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Finite Element Analysis of Human Femur by Reverse Engineering Modeling Method

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Abstract

The femur is one of the most highly loaded bones of the human body and its fracture is a devastating event, especially for the elderly people that the surgery is so difficult for them and athletes that it may occurs after substantial trauma. The one-year mortality after hip/femur fracture is about twenty percent and twenty percent of those living in the community at the time of their femur fracture have to be admitted to a nursing home. In this study have been used the three dimensional finite element model of the human femur that it had been constructed by means of the reverse engineering method and unlike many previous works, in this issue had been used full model instead of partial or half model and this three dimensional finite element model has been analyzed under single, expanded and partial expanded loads. The material is assumed to have isotropic elastic characteristics. The results indicated, there are two region for the maximum stresses and this kind of finite element model and its simplification has been verified with the published experimental results and this study has shown that the real produced stress-strain distribution at the human femur when a person was in the single-leg stance phase of normal running or jumping for the first time.

Keywords: Bone Biomechanics, Finite Element Method, Mechanical Analysis, Reverse Engineering

1. Introduction

A proper understanding of the biomechanical situation of the lower extremity is essential to better elucidate the relationship between its form, structure and function. In many aspects, the mechanical environment is considered a major factor influencing biological processes and therefore vital for surgical procedures, healing processes as well as therapeutic regimens[1].

The skeleton is most common organ to be affected by many diseases like metastatic cancer[2,3], osteoporosis and so on. Therefore to pay more attention to human body bone and its problems are necessary. One of the most important bones in human body is femur. Fracture of the distal part of the femur, especially for the elderly people, athletes and soldiers. The majority will never regain their pre-fracture level of physical and social activities[4] and because rapid increase means age of United States and other countries, the incidence of hip fracture is expected to raise significantly[5]. This shows us, importance of investigating in hip fracture risk estimation, to better understand the etiology of hip fracture and to prevent the patient from worse situation by the best treatment. This aim can't be obtained unless a particular study is done into the femur biomechanics.

The biomechanics of the hip is a complex system resulting from the typical geometry of the femur and muscle forces. It is therefore to obtain theoretical expression of stress-strain or displacement distributions of the femur and results of the numerical models are often compared with those obtained experimentally; using for example strain gauges[6].

Stress fractures result from repetitive cyclical loading or sudden trauma of the skeletal system in primary, over time the bone fatigue and micro-damage manifests as small cracks in the bony matrix[7]. If the accumulation of micro damage exceeds the rate of bone repair, a stress fracture will result[8] about secondary, hip fracture is not only consequence of the maximum stress at one area, rather the femoral structural strength is important factor[5].

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The femur accounts for approximately 10–33% of all stress fractures in military recruits[9,10] and approximately 4–14% in runners[11,12]. In many works had been investigated about the distribution of stress using experimental analysis across the neck of the femur[13]. Also it is presented three-dimensional stress distribution of human femur experimentally[14]. Approximately 50% of all femoral stress fractures occur at the neck[15]. Later, three-dimensional model of femur to show the effect of geometry on stress distribution on human femoral neck[16]. Thereafter, some researchers studied at the geometry of human femur[17,18] and indicated a numerical simulation for stress and displacement of femur in a living and dead phases[19].

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[20]. 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 three goals, at first it aims to construct a three-dimensional (3D) femur bone from 3D laser scanning 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 create a 3D finite element model.

In second step, the Finite Element Method (FEM) is applied to find the strain distribution in different static loadings on half human femur model as a simplified model for method and simplification validation by previous experimental researches and obtained results had good agreement with experimental values and this indicated the applied simplification, modeling method and analysis method accuracy. In continue as third step, complete model of human femur is investigated and proceeded to find its stress-strain distribution under different loadings for the first time. Because this kind of study never performed previously, for the results validating, they have been compared with the obtained facts by previous work in this literature.

2. Reverse Engineering Background

Three dimensional model of human femur was constructed using 3D-Laser scanner DS-3040 (Laser Design Inc., CMM, US). Optical scanning is one of the reverse engineering interfaces for development of solid model. The process of reverse engineering is a three-phase process. These phases are scanning, point processing and application specific geometric model development[21].

Scanning as first phase is involved with the scanning strategy-selecting the correct scanning technique, preparing the part to be scanned, performing the actual scanning to capture information that describes all geometric features of the part such as steps, slots, pockets and holes. 3D scanners are employed 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 range of predefined 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 scanned. 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 scanning 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 create 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-dimensional 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 environments. 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[22].

3. 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[16]. 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 validating the model with previous work which had investigated on half of human femur under 1000 N at first, 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. In the next step for the first time, complete model of human femur has been modeled and meshed by the same element as half model. Complete model mesh consists of 371112 tetrahedral elements and 526625 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[23].

For half model same as experimental previous work, 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 0.4[23]. Single force, full distributed vertical force, partial distributed vertical force as a norm of two previous forces of 1500 N had been applied to the superior surface of femoral head of half model and this load has been changed with 2500 N on complete model[24]. 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. For half model, the middle of the bone shaft has been clamped (Figure 1.) and in complete model, the distal femur has been clamped. At the end, analysis has been spotted elastic static.

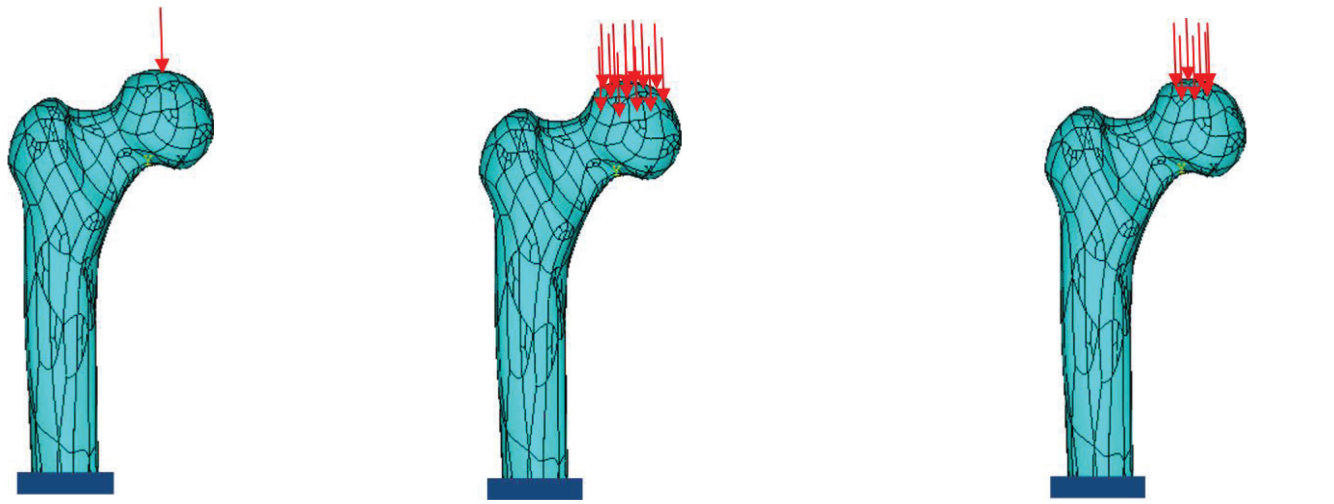
In this issue for half model, three points has been selected at the surface of the femur, for comparing their results with the previous experimental values and numerical method[24]. These points are consists of P1, P2 and P3 and for the better comparison, the values of vertical displacement (Uz) of the femoral head has been calculated (Figure 2).

4. Results and Discussion

4.1 Half Model

The obtained half model strain results of this paper (Figure 3.) have been shown good agreement with previous method and near to experimental values by new modeling method and simplifications and this affirm 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 occurred 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



(a) Single force. **(b)** Full distributed vertical force. **(c)** Partial distributed vertical force.

Figure 1. Loadings and boundary conditions: forces were applied to the superior surface of femoral head and the middle of the bone shaft has been clamped.

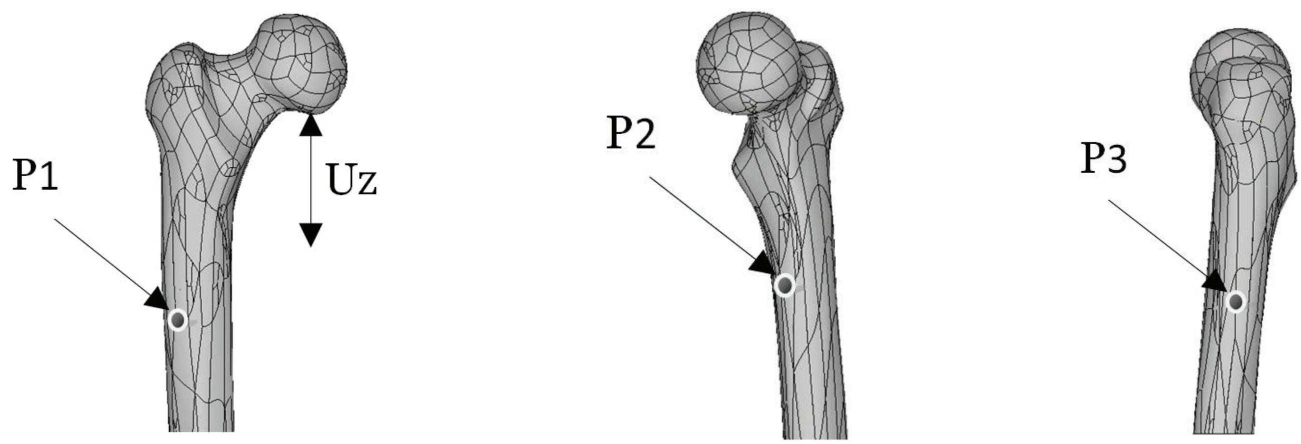
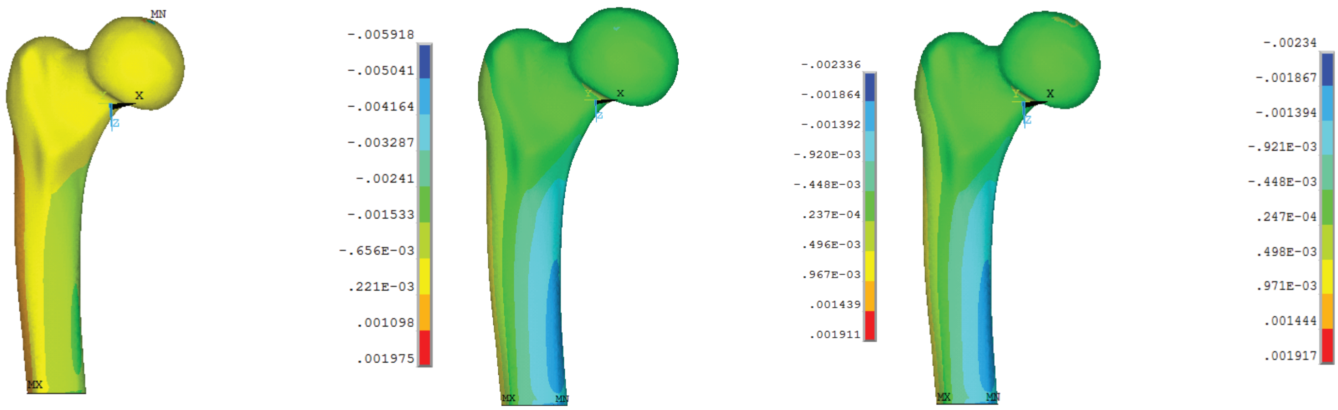


Figure 2. Locations at which displacements and strains were measured.

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[24] 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) (Figure 4.) nearly 5% and their comparison with experimental values and previous method assure us of the high accuracy of the finite element model, reverse engineering as a robustness modeling method and applied simplification in this paper.



(a) Single loading. **(b)** Full loading. **(c)** Partial loading.

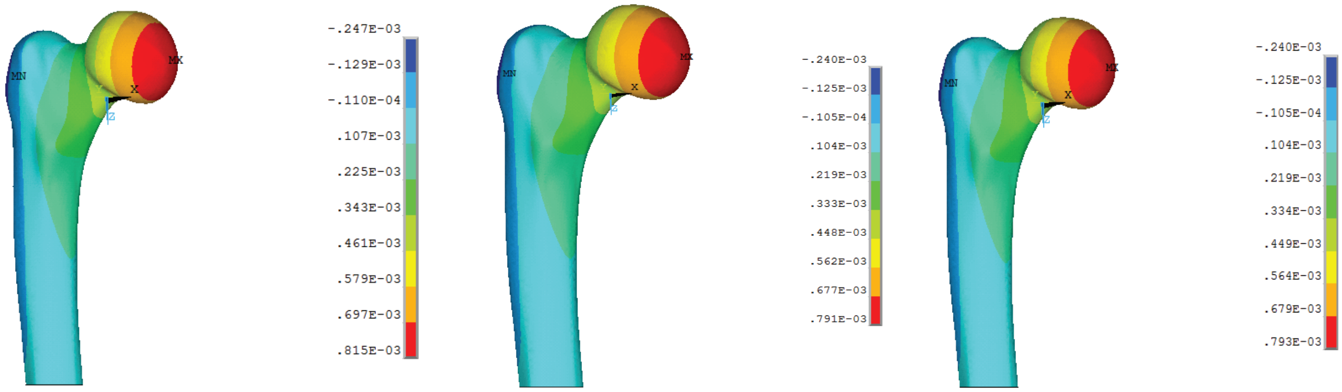
Figure 3. Strains distribution in Z direction at 1500N.

Table 1. The strains of P1, P2 and P3 and total displacement at 1500 N and comparing them with thevalues of previous experimental and numerical method[24]
Δ(%) = 100×(numerical – experimental)/experimental.

Loading type	Experiment	Yosibash et al.	New method	Δ (%) Yosibash et al.	Δ (%) New Method
			Point 1		
Partial load	660	168	735	−75%	−11%
Full load	-	-	731	-	−11%
Single load	-	-	704	-	7%
			Point 2		
Partial load	−1954	−1874	−1630	−4%	−17%
Full load	-	-	−1628	-	−17%
Single load	-	-	−1096	-	−44%
			Point 3		
Partial load	662	1058	734	60%	11%
Full load	-	-	731	-	11%
Single load	-	-	714	-	8%
			Uz		
Partial load	450	350	506	−22%	13%
Full load	-	-	505	-	13%
Single load	-	-	520	-	16%

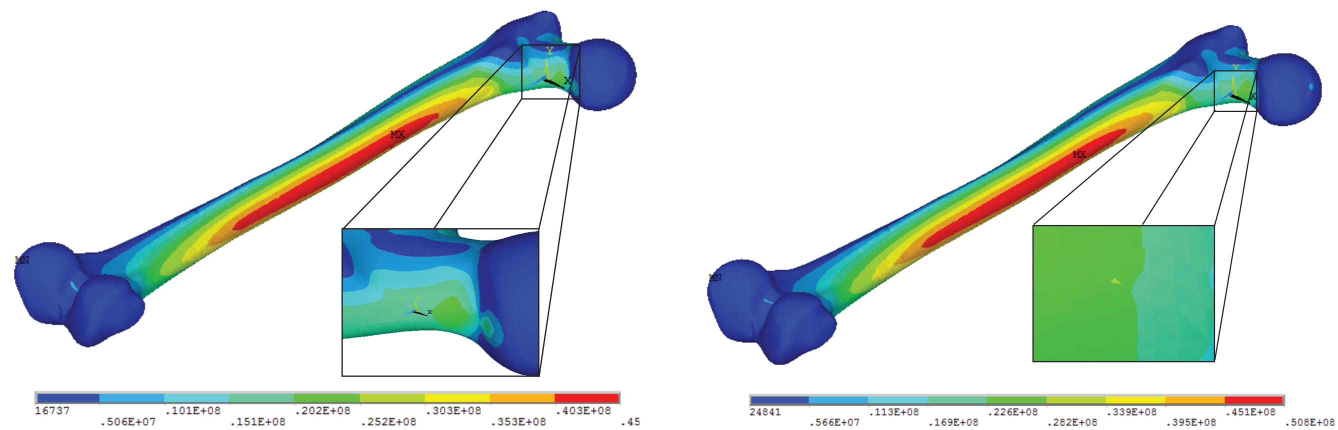
4.2 Full Model

Whereas in past studies have not been investigated full model as original and real model, here we have been studied this model in gait cycle for person with 64 Kg mass approximately. Figure 5 shows the von-Mises stress in different loadings. These plots show two maximum stress regions similar to half model. At the femoral head area, the maximum stress occur at the at the inferior root of the femoral neck, the stress value in the single-leg stance phase of normal running or jumping for complete and partial loading is 39.5 MPa and 25.2 MPa in single loading that is highly different from the other loadings. Another region with maximum stress in whole of the femur bone is middle of the femoral shaft. In this area, stress value is 50.8 MPa in complete and partial loadings and also here the stress value is different in single loading like another hazard region and it equals 45.4 MPa.

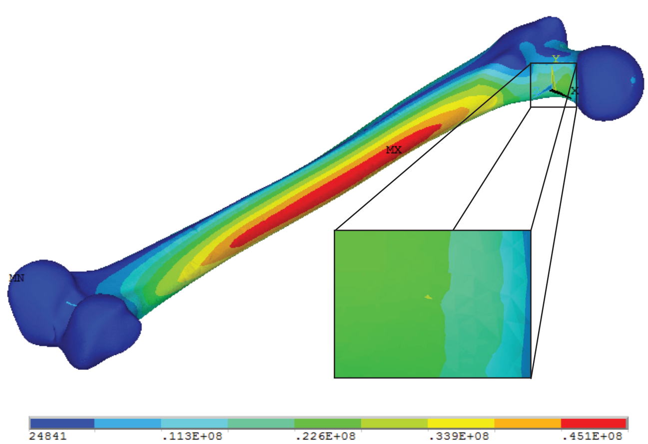


(a) Single loading. **(b)** Full loading. **(c)** Partial loading.

Figure 4. Displacement distribution in Z direction at 1500N.

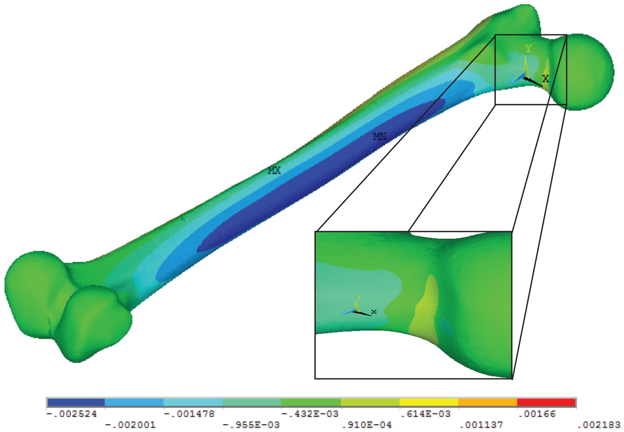


(a) Single loading. **(b)** Full loading.

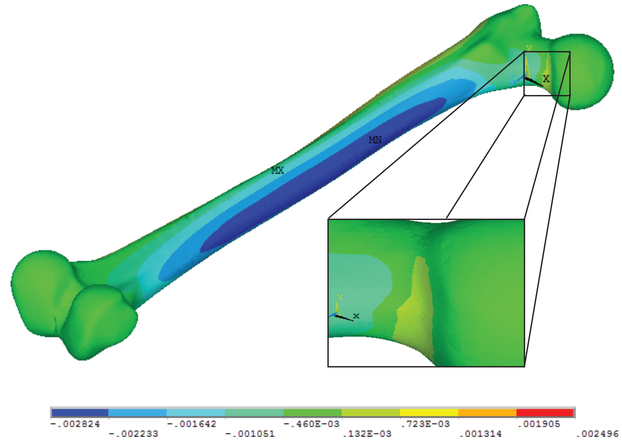


(c) Partial loading.

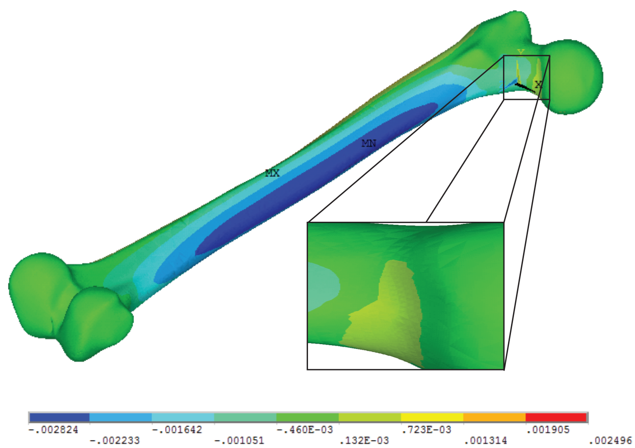
Figure 5. von-Mises stress distribution of complete model under the loading of a 2500 N.



(a) Single loading.



(b) Full loading.



(c) Partial loading.

Figure 6. Strains distribution of complete model in Z direction under the loading of a 2500 N.

Considering the 1000 N increasing load from half model to complete model, the rate of stress increase at two hazard zone in both model shows that the rate of stress increase at femoral neck is higher than femoral shaft. For instance, in partial loading on half model, the maximum stress is 40.1 MPa and it changes to 50.8 MPa in complete model but the maximum stress at femoral neck grow from 17.2 to 39.5 MPa respectively and this phenomenon shows the special human bone geometry and femoral neck as a critical zone in biomechanical failure.

Figure 6 indicates strain distribution plots in different loadings, although the human femur maximum stress occurs at the femoral shaft and the stress at the femoral neck is 10 MPa lower but because of the different bone mechanical properties in compression and tension and lower strength in tension with regard to compression and tensile stress existence at the inferior root of the neck, this region is the critical area at the human femur. By loading at this area in femoral shaft direction like in routine life manner, this region changes to hazard zone in biomechanical failure.

Here, it is intended that the obtained results are compared with previous works but such analysis with absolute model was never performed. Therefore, one of the studies in this domain with similar conditions[16] to this research has been intended to compare with each other. Although, the previous study expressed its results covered the proposition fact but by comparing this issue results with new references, former work results became controversial. So, the results have been compared with previous work in three

Table 2. von-Mises stress comparison between Voo et al. and new method[16]

New Method	Voo et al.	Loading type
Superior of the neck (MPa)		
20.2	-	Single load
22.6	75.2	Full load
22.6	-	Partial load
Inferior of the neck (MPa)		
25.2	-	Single load
39.5	188	Full load
39.5	-	Partial load
Maximum stress (MPa)		
45.4	-	Single load
50.8	188	Full load
50.8	-	Partial load

regions (Table 2.) and all of them have been compared with bone strength[25] at tension and compression (Figure 7).

Considering the comparison in Figure 7, the declared values in previous work is unacceptable because if the whole of inferior region of the neck is under compression, obtained value (maximum stress is 188 MPa) is so near to bone strength in compression (approximately 205 MPa) and this shows the slight force increasing on the bone causes failure. Whereas, new experimental results[26] express that human femur bears up to eleven times of body weight on hard physical activity like intense running, considering that at former study the force was four time of body weight and this shows the lack of results accuracy in that research and indicates approximate logical results of this work.

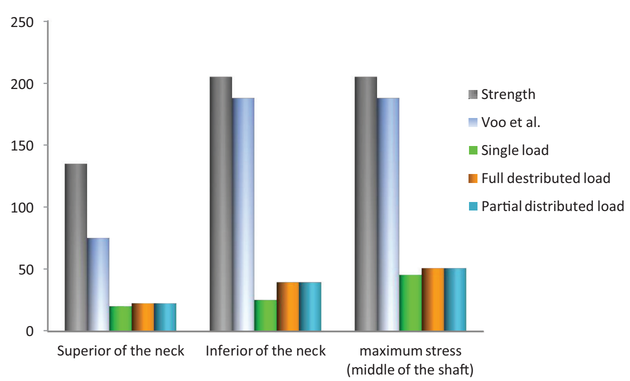


Figure 7. Comparison of peak stresses in the femur with femoral cortical bone strength in compression and tension, under the loading of a 2500-N compressive force at the femoral head between previous[16] and new research.

5. 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 analysis of bone joints which have complicated shape, load and boundary conditions, finite element methods can be a useful tool[27]. 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 analytical FEM software and appearance of many errors when the operations of solving is being done. These problems decrease this method efficiency, because the available powerful software has too many options that they can help the researchers in obtaining the better and higher data in their studies and researches. 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 software 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 really different from the previous credence[23]. 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[25].

To conclude, for the first time in this issue was obtained a neat stress-strain distribution and this consequence can be used to simplify the complicated geometrical model of human femur and cause to new models with real reaction under different loadings in mechanical analysis. Considering the displacement values in different loadings and their good agreement with experimental results at all kind of loadings, this indicated for analysis of displacement like orthopedic studies can be used single loading instead of full and partial one in half model whereas this is not accurate in full model.

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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