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Biomechanical Investigation of Human Femur by Reverse Engineering as a Robust Method and Applied Simplifications

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Abstract: Stress fracture is a type of biomechanical failure of bone caused by loads during intense physical training. This failure is very important for aged persons and athletics. Because of cell death, in some cases after emergency surgery the injured person may suffer from lifelong disability. In this research, our model was construct by means of reverse engineering method and this three-dimensional finite element model of human femur has been analyzed under single, expanded and partial expanded loads. Analysis has been performed using commercially available software. The material is assumed to have isotropic elastic characteristics. The results indicated that the important stress occurred at the inferior root of the femoral neck but maximum stress obtained at the femoral shaft. The magnitude of the strain shows good agreement with the published experimental results. This verifies the finite element modeling and the simplified model used.

Key words: Bone biomechanics · Finite element method · Reverse engineering · Human femur

INTRODUCTION

For many years, human has tried to know how the human body works. This curiosity in biologists and medical staff has pushed them to carry out several experiments to gain deeper knowledge about human organs. After emerging the computer, mathematicians have applied mathematical models to explain how the human's organs such as heart, brain, lung, blood and bone work. One of the important organs in human body is femur and its fracture stress. Hip fracture is a devastating event, especially for the elderly. The one-year mortality after hip fracture is about 20% and 20% of this living in the community at the time of their hip fracture have to admitted to a nursing home. Most patients required a formal period of rehabilitation, however, only half of the patients were successfully discharged to their own homes. Of these returning to living in the community, the majority will never regain their pre-fracture levels of physical and social activities [1].

The studies simulated the impact of oblique fall to the side, a scenario known to account for a large proportion of hip fracture in elderly and have a lower fracture load than alternative loading approaches [2]. Hip fracture is one of the most serious consequences of osteoporosis, leading to significant reductions in mobility, independence, quality of life and in some cases, increased mortality [3, 4]. The incidence and pattern of osteoporotic fractures are changing. These fractures impose a heavy financial and human cost and this is thought to be related to an aging population. Fracture of the femoral shaft are traditionally regarded as high energy injuries sustained by the young. Low energy, osteoporotic fractures are, however increasingly important and the combined effects of an aging population and the greater numbers of hip and knee prostheses being implanted will likely mean that these are often osteoporotic and periprothetic fractures of femur [5].

Because of this rapid increase mean age of the united states and other countries, the incidence of hip fracture is expected to rise significantly. This shows us, the importance of investigating in hip fracture risk estimation, to better understand the etiology of hip fracture and to prevent the patient from the worse situation by the best treatment. In mechanical analysis of the femur, we should know the hip fracture is not only consequence of the maximume stress at one area, rather the femoral structural strength is important factor [6].

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The distribution of stress using experimental analysis across the neck of the femur has been investigated [3]. Also it is presented three-dimensional stress distribution of human femur experimentally [4] and developed three-dimensional model of femur to show the effect of geometry on stress distribution on human femoral neck [7]. Thereafter, some researchers studied at the geometry of human femur [8, 9] and indicated a numerical simulation for stress and displacement of femur in a living and dead phases [10].

Computer-aided diagnosis (CAD) research started in the early 1980s and has gradually evolved as a clinically supported tool. various CAD schemes are being developed for detection and classification of many different kinds of lesions obtained with the use of various imaging modalities [11]. In recent years, the development of computer technology resulted in the integration of design and automated inspection/gauging systems in manufacturing engineering applications. Geometrical information of a product is obtained directly from a physical shape by a digitizing device and the next step is done with the help of Coordinate Measuring Machines (CMM) and CAD software. CMM is used to digitize the mechanical object. Taking coordinates (scan data) of the various points on the surface of the object and converting it into IGES file and using the same in the CAD software with required interfacing creates a surface or solid model of the object, this procedure is named reverse engineering. In fact, reverse engineering is a process of reproducing the geometry of an available physical object.

This paper has two goals, at first it aims to construct a three-dimentional (3D) femur bone from 3D optical scaning as 3D measurement devices and presents a new method means reverse engineering as a suitable method for modeling the bio structures in mechanical analysis and in continue importing this constructed model in the finite element commercial software to creat a 3D finite element model.

In second step, the finite element mothod (FEM) is applied to find the stress distribution in different static loadings on half human femur model as a simplified model. At the end, the obtained results shown good agreement with published experimental results and has better results from another numerical method.

Reverse Engineering Background: Three dimentional model of human femur was constructed using 3D-Laser scanner DS-3040 (Laser Design Inc,CMM, US), optical scaning is one of the reverse engineering interface for development of solid model. The process of reverse engineering is a three-phase process. These phases are scaning, point processing and application specific geometric model development [12].

Scaning as first phase is involved with the scaning strategy-selecting the correct scaning technique, preparing the part to be scaned, performing the actual scaning to capture information that describes all geometric features of the part such as steps, slots, pockets and holes. 3D scanners are imployed to scan the geometry, producing clouds of points, which define the surface geometry.

Point processing as second phase involves importing the point cloud data, reducing the noise in the data collected and reducing the number of points. These tasks are performed using a renge of predifined filters. This phase also allows us to merge multiple scan data sets. Sometimes, it is necessary to take multiple scan of the part to ensure that all required features have been scaned. This involves rotating the part; hence each scan datum becomes very crucial. Multiple scan planning has direct impact on the point processing phase. Good datum planning for multiple scaning will reduce the effort required in the point processing phase and also avoid introduction of errors from merging multiple scan data.

In the third phase, current reverse engineering technologies are helping to reduce the time to creat electronic computer aided design (CAD) models from existing physical representations. The need to generate CAD information from physical components will arise frequently throughout any product introduction process.

The generation of CAD models from point data is probably the most complex activity within reverse engineering because potent surface fitting algorithms are required to generate surface that accurately represent that three-dimentional information described within the point cloud data sets.

Generating surface data from point cloud data is still a very subjective process, although feature-based are beginning to emerge that will enable engineers to interact with the point cloud data to produce complete solid models for current CAD invironments.Although the process had comparatively longer processing time, the obtain results were significantly better than the other methods. The CAD model is much more aesthetic and stable in configuration and has less error data transfer formats, particularly for the integrated CAD and finite element analysis applications [13].

Finite Element Model: 3D finite element analysis is the only available technique that accounts for the complexity of the hip geometry and its material distribution [7]. In this paper, the complete human femur 3D-model whose length was 50 cm imported into the finite element commercial software and because of irregular surface of femur 3D-model, it was meshed by one element with middle node. This element has a quadratic displacement and is well suited to model irregular meshes (such as those produced from various CAD System).

For the sake of the simplicity and time and cost saving, only upper half of the femur has been modeled. This can be justified by the fact that previous studies have revealed that the critical area of interest is located at the neck segment of the upper half of the femur. Mesh of this simplified model consists of 188597 tetrahedral elements and 267076 nodes.

Some of the earlier experimental studies concluded that the trabecular tissue has a modulus in the order of 1 to 10 GPa such that the issues became controversial. However, studies using ultrasound have concluded that values for elastic modulus are about 20 percent lower than for cortical tissue. The combined computer-experiment studies that successfully eliminated end artifacts in the experimental protocols also found modulus values more typical of cortical bone than the much lower values from the earlier studies. Thus an overall consensus is emerging that the elastic modulus of trabecular tissue is similar to and perhaps slightly lower than, that of cortical bone [14]. The material is assumed to have isotropic elastic characteristics and modulus of elasticity of 17.9 GP for whole of the bone model. The Poison's ratio for bone tissue is 0.33 [14]. Single force, full distributed vertical force, partial distributed vertical force as a norm of two previous forces of 1500 N was applied to the superior surface of femoral head [15]. This surface consists of 1042 nodes. In single force application the total has been applied at one single node, in partial distributed case, force has been applied at fifty nodes. For the case of full distributed force, the load has been divided between all surface nodes. The middle of the bone shaft has been clamped and analysis has been assumed elastic static (Fig. 1).

In this issue,three points has been selected at the surface of the femur, for comparing their results with the previous experimental values and numerical method [15]. These points are consists of P_1, P_2 and P_3 and for the better comparison, the values of vertical displacement (Uz) of the femoral head has been calculated (Fig. 2).

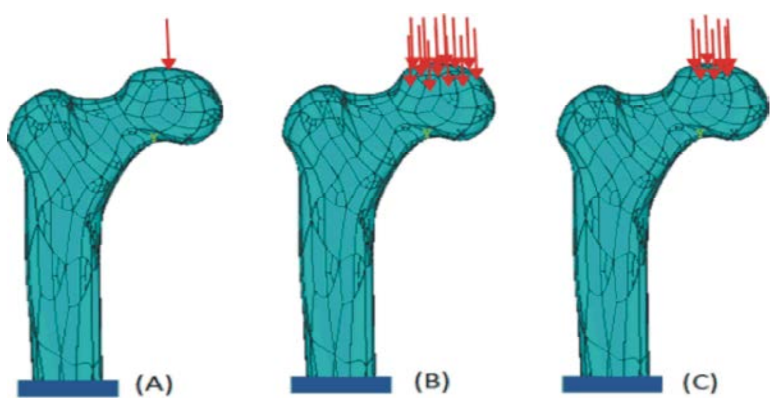

Fig. 1: loadings and boundary conditions: Single force (A). full distributed vertical force(B). partial distributed vertical force(C) was applied to the superior surface of femoral head and the middle of the bone shaft has been clamed.

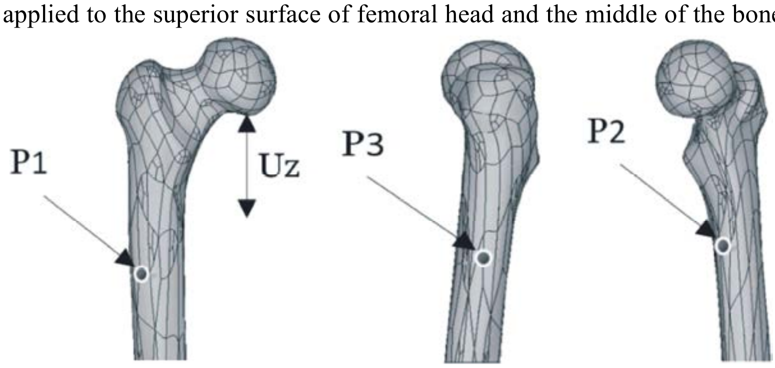

Fig. 2: Locations at which displacements and strains were measured.

Table 1: The strains of P_1, P_2 and P_3 and total displacement at 1500 N and comparing them with the values of previous experimental and numerical method.

Loading type	Experiment [10]	Yosibash *et al.* [10]	New method	Δ (%) Yosibash *et al.*	Δ (%) New mehod
Point 1 (µStrain)					
Partial load	660	168	407	-75%	-38%
Full load	660	-	405	-	-38%
Single load	660	-	792	-	20%
Point 2 (µStrain)					
Partial load	-1954	-1874	-1759	-4%	-10%
Full load	-1954	-	-1756	-	-10%
Single load	-1954	-	-1339	-	-31%
Point 3 (µStrain)					
Partial load	662	1058	944	60%	42%
Full load	662	-	946	-	42%
Single load	662	-	792	-	20%
Uz (mm×10^3)					
Partial load	450	350	475	-22%	5%
Full load	450	-	474	-	5%
Single load	450	-	488	-	8%

Δ(%)= 100×(numerical - experimental)/experimental

RESULLTS AND DISCUSSION

The obtained results of this paper have been shown good agreement with previous method and near to experimental values by new modeling method and simplifications and this affirms the accuracy of the both new modeling method and simplifications in selecting the materials type and characters (Table 1).

Although the partial loading is nearest occured loading position at the superior head of the femur because the total superior femur head has no contact with pelvis and its contact is partially, but comparing the calculated errors in different loadings have indicated the nearest results to experimental values were belong to single force and has 10% to 20% error lower than the other loadings at two points of three points (Table 1) and its reason can be attributed to the loadings situation, because in the previous experiment [15] had been used a vertical cylinder for loadings at the head of the femur bone that is like a half sphere approximately and the interface of these two surfaces is like one point and this is shown the experimental loadings situation is nearer to the single force. The total range of obtained strains values and slight errors in vertical displacement (Uz) nearly 5% and their comparison with experimental values and previous method indicate the high accuracy of the finite element model in this paper.

The stress plots (Fig. 3) show that there are two areas for maximum Von Mises stresses, that one of them is at the femoral bone shaft and the other one is at the the inferior root of the femoral neck. Nevertheless the stress at the shaft is too higher than the neck stress (aproximately 35 MP at the shaft with regard to 15 MP at the neck), because of the huge difference between compression (205 MP) and tension (135 MP) stress of the ultimate stresses of human femoral cortical bone [13] and the high tension and maximum shear stress at the femoral neck make this area to hazardous zone in failure. Of course, the producted stress at the femoral shaft shows if the stress increase by means of impact or the other reasons, the middle of the femoral shaft might occur failure like in the road accidents and so on.

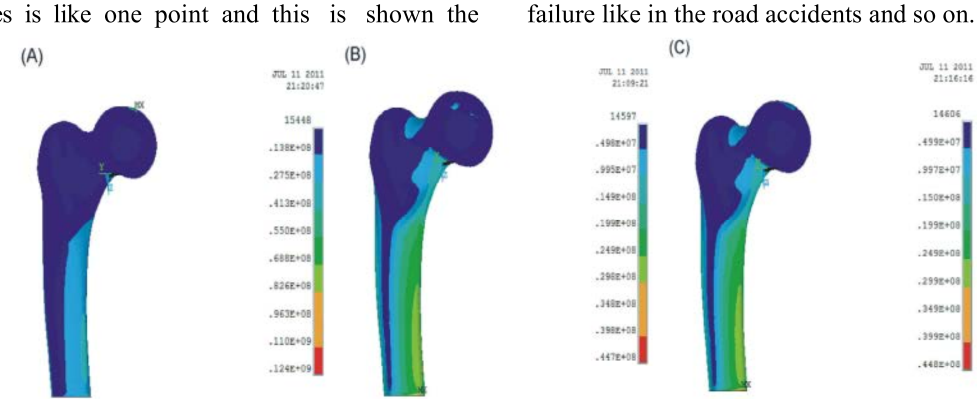

Fig. 3: Von Misses stress distribution at 1500N: Single loading(A). Full loading(B). Partial loading(C).

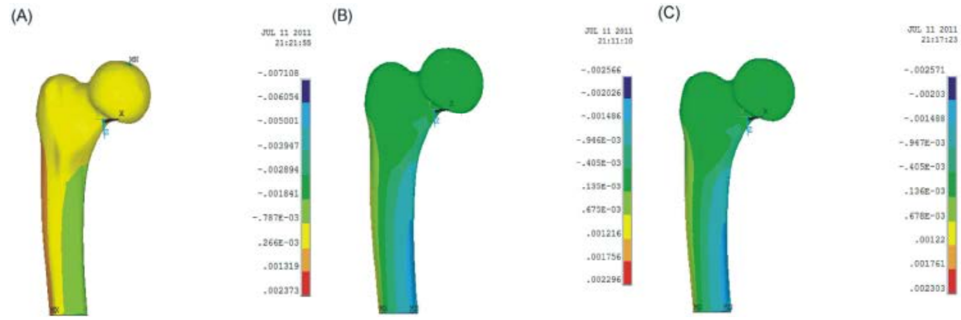

Fig. 4: Strains distribution in Z direction at 1500N: Single loading(A). Full loading(B). Partial loading(C).

In continue, though at the stains plots (Fig. 4), there are better results for the single loading at the points P_1, P_2 and P_3 but stress plots indicate the stress conditions in this loading type is unreal, by comparing the stresses in partial and full loading have found good agreement to each other in stress distribution. Then, these stress results illustrate for the simplification, instead of full loading can be used partial one.

CONCLUSION

At present, there are two methods of biomechanical analysis. One is by experimentation the other is creating a computational model. Thus, there is need for further models to be used in the field of femoral research. In the analyze of bone joints which have complicated shape, load and boundary conditions, finite element methods can be a useful tool [16]. The finite element method is a standard engineering technique in general usages.

Although bone FE models generated from QCT data have many enthusiast because of their high potential in clinic practice but there are lots of problems both in importing these models into the powerful analitical FEM softwares and appearance of many errors when the operations of solving is being done. These problems decrease this method efficiency, because the available powerful softwares have too many options that they can help the researchers in obtaining the better and higher data in their studys and researchs. For this purpose, here have been proceeded to introduce the other bio structures modeling method that it is named reverse engineering (RE) method. This method has lesser errors in importing the models into the FEM softwares and moreover, the obtained results had shown, RE products better results from the previous methods in many cases and it can indicate the robustness of this method.

Frequently, there were difficulties of cortical and trabecular subdomains separation in previous studies. It is important to mention that elastic analysis only needs the Poison's ratio and modulus of elasticity. In new studies using ultrasound and computer have concluded that there are no huge differences between values for the elastic modulus of cortical and trabecular tissue, of course this subject is realy different from the previous credence [14]. Since the Poison's ratio is nearly constant in whole of the femoral bone, here, only one material has been assumed for more simplification and the obtained results have indicated the accuracy of these simplifications and proved, this assumption can be used in elastic analysis.

Another simplification was the use of isotropic characteristics instead of anisotropic characteristics that it is very close type of material to the human bones. Of course, the accuracy of this assumption has been proved in previous works and according to it, the isotropic material is used instead of use of anisotropic material with complexity in data and have many difficulty in solving process [17].

To conclude, it is important to note that although strain obtained results in single loading was closer to experimental values because of the affinity of this kind of loading with experimental test, but according to the human anatomy, the superior surface of the femoral head has contact with pelvis and this loading is like a full one approximately. Therefore, the stress distribution of the femoral bone should be like a full force, while including model verification by results inspection have been cleared for the simplification can be used partial loading instead of full one.

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