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New hip prosthesis design and evaluation with using finite element analysis

Yeni kalça protezi tasarımı ve sonlu elemanlar analizi kullanarak değerlendirilmesi

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New Hip Prosthesis Design and Evaluation with Using Finite Element Analysis

Highlights

- *The use of traditional hip prosthesis has some disadvantages due to mechanical problems. The main problem in the traditional prosthesis is the load transfer. The load transfer of the traditional prosthesis is not the same as the healthy femur. Because of this, the failure of the traditional prostheses occurs. The load transfer of the femur should not be changed in the prosthesis design. In this study, the new prosthesis design was developed taking into account this main issue.*

Graphical Abstract

The femur and prostheses were modeled and analyzed mechanically. The result was shown in the figure. The strain distribution was examined to determine the load transfer. The intact femur is a reference for the traditional and new prosthesis design. The new prosthesis design was given almost the same result as shown in the figure.

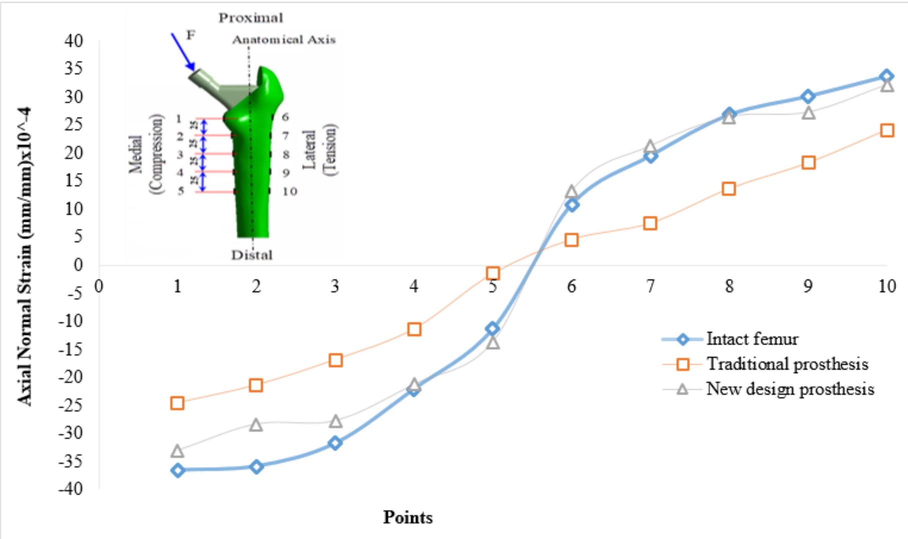

Figure. Strain distribution of ten points determined on the femur

Aim

Two different types of surgery methods, cemented and uncemented, are generally used in surgery applications having advantages and disadvantages each other in long term use. In particular, the use of traditional hip prosthesis has some disadvantages due to mechanical problems that trying to be eliminated by developing many different designs. One of the main problems of the use of hip prostheses is not transferred the bodyweight regularly through the prostheses. In this study, a new hip prosthesis design is developed to transfer the bodyweight to lower extremity without damaging.

Design & Methodology

Both femur and prostheses were modeled using a 3D solid modeling technique and were mounted to each other. The prepared femur-prostheses pairs were transferred into ANSYS Workbench software to simulate using the Finite Element based technique and subjected to the body weight and muscle forces to calculate stresses and strains.

Originality

The new hip prosthesis was designed. The design of the new prosthesis is original.

Findings

The maximum axial strain values were obtained and evaluated to determine the stress shielding.

Conclusion

Based on the results, the new design prosthesis has the risk of lower stress shielding and lower risk of failure. Therefore, the new hip prosthesis design may be used to eliminate the disadvantages in the traditional hip prostheses.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Yeni Kalça Protezi Tasarimi ve Sonlu Elemanlar Analizi Kullanarak Değerlendirilmesi

Araştırma Makalesi / Research Article

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ÖZ

Uzun süreli kullanımda birbirinin avantajları ve dezavantajları olan cerrahi uygulamalarında genellikle çimentolu ve çimentosuz olmak üzere iki farklı ameliyat yöntemi kullanılmaktadır. Özellikle geleneksel kalça protezi kullanımının birçok farklı tasarım geliştirilerek ortadan kaldırılmaya çalışılan mekanik problemler nedeniyle bazı dezavantajları vardır. Kalça protezi kullanımının temel sorunlarından biri de vücut ağırlığının protezler aracılığıyla düzenli olarak aktarılmamasıdır. Bu çalışmada vücut ağırlığının alt ekstremiteye zarar vermeden aktarılması için yeni bir kalça protezi tasarımı geliştirilmiştir. Hem femur hem de protezler 3D katı modelleme tekniği kullanılarak modellendi ve birbirine monte edildi. Hazırlanan femur-protez çiftleri, Sonlu Eleman tabanlı teknik kullanılarak simüle etmek için ANSYS Workbench yazılımına aktarıldı ve stres ve gerilmeleri hesaplamak için vücut ağırlığı ve kas kuvvetlerine tabi tutuldu. Yeni tip kalça protezi tasarımı yapıldı. Bu yeni kalça protezi tasarımı orijinaldir. Maksimum eksenel gerinim değerleri elde edildi ve stress kalkanı olayı belirlemek için değerlendirildi. Sonuçlara göre, yeni tasarım protezinin daha düşük stres kalkanı ve daha düşük başarısızlık riski vardır. Bu nedenle yeni kalça protezi tasarımı, geleneksel kalça protezlerindeki dezavantajları ortadan kaldırmak için kullanılabilir.

Anahtar Kelimeler: Kalça protezi tasarımı, sonlu elemanlar analizi, stres kalkanı, dayanım hasar.

New Hip Prosthesis Design and Evaluation with Using Finite Element Analysis

ABSTRACT

Two different types of surgery methods, cemented and uncemented, are generally used in surgery applications having advantages and disadvantages for each other in long term use. In particular, the use of traditional hip prostheses has some disadvantages due to mechanical problems that trying to be eliminated by developing many different designs. One of the main problems of the use of hip prostheses is not transferred the bodyweight regularly through the prostheses. In this study, a new hip prosthesis design is developed to transfer the body weight to lower extremity without damaging. Both femur and prostheses were modeled using a 3D solid modeling technique and were mounted to each other. The prepared femur-prostheses pairs were transferred into ANSYS Workbench software to simulate using the Finite Element based technique and subjected to the body weight and muscle forces to calculate stresses and strains. The von Mises stresses on the prostheses were examined to evaluate the prosthesis strength. The maximum axial strain values were obtained and evaluated to determine the stress shielding. Based on the results, the new design prosthesis has the risk of lower stress shielding and lower risk of failure. Therefore, the new hip prosthesis design may be used to eliminate the disadvantages in the traditional hip prostheses.

Keywords: Hip prosthesis design, finite element analysis, stress shielding, strength, failure.

1. INTRODUCTION

Total hip surgery is common used in orthopedic area. It is a hip pain relief method using two different techniques, cemented and cementless. Two techniques have advantages (such as better primary stability) and disadvantages (such as cement disease, stress shielding, aseptic loosening). These disadvantages usually caused by mechanical issues require the revisions about 85% of the hip surgery [1]. In literature, many different types of hip prostheses were designed to eliminate the mechanical problems [2-4] but still, have no solution completely.

Because, traditional prostheses, the body forces are applied to the prosthesis head and transferred to the femur through the distal end of the prosthesis. However, if the loads are not carried out and transferred by the bones rather than the prosthesis, the density of the bone is reducing and weakening, so that aseptic loosening and stress shielding are happening.

New hip prosthesis design is developed to eliminate the mechanical problems using 3D solid modeling technique in SolidWorks software. A finite element analysis (FEA) of the prostheses and femur models is performed using ANSYS Workbench software. As a conclusion, better results in terms of the stress shielding and aseptic loosening are obtained in newly designed prosthesis compared with the traditional hip prosthesis models published in the literature.

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2. MATERIAL and METHOD

The developed hip prosthesis design is basically consisting of five features; Head-neck (1), housing (2), compression screw (3), threaded bushing (4), and cortical screw (5) as seen Figure 1. The head-neck (1) is inserted into the housing (2) and fixed with compression screw (3) to prevent the femoral head collapse. The threaded bushing (4) and cortical screw (5) are used to fix the housing (2) and femur together. Traditional uncemented prosthesis was designed to compare with the developed prosthesis as shown in Figure 2a. The assembled femur-stem models were shown in Figure 2b and 2c. The femur bone was modeled with MIMICS 11 software (Materialise, Leuven, Belgium) using computerized tomography (CT) images and the surface errors were corrected. After the operations, the model of the femur was imported into SolidWorks to assemble the prosthesis. The femur-prosthesis couple was transferred into Ansys Workbench software to perform the finite element based simulations.

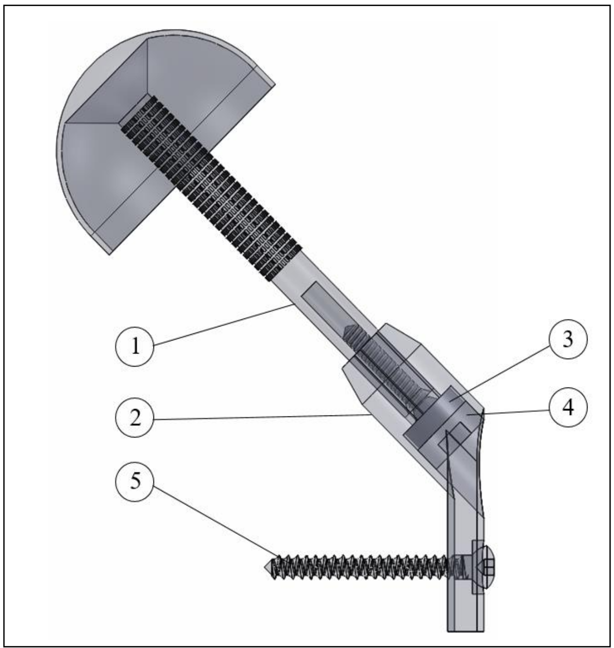

Figure 1. The developed hip prosthesis design

The Ti6Al4V material properties of the prosthesis were assumed and determined as linear isotropic and homogeneous in the ANSYS Workbench software. The Youngs' modulus of 113.000 MPa and Poisson's ratio of 0.33 is defined as the properties in the software for the Ti6Al4V material. The femur material properties were determined to its density using CT images [5].

Finite element models were generated making convergence study. As a result of the mesh convergence tests, the most suitable element sizes for the femur and prosthesis were determined as 4 mm and 1 mm, respectively. In the FEA models, Solid187 tetrahedron element type was selected. Requirement refinements were defined to get convergences in the contact regions. The interfaces between femur and prosthesis were assumed to be frictional and bonded according to the osseintagration process. The coefficient of friction was defined as 0.3 between the prosthesis and femur [6,7]. The contacts between prosthesis parts were described as bonded since the prosthesis parts were fixed each other.

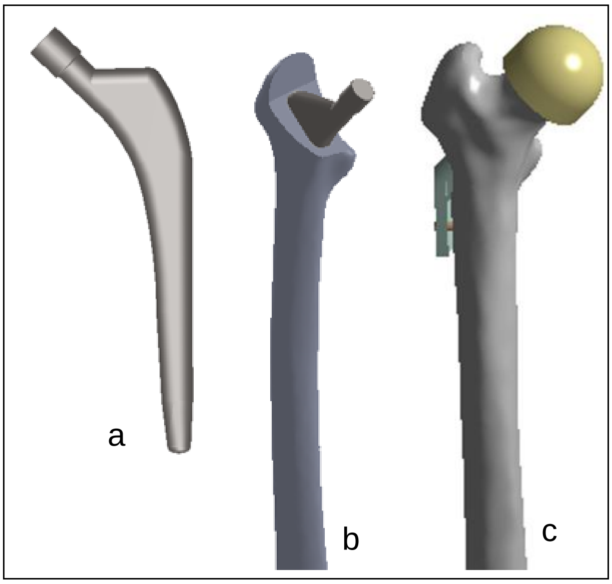

Figure 2. a) and b) The traditional hip prosthesis model with femur and c) the developed hip prosthesis and femur model

In order to simulate the prosthesis-femur couple model using the finite element based technique in the ANSYS software, the loading and boundary conditions are described as shown in Figure 3. As seen, the static loads obtained from the literature according to the body weight of a regular person in normal walking speed were applied to the prosthesis head [8]. The maximum resultant force acting on the hip joint was calculated as 1669 N, consisting of component forces as -378 N, 230 N and 1603 N acting on the directions of x, y and z axes, respectively. The muscle forces were applied to the

Table 1. The loads apllied to the femur considering 700 N weight person

Forces [N]	Fx	Fy	Fz	Fresultant
Hip Joint	378	230	1603	1669.2
Abductors	-406	-30.1	-605.5	729.7
Vastus lateralis	6.3	129.5	650.3	663.1
Tensor Fascia Latae Distal part	3.5	4.9	133	133.2
Tensor Fascia LataeProksimal part	-50.4	-81.2	-92.4	132.9

femur model as given in Table 1 [9]. The region of the femur was fixed in three directions as shown in Figure 3.

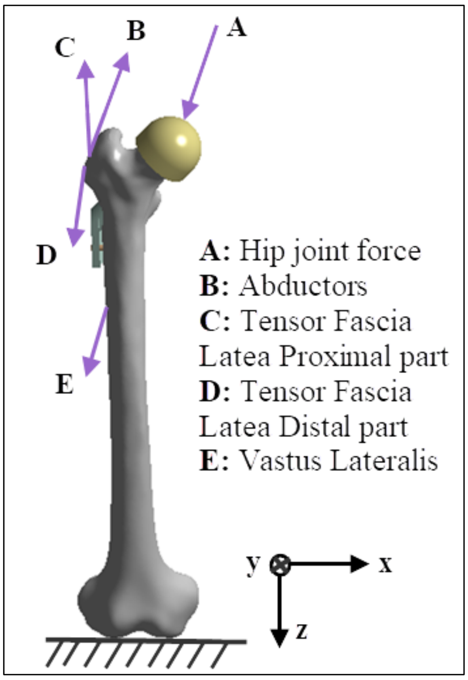

Figure 3. Loads and boundary conditions of the femur-prosthesis models

5. RESULTS AND DISCUSSION

To evaluate the results obtained from FEA, two different evaluation criteria were selected. First, the axial normal strain distributions of the femur models were calculated to indicate the stress shielding. The other one is that the von Mises stresses on both prostheses and femur were calculated to define the strength [10-13].

The maximum von Mises stress values were calculated considering the contacts among the members of the models as seen in Figure 4. The maximum von Mises stresses were obtained higher in newly design prosthesis. However, both von Mises stress values are lower than the yield strength of the Ti6Al4V material so that both models are in safe considering failures. When the contacts between the femur-prosthesis couple were defined as bonded, the stress values on the bones are increasing. The stresses on the newly designed prosthesis were calculated lower than the traditional one. The reason for the increased stress is that the quantity of prosthesis motion was decreased and caused stress concentration. The critical region of the new design is in the cortical screw where the screw and plate intersected.

Ten different point were determined on the proximal femur and the axial normal strain values were calculated at these points as seen Figure 5. As seen, three different graphs were plotted as a function selected points to evaluate the three models easily. The frictional femur-prosthesis contacts were selected to evaluate the effects of the load transfer because of the basis generation of the stress shielding incidence. The intact femur model is assumed as a reference model for the implanted femur models. Therefore, the strain values from the implanted model were calculated close to the intact femur one's which the best results are. It is seen that the traditional hip prosthesis changes the load transfer on the femur as seen in Figure 5. The forces acting on the proximal parts of the femur decreased when the traditional prosthesis was placed in the femur. When the new design was placed into the femur, the strain values were obtained nearly as the intact femur results. It is clearly seen that the traditional prosthesis gives disappointing results in terms of mechanical aspects.

To determine the appropriate hip prosthesis design, considering some problems such as strength, stress shielding, and aseptic loosening were studied to eliminate. The most important issue for the hip prostheses is the aseptic loosening caused by stress shielding [10-14]. which is related to mechanical

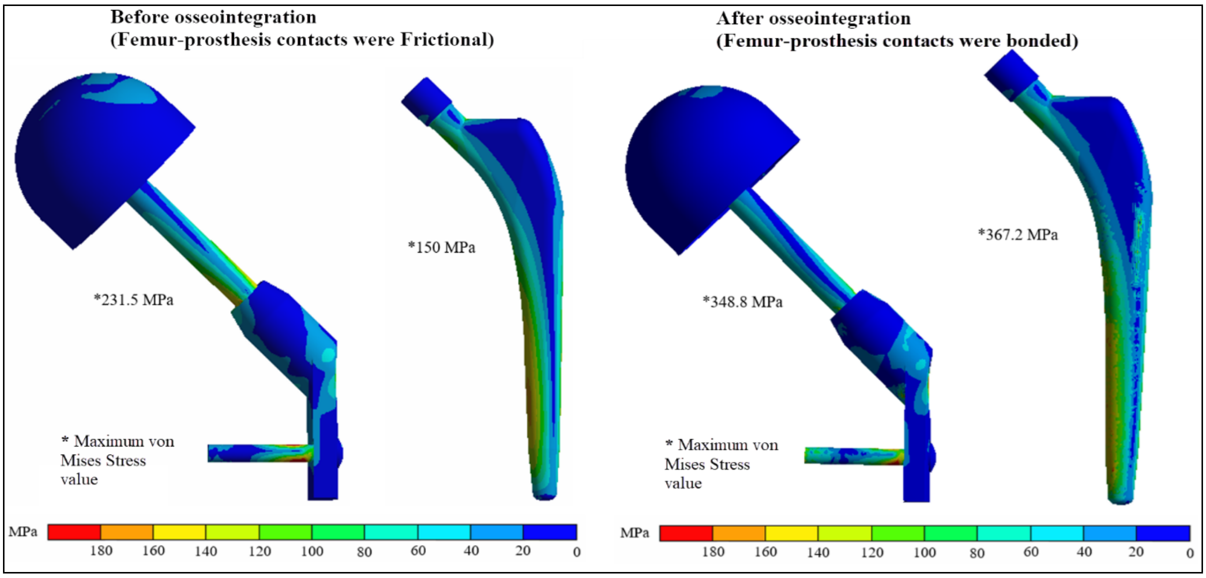

Figure 4. The maximum von Mises stresses of the developed prosthesis (before and after the osseointegration).

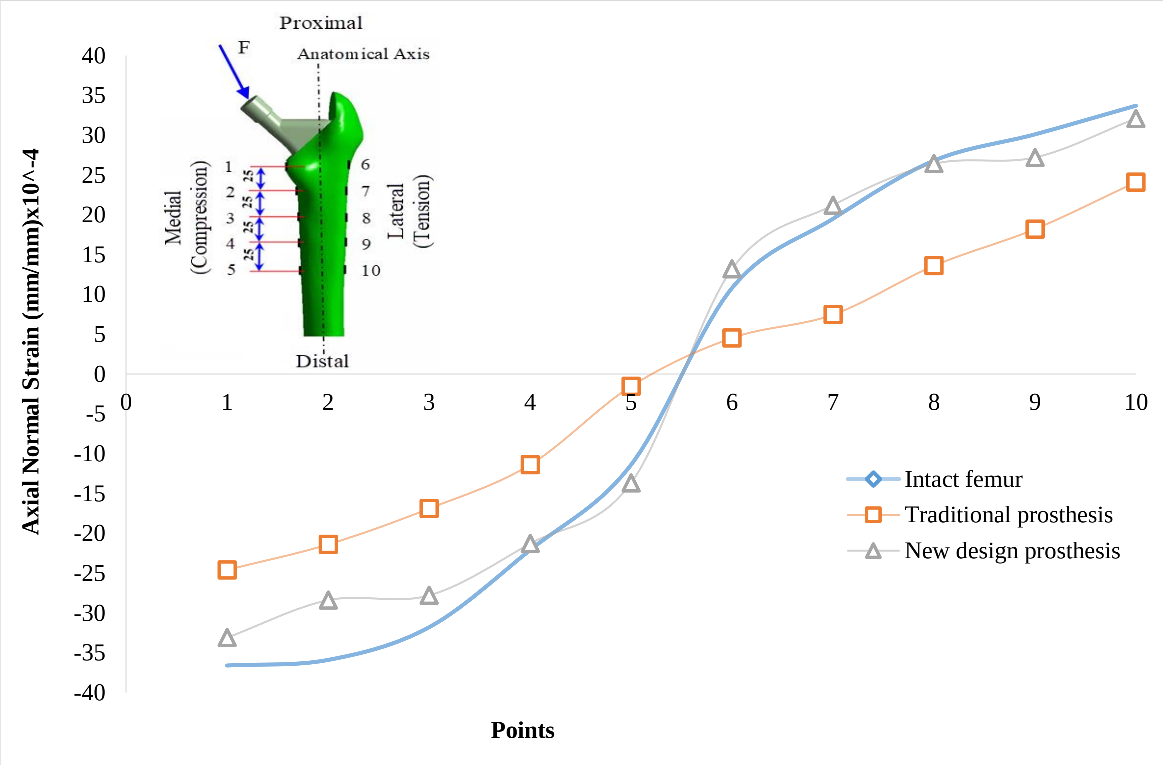

Figure 5. The axial normal strains for selected points.

viewpoints. In this study, the new design was introduced to decrease the mentioned issues. Both new and traditional prostheses were analyzed and compared to each other, referencing the intact femur using the FEA technique.

Many different types of prosthesis designs have been developed to increase prosthesis quality, since the 1950s, having similar concepts that placed into the femur. The load is transferred from the traditional prosthesis to the bones through the prosthesis distal region. The proximal femur is not governing the load transfer so that the proximal region of the femur is weakening. Therefore, the usage of the prosthesis life is shortening and the life quality of the patient is reducing [15]. In this study, a new prosthesis model is designed to change the load transfer path and the issues for the load transferring are eliminated.

The stress shielding is described by Wolff's law that is the decreasing of the stresses on the femur owing to changing load transfer [12]. Removing the bone stresses after prosthesis insertion expresses to the weakening of the femur. Therefore, the design of the prosthesis should be altered. The developed prosthesis design in this study is confirming the elimination of the mentioned issues even dislocations. The developed model is also providing less bone losing since the total femur head along with neck is cut in the traditional models. The percentage of the femur loss is about 4.3% using the developed prosthesis, but 9.1% in using the traditional prosthesis. However, the newly developed system has many parts such as head, screws, etc. that may cause friction.

6. CONCLUSION

In conclusion, the developed new prosthesis has lower stress shielding, lower femur failure, and lower dislocation risks, and provides lower bone loss.

ACKNOWLEDGEMENT

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Talip ÇELİK: Performed 3D modeling and finite element analysis. Examined the results. Wrote the manuscript.

Yasin KİŞİOĞLU: Examined the results. Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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