Evaluating the Partial Fibulectomy on Stress Distribution in Tibiofemoral Joint

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Introduction: Partial fibulectomy has been suggested for patients who encounter with severe varus/valgus or ununited fractures of the tibia. This study develops a finite element (FE) model of partial fibulectomy to study stress distribution in the tibiofemoral joint. **Materials and Methods:** A 3D magnetic resonance imaging (MRI)-based of tibiofemoral joint and FE model was developed for study from a man volunteer with the normal left knee. Components consisted of the exact geometry of femur, tibia, fibula, meniscus, and articular cartilages. Firstly, geometries were constructed in Mimics and then exported to Rapid Forming XOR2 and finally, the Computer-aided design (CAD) model was analyzed in ABAQUS 6.10. Mechanical properties of the model for soft tissues were considered to be linear elastic, isotropic and homogenous and for bony parts were considered to be rigid. **Results:** Model predictions were compared with normal one and used to derive stress distribution under physiological loading for standing in quasi- static condition. The results showed load transferring toward lateral condyle due to partial fibulectomy. The variation of stress distribution would increase the risk of osteoarthritis. **Conclusion**: Our results have been predicted that partial fibulectomy could be an unknown risk factor for osteoarthritis and the model could be used for extended similar studies.

Keywords: Partial Fibulectomy; Tibiofemoral Joint; Stress Distribution; Finite Element Method

Introduction

Partial fibulectomy (proximal, middle and distal) has been described and used for more than four decades to promote healing in tibial non-union because it allows better axial loading of the tibia. Other items that operate of partial fibulectomy are done on the patient include: Promoting union in ununited fractures of the tibia, an Important Adjunct in the Management of Lower Extremity Arterial, and Distal fibulectomy for Ewing's sarcoma. Fracture of the tibia with an intact fibula is prone to delay and nonunion or varus malunion and, as a complication of the latter, late arthritis of the ankle joint. Performing a partial fibulectomy or inserting an intramedullary nail increased anterior compressive loading [1]. This loading alteration may be responsible for the clinical success seen using these treatment methods.The fibula is a valuable source of a bone graft, but because the fibula has a role in lower extremity function, it is important to determine whether partial removal results in dysfunction or other problems. The fibular function has remained obscure despite the historical efforts of past anatomists and clinicians [2]. With modern-day interest in ankle kinematics, the importance of fibular movement has been put forward [3]. However, although the fibula has an important localization between the knee and ankle and contains muscles related with the two joints, its significance for both joints has not been described effectively from the biomechanical aspect. Lambert [4] demonstrated that one-sixth of the force transmitted from the femur was borne by the fibula. Since the fibula is a common donor site in patients undergoing bone reconstruction, there are several studies on leg morbidity and function after fibula resections [5, 6]. bIn the literature, clinical and biomechanical studies have suggested that the length of the residual portion of the distal part of the fibula has an important effect on the stability of the ankle. While previous reports [5, 7] have suggested that 6–8 cm of residual distal fibular length is needed to maintain ankle stability, Pacelli *et al.,* [6] reported that ankle stability could be maintained even with less residual fibular length. Goh *et al.,* [8], in their biomechanical study on the load-bearing characteristics of the fibula and fibular resection, reported that load transmission through the fibula varied with ankle position and maximum loads occurred at full dorsiflexion and eversion. They have further stated that resection of the proximal fibula results in a significant reduction of load through the distal fibular remnant. Bozkurt *et al.,* [9], investigated the dynamic features of fibular movement to gait patterns by analyzing the gait of individuals with three different parts of the fibula resected. Gait analyses revealed that proximal fibula resection impaired knee stability , whereas distal fibula resection disturbed ankle kinematics significantly[10]. Except for a mild secondary quadriceps weakness, middle fibula resection did not cause a significant biomechanical disturbance on gait. bIn literature, However, far too little attention has been paid to research that investigates the effect of partial fibulectomy on stress distribution of the tibiofemoral joint. Partial fibulectomy might change the magnitude or location of the Maximum Stress. Investigating the Partial fibulectomy effect on stress distribution in the tibiofemoral joint may be important. So that if the partial fibulectomy increase stresses in different parts of the joint or stress concentration at a particular point of the joint could be a risk factor for osteoarthritis in the knee joint. Due to problems of practical and ethical constraints and the enormous costs of experimental studies on living and cadaveric knee, the use of mathematical modeling using the finite element method, is an efficient, strong, and complementary tool, to examine the biomechanics of the knee joint. The advantage of the finite element method used in the study of joint biomechanics is its robustness (strong ability) for the combining of three-dimensional knee joint geometry, constraints, and complex loading conditions, as well as substances with linear and homogenous properties.

In this study, we applied a finite element (FE) model with considering three dimensional model of tibiofemoral joint to investigate effects of partial fibulectomy. The distribution of forces in a joint, play a crucial role during physiological functions. In this context we analyzed the stress distribution in different cartilage in tibiofemoral joint. This study could be of help to better understand the relevant pathological events of fibulectomy.

Material and Methods

FE method allows the researcher to understand the functions of the knee in various conditions of loading. In this study, FE method is employed to investigate stress distribution in the tibiofemoral joint. In addition, this method could be helpful in reduced research costs while

Figure 1: Sagittal view of the knee in MR image

researchers encounter complicated problems. Therefore, a 3D finite element model of the tibiofemoral joint was developed in ABAQUS6.10.

MR and CT images are basic sources for creating exact geometry in different fields of study. Soft tissues such as articular cartilages are exclusively visible in MR image, on the other hand, bony parts are more visible in CT images with higher quality. MR image was used (Figure 1) to create 3D (Figure 2)of components since soft tissue plays a critical function in stress distribution. The quality of MR T1 image was 512*512 pixels and the pixel size was 0.352 millimeters with a thickness of 0.9 millimeters for each section. A 25 male with healthy knee was selected as subject and MR image was obtained by the cooperation of Jam institute in Esfahan in DICOM format.

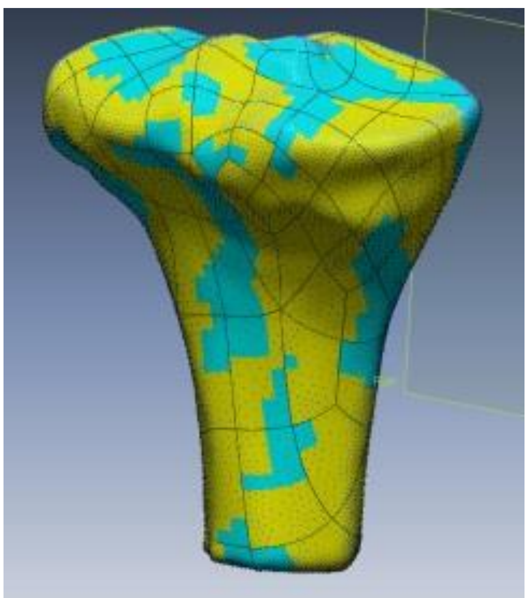

Figure 3: Rapidform view of the tibia to create 3D

Mimics10 interactively read CT/MRI data in the DICOM format. Segmentation and editing tools enable the user to manipulate the data to select a bone and soft tissue. It provides an interface to Rapid Prototyping systems via sliced files with patented support structure generation. The 3D model was finalized in Rapidform XOR2 (Figure 2) and components imported to ABAQUS6.10 to analyze the procedure. Quasi-static loadings were carried out in ABAQUS6 (Figure 3). For the present FE analysis of the model taking into account only the tibiofemoral joint at a fully extended position. The model consists of tibia, femur, articular cartilage of femur and tibia, lateral and medial meniscus, fibula and tibiofibular cartilage. Due to complicated nature of contacts in knee, Dynamic/Explicit method was chosen.

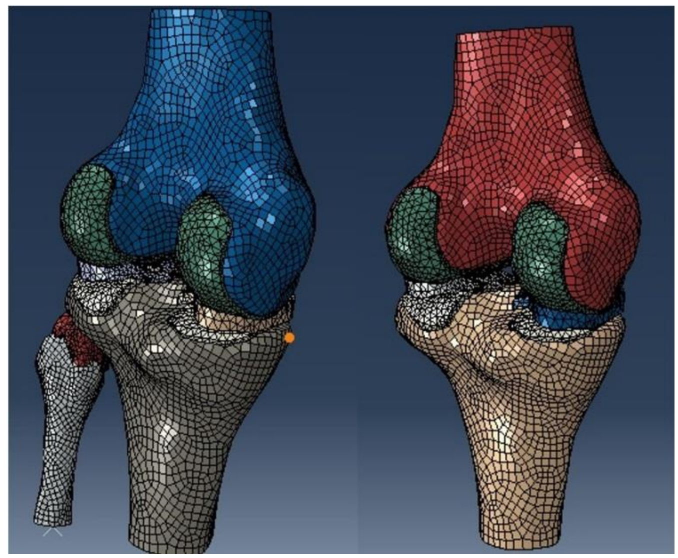

Figure 2: Sagittal view of the knee in MR image

To obtain reasonable results, loading and boundary condition should be introduced correctly. According to literature the load distribution to the fibula averaged 7.12% of the total force transmitted through the tibia and fibula . In order to apply a compressive load, a novel idea was carried out and assumed that femur has no degree of freedom, and Loadings were applied on tibia and fibula. Fibula could only have moved along its axis and restricted in other directions. In addition, all rotational movement of the tibia was limited to stabilize the loading procedure. Concentrated forces were used for both tibia and fibula and assumed that loadings were applied along the axis of bony parts. Besides, Six pairs of contacts were defined in the model and assumed the friction coefficient to be zero. Articular cartilage of femur and femur assumed to be tied, like tibia and tibial cartilage; bCartilages and lateral and medial meniscus have a general contact. The meniscus plays a critical role in stress distribution and it is vital to define proper constraint under compressive loading. Our modeling resembles conditions of in vitro experimental compressive tests, which are usually invasive. For the meniscus, boundary conditions usually affected by in vitro testing protocol, since the external edge of meniscus is connected to the joint capsule, which was cut by the operator. Therefore, the external edge of the meniscus held free of any constrain. In addition, the horns of the meniscus were tied to the tibial plateau. According to the articles, applied force and stress distribution in all components have a nonlinear relationship. This nonlinearity caused by three sources. The first one is the complicated geometries of Component which taking part in our model. The second source of nonlinearity is the material properties of soft tissue. To reduce computation cost, all materials for soft tissues were assumed to be linear, isotropic, and homogenous and the Bony parts were assumed to be rigid (Table2). In addition, considering that the loading time of our model is less than the viscoelastic time constant (1500 s) of hydrate tissue so material assumption for soft tissue is acceptable . The third source of nonlinearity is caused by boundary conditions considered in the model. Due to the complicated geometry of components, tetrahedral mesh (C3D4) and quad lateral mesh (R3D4) was considered for solid and rigid components respectively.

The present study was designed to determine the effect of fibulectomy on stress distribution and was compared with the intact knee. Boundary and loading conditions of the fibulectomy model were as same as the intact model although, Fibula did not participate in load-bearing in fibulectomy and tibia acting as only load-bearing components. It was found that decreasing the edge length of the components by more than 20% resulted in a less than 4% difference in the calculated stresses and therefore the element sizes were deemed adequate and further mesh refinement was not necessary. The convergence tolerance was not altered from the default. Details of meshes used in the tibiofemoral joint are presented in (Table 1).

Table 1: Details of meshes used in tibiofemoral joint.

component	Number of elements	Avg edge mesh(mm)	Element type
Femur	3237	4	R3D4
Tibia	2763	4	R3D4
Fibula	1172	4	R3D4
Tibial cartilage	2585	3	C3D4
Femoral cartilage	5698	3	C3D4
Lateral meniscus	2334	3	C3D4
Medial meniscus	1231	3	C3D4
Tibiofibular cartilage	1369	3	C3D4

Table 2: Material properties of components

Material	Elastic moduli (MPa)	Poisson's ratio	Density(kg/m^3)
Bony parts	Rigid	-------	------
Meniscus	59	0.3	1000
Articular cartilage	15	0.475	1000

Results

The intact and fibulectomy models were demonstrated in ABAQUS6.10 to analyze and compare stress distribution in tibiofemoral joint with each other.

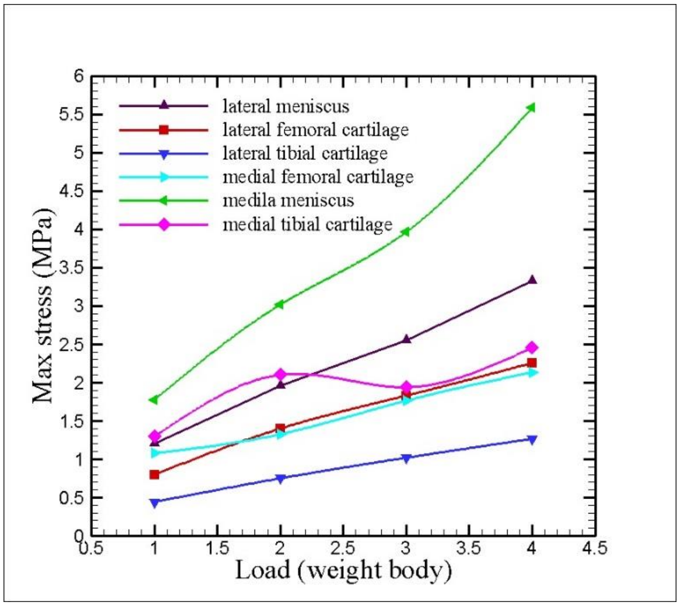

Figure 4: Max von misses stress vs. load in the intact knee

Compressive Loadings were applied in various magnitudes (up to 2800N) and normalized according to the subject's weight. Figure 4 depicts maximum von misses stress vs. Loading in all components in the intact knee.

In tibial cartilage and meniscus, the maximum stress in medial is more than the lateral although, in femoral cartilage and there is no significant difference between medial and lateral. Figure 5 and Figure 6 depict stress contours for tibial cartilage and femoral cartilage. Figure 7 is shown by considering proximal fibulectomy in the tibiofemoral joint. Maximum von misses stress in lateral and medial femoral cartilage has no significant difference and has a similar pattern with the intact knee.

To better understand how maximum stresses change in different parts of the joint between the two cases - intact knee and fibulectomy of the knee- the following diagrams are presented. Our results revealed that fibulectomy

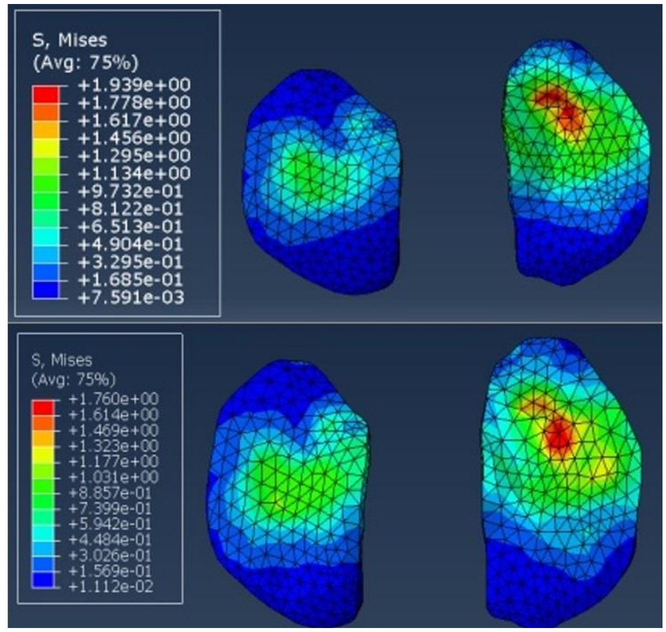

Figure 5: Stress distribution in femoral cartilage in the intact knee (up) and fibulectomy of the knee (down)

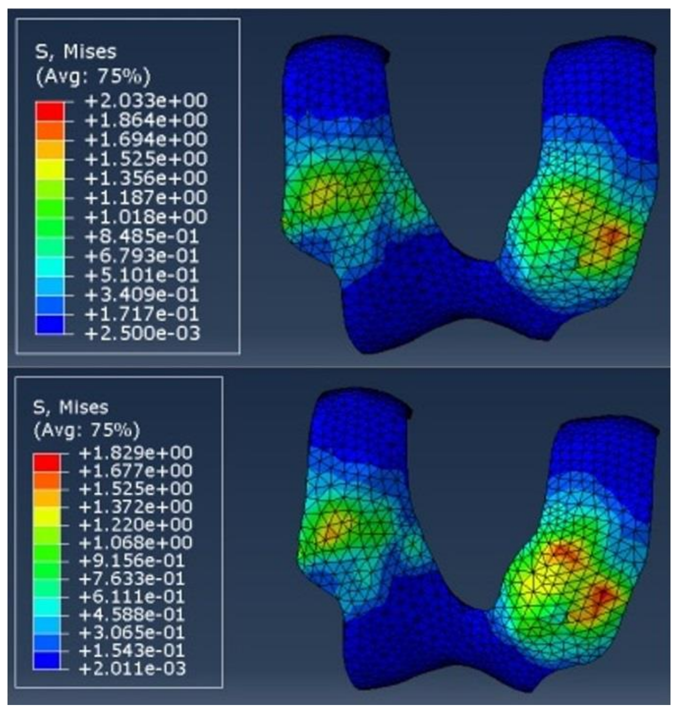

Figure 6: Stress distribution in tibial cartilage in intact knee (up) and fibulectomy of knee (down).

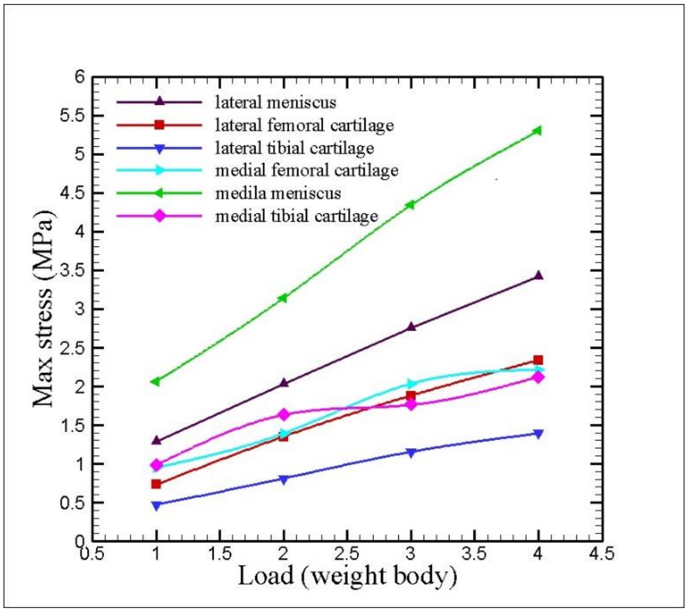

Figure 7: Max von misses stress vs. load in fibulectomy of knee

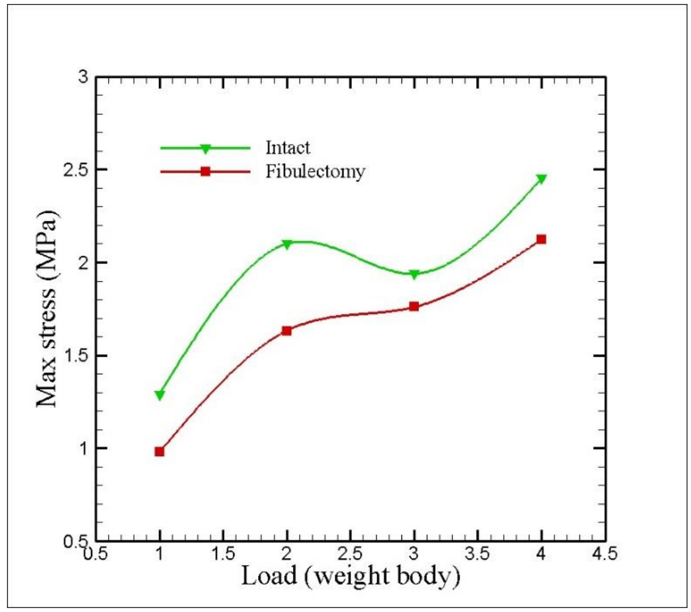

Figure 8: Max von misses stress in medial tibial cartilage in intact knee and fibulectomy of knee

increases the maximum stress in the lateral part and the reduction of the maximum stress can be seen in the medial part (Figure 8 , 9).

According to the results, fibulectomy Increases the maximum stress in the medial part of the femoral cartilage but has no significant effect on the maximum stress of the lateral part (Figure 10,11).

The observed behavior of the results from the meniscus indicates that the fibulectomy increase the maximum stress in the lateral and medial part.

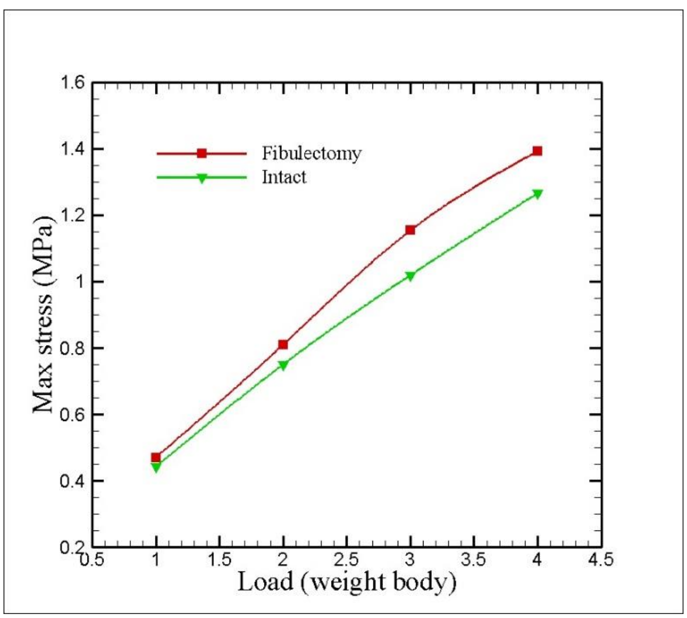

Figure 9: Max von misses stress in lateral tibial cartilage in intact knee and fibulectomy of knee

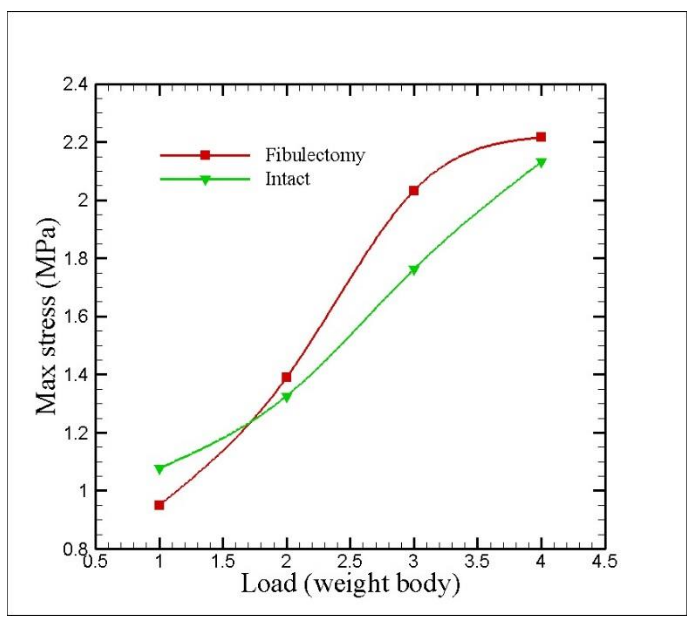

Figure 10: Max von misses stress in medial femoral cartilage in intact knee and fibulectomy of knee

The results of the axial displacement of the tibiofemoral joint depict in Figure 14 suggest that the axial displacement increased with proximal fibulectomy, this result corresponds very well with what has been in previous works.

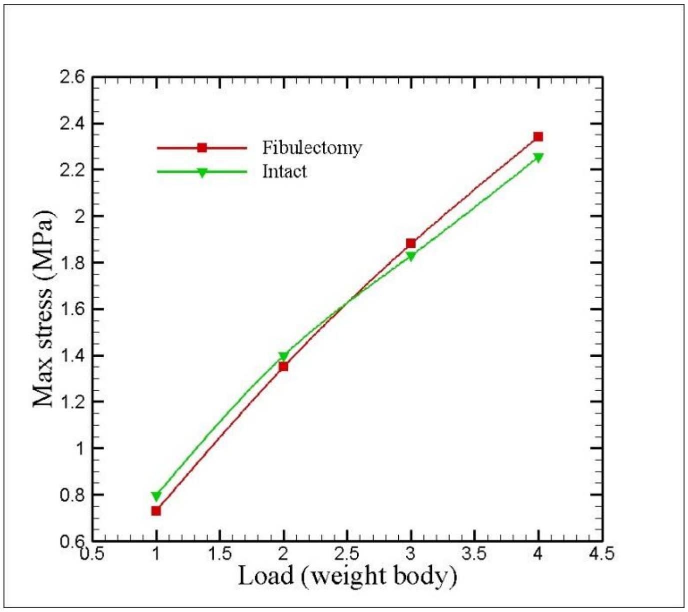

Figure 11: Max von misses stress in lateral femoral cartilage in intact knee and fibulectomy of knee

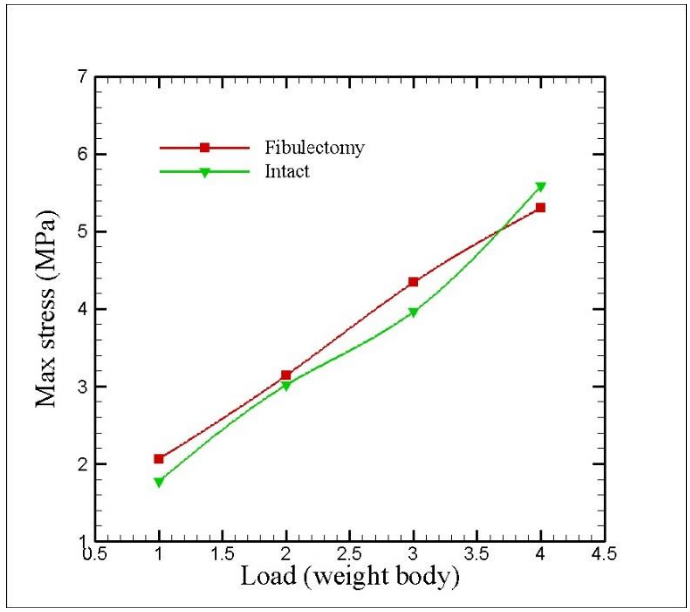

Figure 12: Max von misses stress in medial meniscus in intact knee and fibulectomy of knee

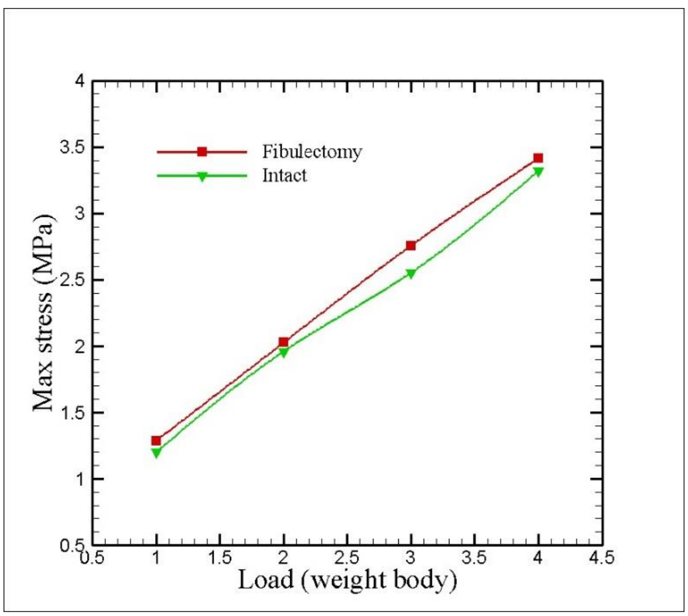

Figure 13: Max von misses stress in the medial meniscus in intact knee and fibulectomy of knee

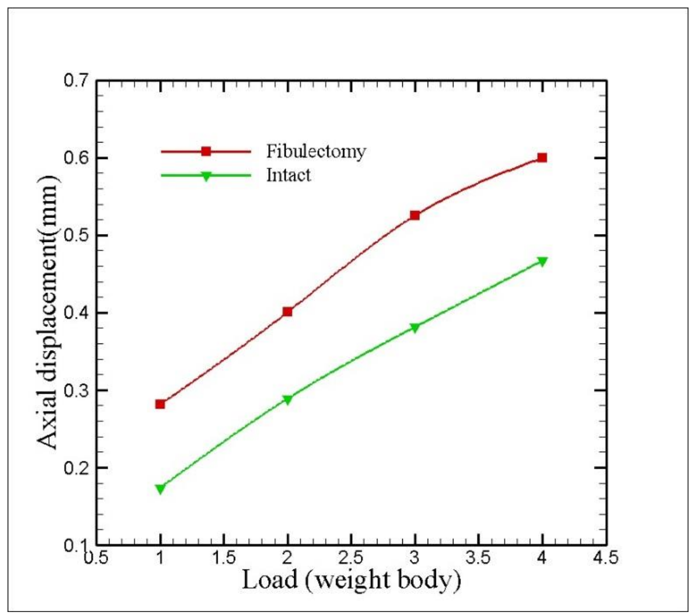

Figure 14: Axial displacement vs.load in intact knee and fibulectomy of knee

Discussion

The underlying motivation for this study was to develop a FE Model of the tibiofemoral joint that could ultimately be used to identify the effect of proximal fibulectomy on stress distribution in the tibiofemoral joint. In this paper, we present a 3D model of the healthy human knee joint. This model includes all the relevant meniscus and articular cartilages. Femur and tibia were considered to be rigid, articular cartilage and menisci linearly elastic, isotropic and homogeneous. With this model, the maximum values of stresses and stress distribution in different parts of the tibiofemoral joint and the axial displacement of the tibiofemoral joint in the intact knee were obtained. This intact model was validated using experimental and numerical results obtained by other authors [8, 11] [12]; [13]. Then for simulating proximal fibulectomy on the model, fibula bone and tibiofibular cartilage were removed from the model. The mechanical behaviors of soft tissues are reported as elastic and viscoelastic properties. In this context, hard tissues such as bone show less viscoelastic behavior under different loading conditions. In this study we study the quasi-static loading in the tibiofemoral joint and as elastic moduli of bony parts are much higher than the cartilages, we assumed them as rigid parts to reduce calculation time and costs. The maximum values of stresses and stress distribution in the fibulectomy model in different parts of the joint and also the axial displacement of the tibiofemoral joint were obtained. Our main goal was to analyze the effect of fibulectomy on the stress distribution in the tibiofemoral joint. To our knowledge, there is no study in the literature based on a finite element knee joint model that investigating the effect of fibulectomy on stress distribution in the tibiofemoral joint. Murat Bozkurt et.al [9] Investigated the dynamic features of fibular movement to gait pattern by analyzing the gait of individuals with three different parts of the fibula resected. In this study effect of fibulectomy on the tibiofemoral joint under quasi-static loading was investigated. Curtis et al., [14] and Thordarson et al., [15] in their studies on the effects of malreduction of the fibula on the tibiotalar contact area and the functions of the ankle, reported that substantial displacement of the fibula increase contact pressure on the ankle joint.

Our fibulectomy model predicted more axial displacement of the tibiofemoral joint compared to the intact model. This further axial displacement of the tibiofemoral joint under compressive loading could increase the pressure on the ankle joint, and increased pressure on the ankle joint can be a risk factor for ankle osteoarthritis. According to the results of the model, fibulectomy increases the maximum stresses in the medial part and reduces the maximum stresses in the lateral in all components of the tibiofemoral joint compared to the intact knee. This means that after applying fibulectomy the stress concentration in the medial part of the joint increase and it could cause extensive damage in the medial part.

Conclusion

Taken together, our finding shed light to the function of fibula in biomechanics of the tibiofemural joint. By using elastic materials for soft componenets, resultant showed that fibulectomy disrupted physiological distribution of stress on cartilages. Our results have been predicted that partial fibulectomy could be an unknown risk factor for osteoarthritis. In future works, we can extend our model and investigate the effect of fibulectomy on the tibiofemoral joint under dynamic loads and look at the gate by using the FE Method.

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