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# MECHANICAL ANALYSIS OF THE PROSTHETIC KNEE IN FLEXION

Daniel Rodrigo Castillo Brito, Olga Lucia Ramos Sandoval and Dario Amaya Hurtado
Nueva Granada Military University, Carrera, Bogotá D.C., Colombia, South America
E-Mail: olga.ramos@unimilitar.edu.co

## ABSTRACT

In early years, virtual simulation tools have allowed a large set of developments, both in education and in the medical field, as in strain analysis, by using finite element methods (FEM) we can get approximations close to the reality of the mechanical behavior of an object. In medicine, specifically in the orthopedic field, it is necessary to perform a biomechanical analysis of the prostheses and of the various elements that they replace, with the aim of identifying possible failures in the tissues. Considering the above, in the following article describes the analysis of movement of the prosthetic knee simulation with elastic elements such as springs to approximate the behavior of the ligaments, including a stress analysis of the joint using finite element, where the results show a coefficient of reliable safety structure, safe from breakage.

**Keywords:** knee motion analysis, stress simulation, strain simulation.

## INTRODUCTION

Cartilage wear is an orthopedic disease that affects the movement of joints, affecting the life quality of people, when this condition is very advanced, often an orthopedic replacement is applied with artificial prostheses, trying to replace the lost motion. In the case of the knee joint, arthroplasty surgery is the most used. With this type of surgery, the affected part of the bone is removed and replaced with components made of titanium alloys, and also, the meniscus is replaced with an element of high density polyethylene [1].

In order to better understand the behavior of this joint, numerous studies have conducted an analysis by finite element including the gait cycle of people and the flexion movement of the joint with or without prostheses [2, 3, 4]. For example, the research in [5] shows the analysis made with ANSYS where the ligaments are modeled with springs and behavior of the joint are studied after an orthopedic replacement, focusing on the importance of the posterior cruciate ligament in the balance of the joint. Similarly, the article found in [6] describes a model and a motion analysis of the knee, that was performed considering flexion of 0 to 135° and determining the internal rotation of the tibia.

With the purpose to improve the quality of the prosthesis, there are many studies that evaluate the effectiveness of the knee joint after an orthopedic replacement, for example, the research presented in [7] compares a computational model based on CAD elements and FEM methods with the Kansas simulator, characterized for the assessment of new prosthetic designs [8]. In this development all the controllers and actuators are included, getting differences less than 1,8mm and 2.2°, demonstrating the accuracy of the model.

Similarly, other research focuses on comparing the knee joints before and after surgical replacement, for example the study in [9] verifies the rotations of the tibia and femur, before and after an insertion of the prosthesis and while this development proves that the prosthesis does not fully restore the movement of the knee, the differences are minimal.

Considering the above, in this article a mechanical analysis of the knee joint after joint replacement is described, considering its flexion and an approximate model of the ligaments, by mechanical springs, where results shows the points of highest force during movement and additionally, the safety factor of the joint component is determined by using a finite element study.

## MATERIALS AND METHODS

To make a proper analysis, should be considered to have virtual 3D models as realistic as possible, so images of magnetic resonance were used for the reconstruction of bone and for the prosthetic elements, the standard measures of prostheses were used through computer-aided design (CAD) to make similar components to the employees in arthroplasty surgery. Later, the ligaments are replaced by resilient elements and a motion analysis is made in order to determine the behavior of these elements during the analysis. Finally, a finite element analysis was developed to know the most likely points to fatigue and demonstrate the safety factor of the elements, the flowchart in Figure-1 shows the process.

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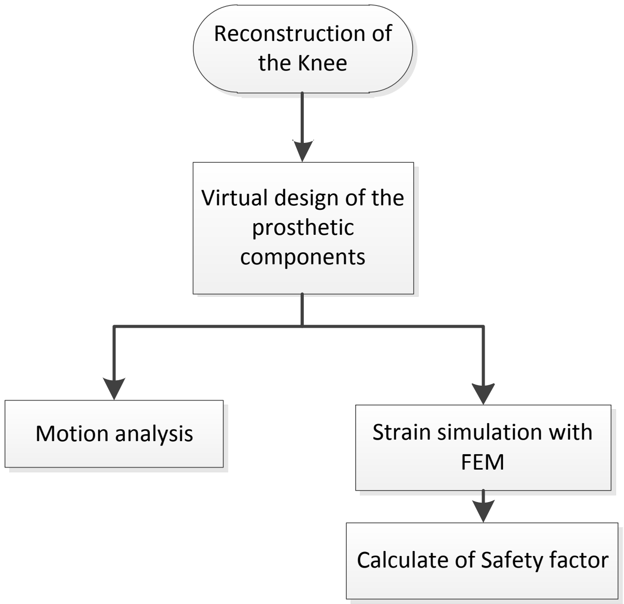


**Figure-1.** Flowchart of the process.

## Model Reconstruction

To have a virtual model of the knee as close as possible compared to an actual joint, image of magnetic resonance were used, after a segmentation process through the software ITK-SNAP [10] and smoothed in Blender, the reconstruction of the hard tissues as the femur and tibia were made. Next, with the standard measurements of the prosthesis, CAD tools are used to rebuild the parts joined in an assembly according to the one used in joint replacement surgery, as shown in Figure-2. In addition, it can be seen the forces interacting in the study, where: $mg$ corresponds to the Tibia weight, approximately 3.5Kg [11], $M$ is the moment of rotation of the Tibia respect to the Femur and $F_R$ is the reaction force of the spring that replaces the medial collateral ligament [12].

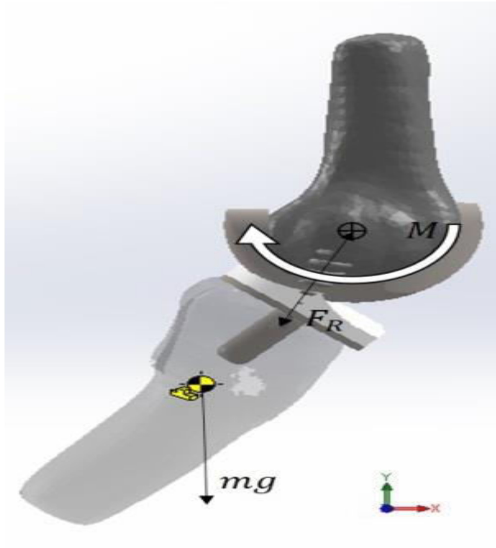


**Figure-2.** Reconstruction of the prosthetic knee.

## Motion Analysis

Motion analysis was developed in Solidworks©, in the study the femur was established as a rigid body, while the tibia showed the flexion movement through a rotation. During flexion, the medial collateral ligament was replaced by a linear spring with a spring constant of K= 120 N/mm, also the lateral and anterior collateral ligaments were replaced with constants of 90 N/mm and 180 N/mm correspondingly [5]. Tensions are described in Figure-3 as the displacement of the tibia is also illustrated with respect to the femur in both the X axis and Y axis.

Consequently, it is analyzed that the reaction force spring has a higher value by about 108° with a magnitude of 143.2N and about the posterior ligament, an upward force at first appears until the point of magnitude of 35N and a value of 2.9° in flexion, until reducing its magnitude to 0N when a flexion angle of 30.56° is presented, then it come back to increase until 120° with a magnitude of 40N. This demonstrates that in the beginning of movement probably the ligament is contracted, but after 30.56°, begins to be tensioned. Considering that the model has linear springs, an additional force is observed in comparison with the normal behavior of the ligaments, since when they are in contraction should not provide any force in the study, however this does not affect the study when the ligaments are in tension, therefore the graphics are similar to the results of similar investigations [13].

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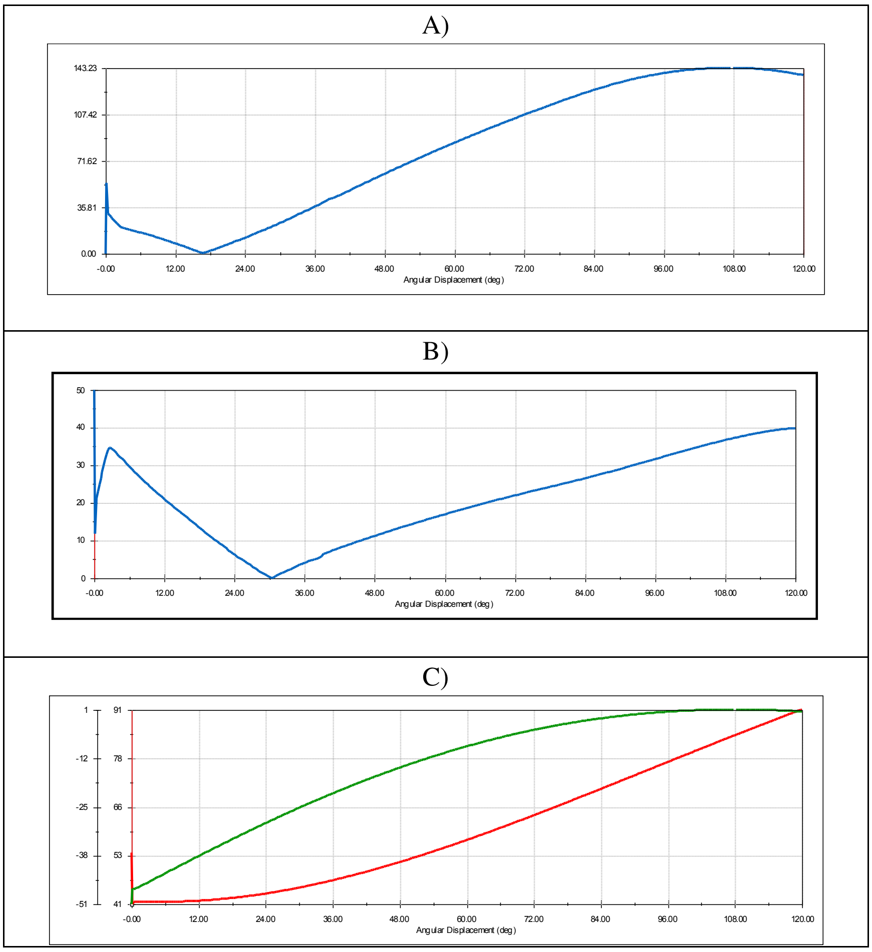


**Figure-3.** Motion analysis of the knee flexion A) Force medial collateral ligament (N). B) Force posterior ligament (N). C) Displacement of the tibia (mm).

## RESULTS

It is considered that in the finite element study, the joint had a hinge type behavior, in which the tibia and corresponding component remained fixed on the environment, whereas the femur presented the rotation of the structure, contrary to the motion analysis. The analysis was developed with a 0° flexion with an equivalent distributed load of 70 kg (686.7 N) in the perpendicular direction of the femoral component. Figure-4 shows the restriction applied and the distributed load.

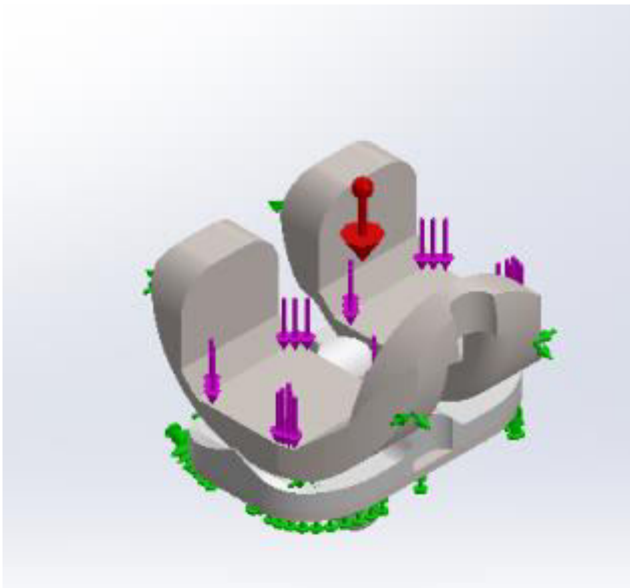

**Figure-4.** Boundary conditions.

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**Stress Simulation**

Figure-5 illustrates the produced finite element analysis results of deformation and strain where it can be analyzed that the tension is distributed evenly in the femoral component, with larger magnitudes parallel to the component location faces which replaces the meniscus also, it is observed that deformation has an evenly distribution with higher values in the external surface of the structure.

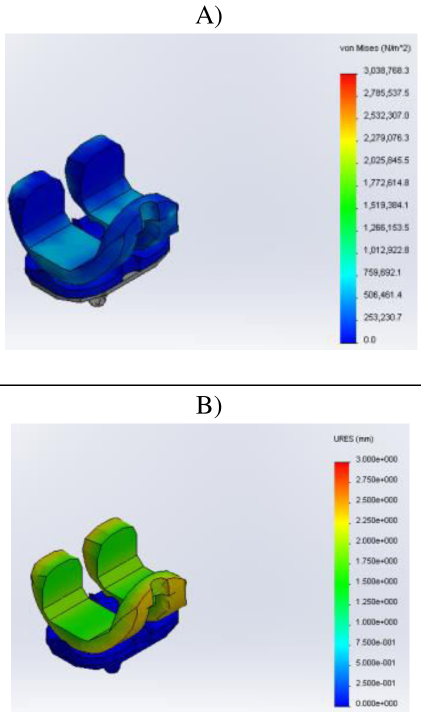


**Figure-5.** Finite element analysis in the prosthetic component. A) Von-mises stress. B) Displacements.

Figure-6 shows in more detail the stress and displacements in the prosthetic meniscus, therefore it is analyzed the greater stresses are generated in this component and even its distribution is uniform, it has higher values toward the center of the element, due to the weight of the tibial component and the loads applied in this. Regarding the deformations, minimum values can be observed throughout the structure, but in a distribution similar that it has the stress graphic.

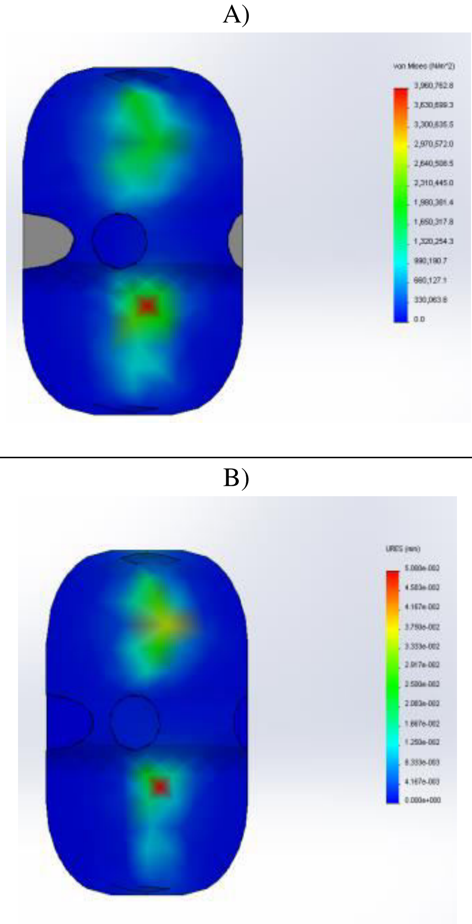


**Figure-6.** Finite element analysis in the prosthetic meniscus component. A) Von-mises stress. B) Displacement.

Subsequently, the safety factor is determined by the Equation. 1. considering that it took into account an elastic limit of 20MPa for the material of high-density polyethylene [14].

$$Fs = \frac{\sigma_{limit}}{\sigma_{VonMises}} = \frac{20MPa}{3.96\ MPa} = 5.05 \qquad (1)$$

**CONCLUSIONS**

The motion study allows observing the approximate behavior that the ligaments have after an orthopedic replacement, however because the mechanical behavior is simulated through linear springs, There are some differences with the normal movement of a ligament in the joint and although it was shown that there is a high enough safety factor, with conditions of a different inclination angle, a loads of these efforts may increase, however, still there would be no risk of breakage at any of the elements. It can also be observed that deformations or displacements in the tibial and meniscus component presented minimum values, noting that in the prosthetic meniscus is insignificant, confirming the stability of the orthopedic implant studied.

To learn more about the behavior of this orthopedic replacement in future research is going to be study the movement cycle considering the motion of a person, because this kind of movement can be significant in the calculation of the stress and deformations.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] S. Affatato. 2014. Surgical Techniques in Total Knee Arthroplasty and Alternative Procedures. Elsevier.

[2] O. Tanifuji, T. Sato, K. Kobayashi, T. Mochizuki, Y. Koga, H. Yamagiwa, G. Omori, and N. Endo. 2011. Three-dimensional in vivo motion analysis of normal knees using single-plane fluoroscopy," Journal of Orthopaedic Science. 16(6): 710–718.

[3] J. Zelle, A. C. Van der Zanden, M. De Waal Malefijt, and N. Verdonschot. 2009. Biomechanical analysis of posterior cruciate ligament retaining high-flexion total knee arthroplasty. Clinical Biomechanics. 24(10): 842–849.

[4] H. R. Fallah-Yakhdani, H. Abbasi-Bafghi, O. G. Meijer, S. M. Bruijn, N. van den Dikkenberg, M.-G. Benedetti and J. H. van Dieën. 2012. Determinants of co-contraction during walking before and after arthroplasty for knee osteoarthritis. Clinical Biomechanics. 27(5): 485-494.

[5] A. Steinbrück, M. Woiczinski, P. Weber, P. E. Müller, V. Jansson, and C. Schröder. 2014. Posterior cruciate ligament balancing in total knee arthroplasty: a numerical study with a dynamic force controlled knee model. BioMedical Engineering. OnLine. 13(1).

[6] K.-J. Lin, C.-H. Huang, Y.-L. Liu, W.-C. Chen, T.-W. Chang, C.-T. Yang, Y.-S. Lai and C.-K. Cheng. 2011. Influence of post-cam design of posterior stabilized knee prosthesis on tibiofemoral motion during high knee flexion. Clinical Biomechanicals. 26(8): 847-852.

[7] M. A. Baldwin, C. W. Clary, C. K. Fitzpatrick, J. S. Deacy, L. P. Maletsky, and P. J. Rullkoetter. 2012. Dynamic finite element knee simulation for evaluation of knee replacement mechanics. Journal. Biomechanics. 45(3): 474–483.

[8] R. B. Durairaj, J. Shanker, P. V. Kumar, and M. Sivasankar. 2012. A Study on Development of Knee Simulator for Testing Artificial Knee Prosthesis. in Emerging Trends in Science, Engineering and Technology. pp. 351-360.

[9] A. M. Merican, K. M. Ghosh, F. Iranpour, D. J. Deehan, and A. A. Amis. 2011. The effect of femoral component rotation on the kinematics of the tibiofemoral and patellofemoral joints after total knee arthroplasty. Knee Surg. Sports Traumatol Arthrosc. 19(9): 1479-1487.

[10] P. A. Yushkevich, J. Piven, H. C. Hazlett, R. G. Smith, S. Ho, J. C. Gee, and G. Gerig. 2006. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. NeuroImage. 31(3): 1116-1128.

[11] K. B. Shelburne and M. G. Pandy. 1997. A musculoskeletal model of the knee for evaluating ligament forces during isometric contractions. Journal of Biomechanics. 30(2): 163-176.

[12] Y. Zhu, J. X. Chen, S. Xiao, and E. B. Mac Mahon. 1999. 3D knee modeling and biomechanical simulation. Computing in Science & Engineering. 1(4): 82-87.

[13] K. E. Moglo and A. Shirazi-Adl. 2005. Cruciate coupling and screw-home mechanism in passive knee joint during extension–flexion. Journal of. Biomechanics. 38(5): 1075–1083.

[14] G. Ayoub, F. Zaïri, M. Naït-Abdelaziz, and J. M. Gloaguen. 2010. Modelling large deformation behaviour under loading–unloading of semicrystalline polymers: Application to a high density polyethylene. International Journal of Plasticity. 26(3): 329–347.