angle change on total knee prosthesis: 3D finite elements analysis

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ABSTRACT

Aim: In total knee arthroplasty, finding the correct tibial slope angle while placing the prosthesis affects the joint load. In our study; the load on the tibial insert and the notch of the insert as a result of flexion of the knee joint 0-30-60-90 degrees at each inclination in prostheses applied with posterior inclination angles of 0,3,5 and 7 degrees was examined in the three-dimensional right knee finite element structural model. In this way, it was aimed to reveal at which slope the resulting load is the lowest.

Materials and Methods: The finite element structural model was created using the 3D 2.5 number right knee solid model. Two types of analysis were performed to examine the effect of angle change of the PE Insert on tibia component; static structural analysis with static loads at certain fixed flexion angles, and transient analysis with time for varying loadings at dynamically changing flexion angles with rotation of the knee between 0-90 degrees.

Results: In the 0 and 30 degree models, the least load on the tibial insert was found at 7 degree tibial slop angle (11.6 and 9.87 mpa, respectively), in 60 and 90 degree models at 5 degree tibial slop angle (9.07 and 11.4 mpa respectively). In the models of 0 and 30 degrees, no pressure occured on the tibial insert notch at 3,5,7 degrees of tibial slop angles, while in the 60 degree model, a pressure of 0,153 MPa occured at all 0,3,5,7 degrees at 0 degrees tibial insert slop angle and this pressure was centered at the junction with the tibial insert.

Conclusion: The higher the load on the tibial insert, the greater wear of the tibial insert in the knee prosthesis. For this reason, it is important with which slop angle the tibial insert should be placed during surgery.

1. Introduction

The knee joint, considering the number of components, spatial geometry, mechanical and contact characteristics among all joints in the human body, has a very complex structure. It is also one of the largest joints in the body that carried a high amount of load.[1] Located between the distal of the femur and the proximal of the tibia, the knee joint consists of two articular surfaces, tibiofemoral and patellofemoral, and has 6 different movements: flexion-extension, external-internal rotation, varus-valgus, anterior-posterior translation, medial-lateral translation, and proximal-distal translation.[2] The load on this joint can go up to 3 times the body weight in activities such as walking and running, and up to 4 times in activities such as climbing stairs.[3] For this reason, the knee joint is very prone to injury and degeneration.

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Finite element (FE) modeling, which is widely used in biomechanical analysis of human bones and joints, can help determine the mechanical stress and changes that occur at the tissue level under different configurations and loads, and explain the relationship of these parameters with potential joint and cartilage pathologies.[4] With this method, local parameters such as internal stress, strain, and displacement, which are difficult to examine with experimental studies, can be predicted and measured. In addition, it is very advantageous in terms of cost, time, and availability.[5] The accuracy of the FE model is proportional to how precisely it can simulate the real structure and can depend on multiple variables such as the geometry of the joint surfaces, models, and properties of the material.

Total knee arthroplasty (TKA) has an important place in orthopedic surgery. The purpose of TKA is to improve the patients' long-term clinical well-being by restoring the tibiofemoral and patellofemoral joints in a stable and well-aligned manner. Many different types of knee prostheses are used in this surgery to restore joint function. Previous clinical studies have revealed that results perceived by patients are affected by the alignment of prosthetic components, and this is supported by kinematic data from different biomechanical studies.[6] Misalignment has been reported as the most common cause of revision TKA.[7] One of the measurements that need to be considered here is the tibial slope angle (TSA), which indicates the posterior slope of the tibial plateau in the sagittal plane. TSA balances the forward force that arises from the transmission of weight from the femur to the tibia. The TSA of the prosthesis used in TKA can significantly affect the flexion gap of the joint, the tension of the posterior cruciate ligament, the contact stress of the patellofemoral joint, the strength of the quadriceps muscle, and the stability of the joint.[8,9] In conventional TKA, it is not always possible to fix TSA correctly to its previous state due to the inadequacy of surgical tools and high rates of patient variability. Generally, the goal is to maintain certain angles based on the recommendation of the prosthesis manufacturers. In the literature, 3° and 7° are common options.[10]

In the presented study, an FE modeling of the knee prostheses with ligament preserving features was made with a TSA of 0-3-5-7 degrees and 0-30-60-90 degree flexion of the knee joint at each slope angle, and the load on the tibial insert and the insert notch were modeled. Our aim in this study is to identify how much load is placed on the region at certain flexion degrees in prosthesis models at different slope angles and to make a recommendation against the risk of future loosening and reoperation in the prosthesis if there is an excessive load on any of them.

2. Materials and Methods

Finite elements method (FEM) is a mathematics-based calculation technique used in solving complex analytical structural problems. In this way, a model similar to the real body is created with solid modeling programs such as solid works. This model is obtained from real CT scans using real computed tomography (CT) images. Modified solid models are produced with a problem-based solid modeling program, then transferred to a Finite Element Analysis software such as Ansys Workbench, a useful tool specifically for engineers to solve various engineering problems.[11]

In this study, a 3-dimensional (3D) 2.5 number right knee solid model obtained from Mikron Makine (Yenimahalle/Ankara/Turkey) was used (Real Figure). The finite elements structural model was created using this solid model. This 3D knee rigid model was combined with the femur and tibia rigid models of a patient through SpaceClaim Software to obtain models for analysis. In the knee model combined with the femur and tibia, the Femur component-Femur and Tibia component-Tibia junctions were assumed to be completely connected as it is in reality. Although the contact area and location between the femur component and PE Insert varies according to the flexion angle, it is considered to be frictional because it is continuous and dynamic, and the friction coefficient has been accepted as 0.04 as in previous studies.[12]

In this study, the following materials and properties were taken as a basis for the parts used in the model. Bone characteristics of femur and tibia are Elastic modulus (E) 16.8 GPa, Poisson's Ratio (u) 0.47. Cobalt-Chromium alloy material was used for the femur component, E = 195 GPa, u= 0.3, High density molecular weight polyethylene was used for PE Insert (ultra-high molecular-weight-polyethylene - UHMWPE) E = 685 MPa, u= 0.47, titanium alloy (Ti6Al4V) was used for the Tibia component, and E = 110 GPa, u= 0.3 was accepted.[12]

In order to examine the effect of the orientation (angle change) of the PE Insert of the Tibia component on the PE Insert, two types of analyses were carried out. The first is static structural analyzes with static loads at fixed flexion angles, the second is dynamically changing flexion angles with knee rotation starting from 0 to 90 degrees, and transient analysis for time-dependent loads at every angle. The fixed and variable loads used for these analyzes are those obtained in experiments with cadavers, which were taken from studies published in the literature, to identify and verify string loads under different conditions.[4] These loads are the quadricep actuator force that increases linearly with constant forces acting as 50 N in the vertical direction on the femur and 10 N on the hamstring and reaching 600 N at 90 degrees of flexion. The application directions and directions of the forces have been taken in accordance with the actual operating conditions.

In this study, the evaluation of the loads on the tibial insert applied on a knee prosthesis with a "ligament cutting" feature is modeled as follows.

The 0 degree model was named "model A 1" and the tibial slope angles of 3, 5, 7 degrees and the load distributions on the tibial insert at 0 degrees of flexion have been evaluated. The 30-degree model was named "Model B 1" and the tibial slope angles of 3, 5, 7 degrees and the load distribution on the tibial insert at 30 degrees of flexion have been evaluated. The 60-degree model was named "Model C 1" and the tibial slope angles of 3, 5, 7 degrees and the load distributions on the tibial insert at 60 degrees of flexion have been evaluated. The 90-degree model was named "Model D 1" and the tibial slope angles of 3, 5, 7 degrees and the load distributions on the tibial insert at 90 degrees of flexion have been evaluated.

In addition, in the model of the load on the tibial insert notch, the 0 degrees model was named "Model A2" and the tibial slope angles of 3, 5, 7 degrees and the load distribution on the tibial inset notch at 0 degree of flexion have been evaluated. The 30-degree model was named "Model B 2" and the tibial slope angles of 3, 5, 7 degrees and the load distribution on the tibial insert notch at 30 degrees of flexion have been evaluated. The 60-degree model was named "Model C 2" and the tibial slope angles of 3, 5, 7 degrees and the load distributions on the tibial insert notch at 60 degrees of flexion have been evaluated. The 90-degree model was named "Model D2" and the tibial slope angles of 3, 5, 7 degrees and the load distributions on the tibial insert notch at 90 degrees of flexion have been evaluated.

The finite element models created for this study were created on Ansys Workbench 2020 R2 software and their solutions were carried out.

3. Results

When the findings of the study models are examined:

In model A1, tibial slope angles of 3, 5, 7 degrees were measured as 20.026, 21.028, and 11.06 MPa, respectively, and the load was centered at the medial of the tibial insert. When the loads were examined, it was found to be lowest at the tibial slope angle of 7 degrees and a statistically significant difference was found (p = 0.04) (Table 1). In model B1, the loads at tibial slope angles of 3, 5, 7 degrees were measured as 13.6, 11.11, and 9.87 MPa, respectively, and the load was centered at the medial of the tibial insert. No statistically significant difference was found between the loads (p = 0.740) (Table 1).

The loads at tibial slope angles of 3, 5, 7 degrees in model C1 were measured as 18.4, 9.07, and 32.2 MPa, respectively, and the load was centered at the medial of the tibial insert. When the loads were examined, a statistically significant difference was found (p = 0.30) (Table 1). In model D1, the loads at tibial slope angles of 3, 5, 7 degrees were measured as 27.9, 11.4, and 38.6 MPa, respectively, and the load was centered at the medial of the tibial insert. When the loaded loads were examined, a statistically significant difference was found (p = 0.260) (Table 1).

In model A1 and model B1, the least load on the tibial insert was found at the tibial slope angle of 7 degrees (11.6, 9.87 MPa), while it was found at the tibial slope angle of 5 degrees in the 60 and 90 degrees models (9.07 and 11.4 MPa, respectively).

In the 0 and 30 degrees flexion models, there was no pressure on the tibial insert notch at the tibial slop angles of 3, 5, 7 degrees. However, in the 60-degree model, it was seen that a pressure of 0.153 MPa occurs at all 3, 5, 7 degrees and this pressure is centered at the point where the tibial insert notch joins the tibial insert. In addition, in the 90-degree model, it was seen that the pressure occurs at the junction of the tibial insert notch and the tibial insert, and the highest pressure occurs at a slope angle of 0 degree (Table 2).

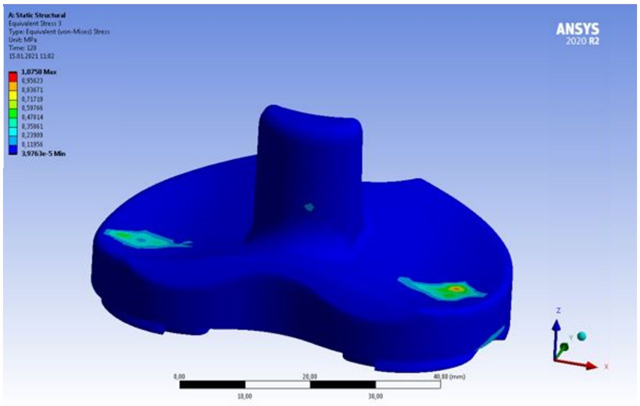

Fig. 1: Demonstration of the load on the Tibial insert at 3 degrees of Tibial angle with 0 degree of flexion movement

4. Discussion

In total knee arthroplasty (TKA), correct angulation of the tibial component in the sagittal plane is important for correct load distribution during flexion-extension and rotation movements of the knee. After TKA, a higher load on the tibial insert during the movement of the knee joint will result in more abrasion on the tibial insert in the knee prosthesis. The tibial angle should be considered in both single and double compartment prostheses. Although there is no standard range of values, the posterior angle of the tibial component between 0-7 degrees is generally accepted in practice.[13] Many studies have revealed that as a result of the different alignment of the prostheses used in TKA, the load on the tibial insert and insert notch vary, thus affecting the lifetime of the prosthesis and the clinical satisfaction of the patient.[3,6,8,9,13,14] There is no generally accepted technique for the measurement of tibial slope angles (TSA) in the literature. Lateral direct X-rays and/or CT/MR images have been used in most of the studies. However, overlapping of the images of the medial-lateral condyles in those studies conducted with direct radiography, and the effects of other factors such as age, gender, weight, and some

Table 1: Evaluation of the load on the tibial insert attibial slope angles of 3, 5, 7 degrees according to the created models

	Tibial Slope Angle			
	3 Degrees	**5 Degrees**	**7 Degrees**	**P Value**
Model A1	20,026 MPa	21,028 MPa	11,6 MPa	0,04
Model B1	13,6 MPa	11,11 MPa	9,87 MPa	0,740
Model C1	18,4 MPa	9,07 MPa	32,2 MPa	0,30
Model D1	27,9 MPa	11,4 MPa	38,6 MPa	0,260

Table 2: Evaluation of the load on the tibial insert notch at tibial slope angles of 3, 5, 7 degrees according to the created models

	Tibial Slope Angle			
	0 Degree	**3 Degrees**	**5 Degrees**	**7 Degrees**
Model A2	-	-	-	-
Model B2	-	-	-	-
Model C2	0,153 MPa	0,153 MPa	0,153 MPa	0,153 MPa
Model D2	0.585 MPa	0.583 MPa	0.5839 MPa	0.584 MPa

physiological characteristics have also been considered in studies conducted by using CT and MRI to rule out this situation.[13] In the present study, a 3D rigid model of the human knee was created with finite element modeling on a computer simulation program and after the knee prostheses applied in different posterior TSA of 0, 3, 5, and 7 degrees in the sagittal plane, the loads on the tibial insert and the insert notch were calculated with 0, 30, 60, and 90 degrees of flexion movement of the joint. Carrying out all measurements on a single model using computer simulation, enabled us to obtain results that demonstrate the effect of the tibial slope on the joint, isolated from many factors that may affect the results such as ethnic characteristics, weight, height, bone structure, connective tissue features, and joint size of the patient.[15]

According to the results of our study, although there is no statistical significance with 0 and 30 degrees of flexion, the load on the tibial insert respectively decreases at 3, 5, 7 degrees of TSA, with the lowest load being observed at 7 degrees. In flexions of 60 and 90 degrees, while the load on the insert is at the lowest at 5 degrees, it gradually increases at 3 and 7 degrees, respectively. Considering the results, although the pressure on the tibial insert at 3 degrees of TSA was not found to be significant at 0-30 degrees, it is higher at 5 degrees with all degrees of flexion. Although 7 degrees of TSA is safe with 0 and 30 degrees of flexion, it applied the highest pressure to the tibial insert at 60 and 90 degrees of flexion. When the load on the tibial insert notch is examined in our study, while no load was observed on any tibial slope angles with 0 and 30 degrees of flexion, the pressure was found in all tibial slope angles with 60 degrees of flexion, and at 0 degrees of tibial slope angle with 90 degrees of flexion.

Based on these results, in terms of the pressure, it creates on the tibial insert, the most appropriate TSA to be used in the alignment of the prosthesis appears to be 5 degrees. Dejour and Bonnin reported that a high tibial slope angle resulted in a significantly higher rate of anterior translation of the tibia.[16] With this in mind, some researchers concluded that high tibial angle degrees may increase the in-situ strength of the anterior crural ligament (ACL) and therefore increase the likelihood of ACL injury.[17] However, the angles discussed here are over 10 degrees and were not examined in our study. Gwinner et al[18] examined the effects of TSA on knee joint stability in the long-term follow-up of patients who had posterior crural ligament reconstruction. According to them, while the stability of the joint is better in patients with an angle of 5 degrees or less, especially at 8 degrees and above, it is quite impaired and the need for reduction increases. Lerat and Moyen reported that postoperative TSA decreased in patients who underwent high tibial osteotomy, resulting in less load on the anterior crural ligament.[19] Alici et al. found a significant relationship between the increase in TSA and the susceptibility to meniscal tear.[20] In another study supporting the hypothesis put forward in this study, polyethylene abrasion in the knee prosthesis and damage rates at the posterior part of the tibial insert and potentially osteolysis, particle-induced synovitis, and implant failure risks were found to be significantly higher at 7 degrees of TSA and above.[21] In the same study, it was stated that TSAs below 3 degrees do not cause polyethylene wear, but are not recommended because of their negative effects on joint performance and posterior stabilized knee inserts. Considering the relevant literature, angles that are often associated with negative consequences are higher angles. The results of our study are also in line with these data. However, in our study, a slight increase in load was found below 5 degrees, although it was not statistically significant, and similar studies are needed for more precise results.

5. Conclusion

According to the results of our study, a TSA of less than 7 degrees (preferably 5 degrees) should be preferred in TKA in terms of the loads on the tibial insert and the insert notch.

Further comparative studies are needed to make a more accurate interpretation of a TSA of 3 degrees and below.

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None.

7. Conflict of Interest

None.

References

1. Penrose JM, Holt GM, Beaugonin M, Hose DR. Development of an accurate three-dimensional finite element knee model. *Comput Methods Biomech Biomed Engin*. 2002;5(4):291–300.
2. Woo SL, Debski RE, Withrow JD, Janaushek MA. Biomechanics of knee ligaments. *Am J Sports Med*. 1999;27(4):533–43.
3. Mündermann A, Dyrby CO, Lima DD, Colwell CW, Andriacchi TP. In vivo knee loading characteristics during activities of daily living as measured by an instrumented total knee replacement. *J Orthop Res*. 2008;26(9):1167–72.
4. Kazemi M, Dabiri Y, Li LP. Recent advances in computational mechanics of the human knee joint. *Comput Math Methods Med*. 2013;2013:718423.
5. Radke H, Aron DN, Applewhite A, Zhang G. Biomechanical Analysis of Unilateral External Skeletal Fixators Combined with IM-Pin and Without IM-Pin Using Finite-Element Method. *Vet Surg*. 2006;35(1):15–23.
6. Kang KT, Kwon SK, Son J, Kwon OR, Lee JS, Koh YG. The increase in posterior tibial slope provides a positive biomechanical effect in posterior-stabilized total knee arthroplasty. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(10):3188–95.
7. Stulberg SD, Loan P, Sarin V. Computer-assisted navigation in total knee replacement: results of an initial experience in thirty-five patients. *J Bone Joint Surg Am*. 2002;84(Suppl 2):90–8.
8. Bae DK, Song SJ, Yoon KH, Noh JH, Moon SC. Comparative study of tibial posterior slope angle following cruciate retaining total knee arthroplasty using one of three implants. *Int Orthop*. 2012;36(4):755–60.
9. Okamoto S, Mizu-Uchi H, Okazaki K, Okazaki K, Hamai S, Nakahara H, et al. Effect of tibial posterior slope on knee kinematics, quadriceps force, and patellofemoral contact force after posterior-stabilized total knee arthroplasty. *J Arthroplasty*. 2015;30(8):1439–43.
10. DeBoer JJ, Blankevoort L, Kingma I. In vitro study of inter-individual variation in posterior slope in the knee joint. *Clin Biomech (Bristol, Avon)*. 2009;24(6):488–92.
11. Öner K, Paksoy AE, Özer A. Fixation of femoral neck fractures with three cannulated screws: biomechanical changes at critical fracture angles. *J Surg Med [Internet]*. 2020;4(8):660–3.
12. Suh DS, Kang KT, Son J, Kwon OR, Baek C, Koh Y. Computational study on the effect of malalignment of the tibial component on the biomechanics of total knee arthroplasty A Finite Element Analys. *Bone Joint Res*. 2017;6(11):623–30.
13. Berger RA, Crossett LS, Jacobs JJ, Rubash HE. Malrotation causing patellofemoral complications after total knee arthroplasty. *Clin Orthop Relat Res*. 1998;356:144–53.
14. Wong J, Steklov N, Patil S, Flores-Hernandez C, Kester M, Colwell CW, et al. Predicting the effect of tray malalignment on risk for bone damage and implant subsidence after total knee arthroplasty. *J Orthop Res*. 2011;29(3):347–53.
15. Thompson JA, Hast MW, Granger JF, Piazza SJ, Siston RA. Biomechanical effects of total knee arthroplasty component 351 malrotation: a computational simulation. *J Orthop Res*. 2011;29(7):969–75.
16. Dejour H, Bonnin M. Tibial translation after anterior cruciate ligament rupture. Two radiological tests compared. *J Bone Joint Surg Br*. 1994;76(5):745–9.
17. Feucht MJ, Mauro CS, Brucker PU, Imhoff AB, Hinterwimmer S. The role of the tibial slope in sustaining and treating anterior cruciate ligament injuries. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(1):134–45.
18. Gwinner C, Weiler A, Roider M, Shaefer FM, Jung TM. Tibial Slope Strongly Influences Knee Stability After Posterior Cruciate Ligament Reconstruction A Prospective 5- to 15-Year Follow-up. *Am J Sports Med*. 2016;45(2):355–61.
19. Lerat JL, Moyen B, Garin C, Mandrino A, Besse JL, Brunetguedj E. Laxité antérieure et arthrose interne du genou. *Rev Chirurgie Orthop*. 1993;79:365–74.
20. Alici T, Esenyel CZ, Esenyel M, Imren Y, Ayanoglu S, Cubuk R. Relationship between Meniscal Tears and Tibial Slope on the Tibial Plateau. *Eurasian J Med*. 2011;43(3):146–51.
21. Pourzal R, Cip J, Rad E, Pourzal R, Cip J, Laurent M, et al. Joint line elevation and tibial slope are associated with increased polyethylene wear in cruciate-retaining total knee replacement. *J Orthop Res*. 2020;38(7):1596–1606.

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