International Journal of Applied Engineering Research ISSN 0973-4562 Volume 19, Number 4 (2024) pp. 364-366

A Three-Dimensional Finite Element Analysis of the Biomechanical Behavior of Menisci in the Healthy Human Knee Joint

[1]Amitesh Shrivastava[*], [2]N. K. Jain and [3]R. Salhotra

[(1, 2, 3)]Department of Mechanical Engineering, National Institute of Technology Raipur, Raipur, Chhattisgarh-492010, India

Abstract

The objective of this study is to evaluate the stresses in healthy meniscus of the knee joint. For this study 3D model of healthy meniscus is developed by utilizing magnetic resonance imaging (MRI) in materialise MIMICS software and analysis of the 3D model on meniscus is performed on Ansys software package. A compressive load of 1150 N is applied on the medial and lateral menisci simultaneously. This study will provide better understanding of load distribution and maximum stress developed under meniscus on knee joint by compressive loading. Also this study established a non-invasive technique to determine the meniscus stress generation.

1. Introduction

The knee joint has a complex synovial functionality joint and it exhibits multiple degree of freedom (DOF) during different load carrying conditions while performing activities on the lower extremities movement [1]. While performing the activities ground reaction on knee joint is counterbalanced by cartilages, meniscus and bundles of tendons and ligaments under static and dynamics loading conditions [2]. Tear of cartilages and meniscus can occur on the knee joint under different loading conditions which results on cause pain and proper gait movement is restricted for the person [3]. Under vertical loading conditions there is reduction in the effectiveness and performance of a person activity, mainly on hip and knee joints [4]. Even though meniscus, and cartilages on knee joint have their own self-healing property but is limited due to their non-vascularization behaviour [5]. But for osteoarthritis which cause degeneration of menisci the surgical procedures is way to get relief from pain [6]. For better understanding of knee joint working finite element technique is often adopted and operated under different loading conditions [7]. The stress on knee joint increases on increase of meniscus subluxation while establish relation [8]. The compressibility and permeability on the meniscus considerable increases with progression of degeneration [9]. Performed ex vivo study on the individual between 40 years to 65 years of age and found that shear, tensile and compressive moduli of meniscus have large variations based on the test parameters [9]. Determined the material properties for meniscus is by a non-invasive method using inverse finite element analysis and in their computational study [10]. TKA (Total Knee Arthroplasty) is a surgical procedure that has been considered suitable solution for person suffering severe osteoarthritis, the surgical procedure includes replacement of the human knee joint with implants of non-metallic and metallic character for restoration of joint functionality. Reliability and durability of implants increases life span of the joint depends under loading conditions of joint [11]. The objective of this work is to get better understanding of stresses generated meniscus during static loading condition.

2. Materials and Methods

A biomechanical study with similar boundary conditions and load is conducted to examine the stress generated on menisci. A compressive load is applied on lateral and medial meniscus simultaneously and fixed supported boundary condition is used to carry out the numerical analysis [12]. The menisci were composed of a linear elastic and isotropic material with the average properties: E = 120 MPa, poisson's ratio = 0.47 respectively [13].

3. Finite Element 3D Models

From magnetic resonance imaging (MRI) scan multiple images were collected to develop 3D model of menisci in knee joint. The person undergoing scanning was kept as supine position, patella facing toward celling, complete extension of knee and hip joint. Images generated through scans were collected in DICOM (The Digital Imaging and Communications in Medicine) images files formal and were utilized to generated 3D models using MIMICS (Materialise's Interactive Medical Image Control System, Materialise-Belgium). By performing region growth and segmentation operation manually accurate 3D model of menisci is developed.

3.1 Material, Mesh Properties and Boundary Conditions

The material property of bones and soft tissues used for numerical analysis are derived from series of literatures that experimentally and computationally derived and evaluated material properties. The menisci were composed of a linear elastic and isotropic material with the average properties: E = 120 MPa, poisson's ratio = 0.47 respectively [14]is shown in table 1.

Table 1 Material property

Knee Component	Assigned material	Young modulus E (MPa)	Poisson's ratio ν
3D lateral and medial meniscus	Linear elastic and isotropic	120	0.45

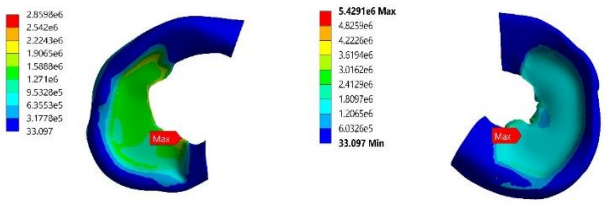
Meshing is performed in ansys software with tetrahedron mesh method and of size 1mm is generated for better mesh accuracy. The total meshed elements are 59022 & 89845 nodes and to ensure the quality of result mesh sensitivity study is conducted. The boundary condition is as the compressive load on medial and lateral meniscus of 1150 N is applied [15] shown in table 2:

Table 2 Mesh property

Knee Component	Mesh Type	Elements	Nodes
3D lateral and medial meniscus	Linear elastic and isotropic	59022	89845

4. Results

Under static simulation the compressive stresses on medial and lateral meniscus are generated on a healthy human knee joint when evaluated by finite element analysis. The principal goal of analysis is to analyse the critical point for development of stress generation. From analysis it is observed that maximum stresses in both medial and lateral meniscus is generated an anterior horn. The max stress of 5.4 MPa is generated on the meniscus on anterior rim similar to those of the previous study thus it demonstrate reliability of model. The stress on anterior horn likely to cause degeneration and tear at the inner rim which may lead to sever pain. The degeneration and tear in meniscus severely changes biomechanics of knee joint by decreasing the shock absorbing and load transmission capacity of meniscus and the joint. With increase of severity of meniscus it affects cartilages and may leads to osteoarthritis, which requires total knee arthroscopy (TKA) for the treatment.



(a) Medial Meniscus **(b)** Lateral Meniscus

Figure 1: Max compressive stress on meniscus under compressive load

5. Discussion

For healthy meniscus the maximum compressive stresses obtained in our study is for medial menisci is 2.85 MPa and for lateral meniscus the peak stress is 5.4 MPa and is between the range derived by [13][15] of stresses 3.11 MPa and 9.15 MPa respectively. Although further research can be done with more complexities and load condition on meniscus.

Conclusion

For this study, a 3D model of meniscus is created for finite element analysis to investigate stress on meniscus at full stance position of knee joint. As a general conclusion, on the basis the obtained result from biomechanical computational analysis of meniscus under compressive loading by finite element analysis. The model has been compared with the results of previous literatures and this study may help in better understanding of mechanical behaviour of joint.

Acknowledgement

This research work is not funded by any organisation.

Conflict of interest

There are no conflicts of interest related to the manuscript.

References

[1] B. Section and I. College, "Knee joint motion : description and measurement," no. June, pp. 357–372, 1998.

[2] I. Kutzner et al., "Loading of the knee joint during activities of daily living measured in vivo in five subjects," J. Biomech., vol. 43, no. 11, pp. 2164–2173, Aug. 2010, doi: 10.1016/j.jbiomech.2010.03.046.

[3] J. L. Astephen Wilson and D. Kobsar, "Osteoarthritis year in review 2020: mechanics," Osteoarthritis and Cartilage, vol. 29, no. 2. W.B. Saunders Ltd, pp. 161–169, Feb. 01, 2021. doi: 10.1016/j.joca.2020.12.009.

[4] D. J. Cleather, J. E. Goodwin, and A. M. J. Bull, "Clinical

Biomechanics Hip and knee joint loading during vertical jumping and push jerking," JCLB, vol. 28, no. 1, pp. 98–103, 2013, doi: 10.1016/j.clinbiomech.2012.10.006.

[5] A. R. Farooqi, J. Zimmermann, R. Bader, and U. van Rienen, "Computational study on electromechanics of electroactive hydrogels for cartilage-tissue repair," Comput. Methods Programs Biomed., vol. 197, Dec. 2020, doi: 10.1016/j.cmpb.2020.105739.

[6] P. Sarzi-puttini et al., "Osteoarthritis : An Overview of the Disease and Its Treatment Strategies," no. 4, 2005, doi: 10.1016/j.semarthrit.2005.01.013.

[7] S. K. Easley, S. Pal, P. R. Tomaszewski, A. J. Petrella, P. J. Rullkoetter, and P. J. Laz, "Finite element-based probabilistic analysis tool for orthopaedic applications," Comput. Methods Programs Biomed., vol. 85, no. 1, pp. 32–40, Jan. 2007, doi: 10.1016/j.cmpb.2006.09.013.

[8] K. Gokkus, H. Atmaca, L. Uğur, A. Özkan, and A. T. Aydin, "The relationship between medial meniscal subluxation and stress distribution pattern of the knee joint: Finite element analysis," J. Orthop. Sci., vol. 21, no. 1, pp. 32–37, Jan. 2016, doi: 10.1016/j.jos.2015.10.001.

[9] J. Schwer, F. Galbusera, A. Ignatius, L. Dürselen, and A. M. Seitz, "Non-invasive regional parameter identification of degenerated human meniscus," Comput. Biol. Med., vol. 182, no. July, 2024, doi: 10.1016/j.compbiomed.2024.109230.

[10] M. Freutel, F. Galbusera, A. Ignatius, and L. Dürselen, "Material properties of individual menisci and their attachments obtained through inverse FE-analysis," J. Biomech., vol. 48, no. 8, pp. 1343–1349, 2015, doi: 10.1016/j.jbiomech.2015.03.014.

[11] H. Lee, S. Park, K. R. Kwon, and G. Noh, "Effects of cementless fixation of implant prosthesis: A finite element study," J. Adv. Prosthodont., vol. 11, no. 6, pp. 341–349, 2019, doi: 10.4047/jap.2019.11.6.341.

[12] K. Gökkuş, E. Sagtas, E. Demirci, M. Saylik, and A. T. Aydin, "Degenerative arthritis of pseudoarticulation between the os peroneum and cuboid: A rare cause of lateral foot pain," Foot Ankle Surg., vol. 21, no. 1, pp. e9–e11, Mar. 2015, doi: 10.1016/j.fas.2014.08.011.

[13] K. Zhang et al., "ScienceDirect Effect of degenerative and radial tears of the meniscus and resultant meniscectomy on the knee joint : a finite element analysis," J. Orthop. Transl., vol. 18, pp. 20–31, 2019, doi: 10.1016/j.jot.2018.12.004.

[14] L. Li, L. Yang, K. Zhang, L. Zhu, X. Wang, and Q. Jiang, "Three-dimensional fi nite-element analysis of aggravating medial meniscus tears on knee osteoarthritis," J. Orthop. Transl., vol. 20, no. March 2019, pp. 47–55, 2020, doi: 10.1016/j.jot.2019.06.007.

[15] E. Peña, B. Calvo, M. A. Martínez, and M. Doblaré, "A three-dimensional finite element analysis of the combined behavior of ligaments and menisci in the healthy human knee joint," J. Biomech., vol. 39, no. 9, pp. 1686–1701, 2006, doi: 10.1016/j.jbiomech.2005.04.030.