International Conference on
RESEARCH IN
MECHANICAL ENGINEERING
15 December 2016 Singapore
www.rmeconf.com
RMECONF

Resistance analysis of Tibia bone on upper, midell and terminal sections by compressive strength testing and FEM

Farshad Vatankhahan [1]
B.Sc., Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Iran
fvatank@gmail.com

Moeinoddin Mahmoudi [2*]
B.Sc., Department of Mechanical Engineering, Central Tehran Branch, Islamic Azad University, Iran
moienmahmoudi@yahoo.com

Majid Salehi [3]
M.S., Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Iran
Salehi.majid89@yahoo.com

Abstract

So far different researches have been done on human Tibia bone via various tests such as impact and torsion test and the effects of different parameters have been examined; for example age, height and sexuality on the bone resistance and strength. In this paper, the purpose is, study of Tibia bone resistance in three upper, middle and terminal parts as experimental through compressive test and finite element method. In this way that a Tibia bone has been cut to the three equal parts with the length 30 mm of three upper, middle and terminal districts, and it has been tested and assessed separately and the results have been compared with each other at the end. The results of stress-strain changes graph and force-extension graph showed that pushing resistance in the middle part was more than other parts and upper district of Tibia has less resistance than others, and Tibia bone had a fragile and crisp behavior, and it breaks quickly after passing of yield stress.

Keywords: Human Tibia, Stress on Tibia, Bone strength, Biomechanics, Finite element

1. Introduction

The most important parts of human skeleton include main bones of basin (hip), thigh, and ankle. Nowadays, in biomechanics and anatomy sciences, various researches do on human bones. Because of the different exterior tensions on foot bones like Tibia and Femur (Dall'Ara et al, 2016) daily, and the fact that they are the strongest bones of mammals like human, biomechanics and anatomy researchers have decided to do more researchers on this bones to examine the behavior of them in different positions. The sample of such researchers include fatigue effects of long-term standing on ankle (Mehboob and Chang, 2014), stress analysis in basin, thigh and Tibia bones (Filardi and Milardi, 2017), Tibia fracture behavior in street crashes (Mo et al, 2012), examining of fracture development behavior in Tibia bone breaking (Avery et al, 2013). Effects of caries age and sexuality (Rabl et al, 1996) on the strength and resistance of human Tibia and Fibula and stress-strain changes analysis in finite element (FE) analysis (Filardi and Milardi, 2017), (Mehboob and Chang, 2014), and Tibia assimilation-totally the done tests on the bones are torsion (Cristofolini et al, 2013) and impact (Rabl et al, 1996) destructive test. Because the exterior and interior different factors effect on bones strength reduction. Especially Tibia some of the researchers have tried to rise the resistance, strength and utility of these bones in different tests by different biomechanics methods which it can refers to the use of biodegrable composite plates (Mehboob and Chang, 2014) and the types of implants (Kumbhalkar et al, 2013).

In this paper, the purpose of examining human Tibia bone strength is in three upper, middle and terminal areas. In all of the done researches, Tibia complete bone has been used. But in this research, three mentioned areas have tested practically and separately. Tibia bone has been chosen and cut to the three equal districts 30 mm of three upper, middle and terminal areas. These three areas have had a pressure and the strength of Tibia has been examined completely. At the end, curve effects, casing thickness, cross section and the shape of sections in bone on its strength have been examined. Final results showed that Tibia bone resistance in upper area had been less than other areas and the most resistance belongs to the middle area of Tibia.

2. The introduce of Tibia and Fibula

2.1. Tibia

The Tibia known as the Shinbone or Shank bone, is the larger and stronger of the two bones in the leg below the knee in vertebrates (the other being the Fibula), and it connects the knee with the ankle bones. The Tibia is found on the medial side of the leg next to the Fibula, and closer to the median plane or center-line. The Tibia is connected to the Fibula by the interosseous membrane of the leg, forming a type of fibrous joint called a syndesmosis with very little movement (Drake et al, 2010). The Tibia is named for the flute Tibia. It is the second largest bone in the human body next to the Femur. The leg bones are the strongest long bones as they support the rest of the body. In human anatomy, the Tibia is the largest bone after the Femur. This component of human body as another vertebrates, locate between the knee and ankle joints. Femur, Tibia and Fibula are the strongest long bones and they have to support the weight of the body.The Tibia is connected to four parts; the knee and ankle join, superior and inferior Tibia Fibular joint. In the knee the Tibia forms one of the two articulations with the Femur, often referred to as the Tibia femoral components of the knee joint (Drake et al, 2010). The Tibia Fibula joints are the articulations between the Tibia and Fibula which allows very little movement the proximal Tibia Fibular joint is a small plane joint. The joint is formed between the undersurface of the lateral Tibia condyle and the head of Fibula. The joint capsule is reinforced by anterior and posterior ligament of the head of the Fibula. The distal Tibia Fibular joint is formed by the rough, convex surface of the medial side of the distal end of the Fibula, and a rough concave surface on the lateral side of the Tibia. The part of the ankle joint known as the talocrural joint, is a synovial hinge joint that connects the distal ends of the Tibia and Fibula in the lower limb with the proximal end of the talus. As mentioned, the top of the Tibia connects to the knee joint and the bottom of the Tibia connects to the ankle joint although this bone carries all the body's weight, it needs support from the Fibula (Nelson et al, 1960).

2.2. Fibula

The Fibula or calf bone is a leg bone that is located on the lateral side of the Tibia, with which it is connected above and below. It is the smaller of the two bones, and, in proportion to its length, the slenderest of all the long bones. Its upper extremity is small, placed toward the back of the head of the Tibia, below the level of the knee joint, and it is excluded from the formation of this joint. Its lower extremity inclines a little forward, so as to be on a plane anterior to that of the upper end; it projects below the Tibia, and forms the lateral part of the ankle-joint (Bojsen-Møller et al, 2001).

2.2.1. Borders

The anterolateral border begins above in front of the head, runs vertically downward to a little below the middle of the bone, and then curving somewhat lateral ward, and bifurcates so as to embrace a triangular subcutaneous surface immediately above the lateral malleolus. This border gives attachment to an intramuscular septum, which separates the extensor muscles on the anterior surface of the leg from the peroneus longus and brevis on the lateral surface (Bojsen-Møller et al, 2001). The antero medial border, or interosseous crest, is situated close to the medial side of the preceding, and runs nearly parallel with it in the upper third of its extent, but it diverges from it in the lower two-thirds. It begins above just beneath the head of the bone (sometimes it is quite indistinct for about 2.5 cm. below the head), and ends at the apex of a rough triangular surface immediately above the articular facet of the lateral malleolus. It serves for the attachment of the interosseous membrane, which separates the extensor muscles in front from the flexor muscles behind (Bojsen-Møller et al, 2001). The poster lateral border is prominent; it begins above at the apex, and ends below in the posterior border of the lateral malleolus. It is directed lateral ward above, backward in the middle of its course, backward, and a little medial ward below, and gives attachment to an aponeurosis which separates the peronaei on the lateral surface from the flexor muscles on the posterior surface. The postero medial border, sometimes called the oblique line, begins above at the medial side of the head, and ends by becoming continuous with the interosseous crest at the lower fourth of the bone. It is well-marked and prominent at the upper and middle parts of the bone. It gives attachment to an aponeurosis which separates the Tibialis posterior from the soleus and flexor hallucis longus. The anterior surface is the interval between the anterolateral and antero medial borders. It is extremely narrow and flat in the upper third of its extent; broader and grooved longitudinally in its lower third; it serves for the origin of three muscles: the extensor digitorum longus, extensor hallucis longus, and peroneus tertius (Bojsen-Møller et al, 2001).

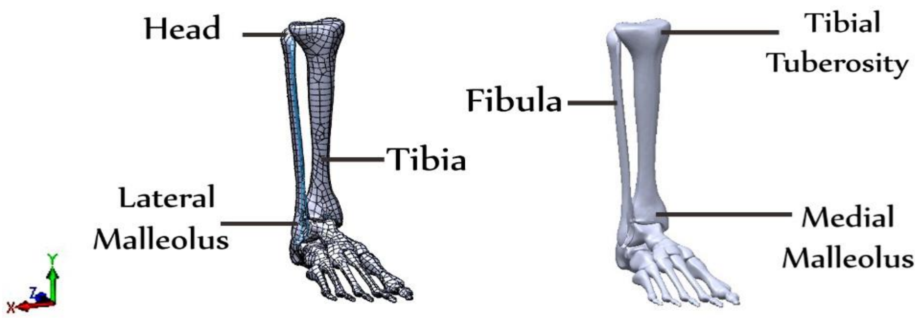


Fig. 1. The main components of the human Tibia and Fibula in the lower leg (model designed in software)

In Figure 1, all of the Tibia and Fibula bone main parts and the method of joining joints have mentioned. The shown bones have been designed three-dimensional in software. Tibia bone is connected to the knee joint from the upper and it is connected to the ankle of down (Filardi, 2015). Tibia bone is one of the strongest bones of the human body which it will be examined and tested.

In this research in upper areas (near to the knee joint) and in the middle and terminal areas (near to the ankle) for the strength. In the following section, a Tibia bone has been shown and the selection method of three parts has been described.

3. Method

According to Figure 2, Tibia bone main length is 359 mm and Fibula bone strength is 365 mm. main characteristics of provided bones have been brought in Table 1. Tibia bone has provided of dissection laboratory which belongs to a thirty-seven years old. He has died in 2013, but because it has been in a protected environment followed by the preservative materials, so it has been prevented of the relative decay and it was chosen for the destructive tests. According to the previous section, bone rather than other members of body destroys will less incline because it has a higher strength than other bones of human body. This case caused to use of this bone in its equality with the ideal position of bone.

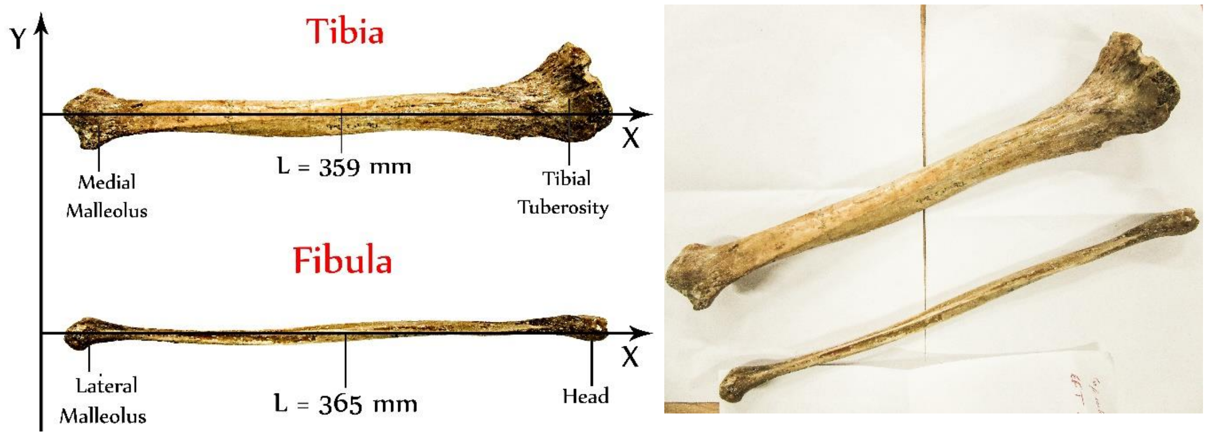


Fig. 2. Tibia and Fibula bones prepared for the compressive test. In the left image, the original size and the bones shown.

Other mechanic characteristics (and properties) of bone like elasticity modules and poisson's ratio have been shown in Table 1 (Rabl et al, 1996):

Table. 1. Main specifications of Tibia bone

Specifications of Tibia						
Age	**Gender**	**Date of Death**	**Cause of Death**	**Tibia Elasticity Modulus (MPa)**	**Fibula Elasticity Modules (MPa)**	**Poisson Ratio**
37	Male	2013	Natural Death	185	188	0.48

In this paper, the aim is to examine the resistance and strength of three parts of Tibia and Fibula bone has not been examined. Tibia bone has been divided in three equal parts 30 mm. upper part is near to the knee joint and terminal part is near to the ankle. Because the cross sections in the length of bone are not the same and bone central hole has a variant diameter and the exterior surfaces of Tibia bone are not the same (in some parts circle and in some parts triangular), as a result resistance and length in the ankle are not the same. According to Figure 3-b, each three chosen part has been cut vertically and cross sections in each three parts have been shown. Cross sections in the bone length are different very much. In Tibia 1 which has located in the upper part, it has circle surface but in the middle part, it has an irregular shape. Casing and thickness of bone are variant completely. According to Figure 3-b, in each section thickness of casing is not the same. This cause to see a different behavior of bone in different sections in a destructive test like press (pushing) test. In the following, the beginning in the areas with less thickness, fracture has made. Whatever casing thickness is more and cross section has a less angle, so bone resistance is higher. In the following section, each three introduced parts have cut and tested.

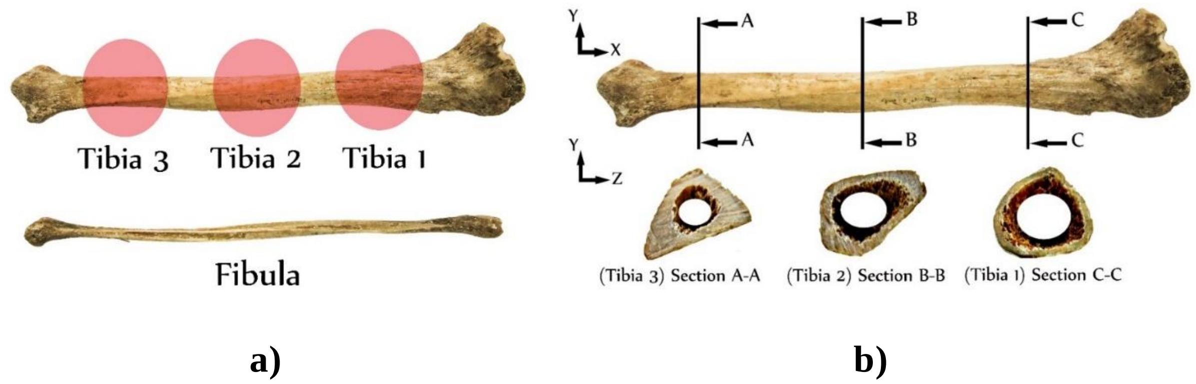


Fig. 3. a) In this image, three parts of the Tibia is marked with a red circle (the upper part, middle part and end). Those three points were selected for the compressive strength test (the length of each part is considered identical with each other). b) Outlined in the previous section, in this photo are shown as vertical sections. As you can see, the cross-section and main cavities (holes) of the Tibia is variable. And in bone length, size is not the same size.

Mentioned areas in the previous section have cut the same. In Figure 4, you can see the difference in central hole, casing thickness and cross sections in three areas. It is expected that in Tibia upper part, resistance and strength be less. Because it has the most diameter of central hole and the less thickness than other areas (Figure 4 part 2). Part three in Figure 4 belongs to the terminal part of Tibia bone which shows whatever we can be nearer to the ankle, cross section behavior in Tibia will be triangular.by digit method mentioned bone in software has been modeled to measure cross sections with a high care (Figure 4).

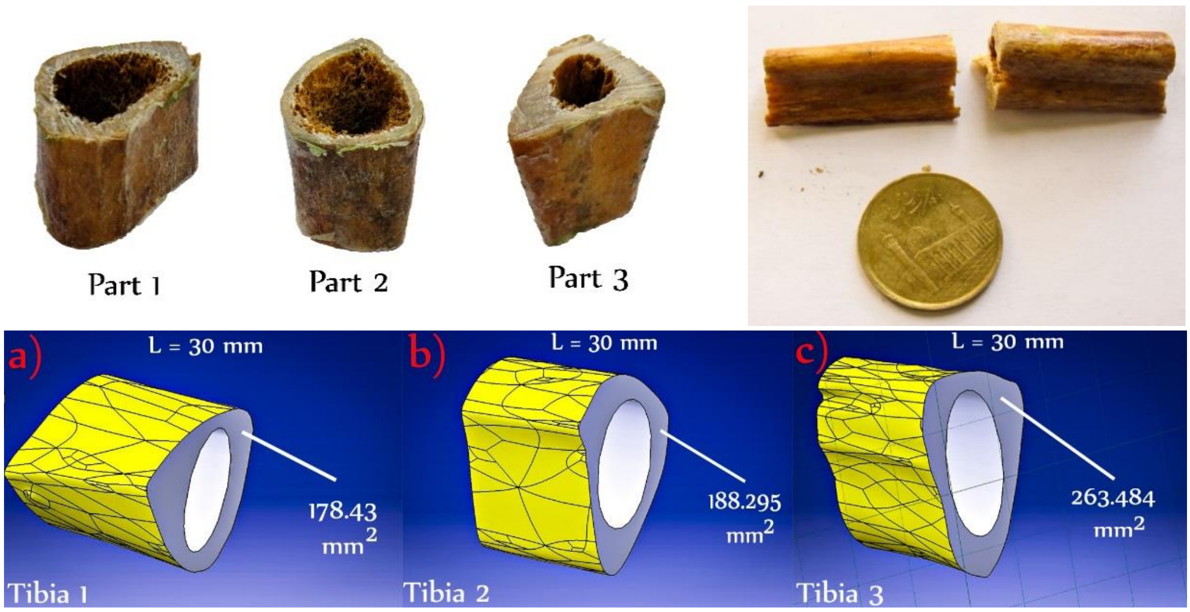


Fig. 4. Three-dimensional view of the Tibia 1, 2 and 3 (three parts of the Tibia is cut with saw) and simulation of selected samples of the Tibia using the digit. According to the picture, the sections are cut from Tibia length 30 mm. Levels of sections are not identical with each other. (Sections, is obtained with digit levels and bone modeling in CATIA software).

4. Compressive strength testing

Compressive strength or compression strength is the capacity of a material or structure to withstand loads tending to reduce size, as opposed to tensile strength, which withstands loads tending to elongate. In other words, compressive strength resists compression (being pushed together), whereas tensile strength resists tension (being pulled apart). In the section of strength of materials, tensile strength, compressive strength, and shear strength can be analyzed independently. Some materials fracture at their compressive strength limit; others deform irreversibly, so a given amount of deformation may be considered as the limit for compressive load. Compressive strength is a key value for design of structures.

Compressive strength is often measured on a universal testing machine; these range from very small table-top systems to ones with over 53 MN capacity. Measurements of compressive strength are affected by the specific test method and conditions of measurement. Compressive strengths are usually reported in relationship to a specific technical standard.

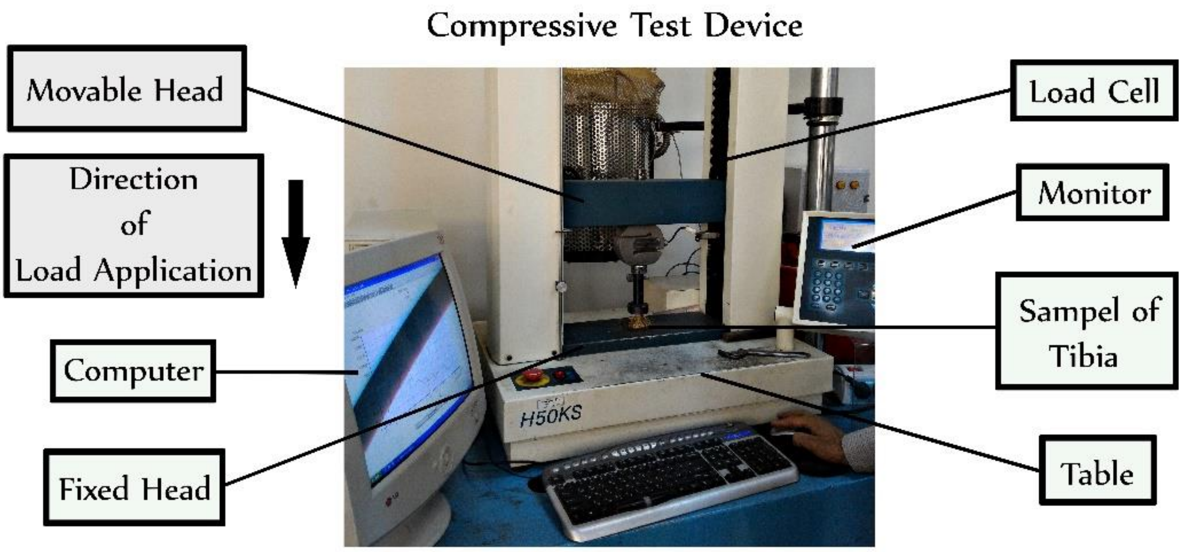


Fig. 5. Compressive strength testing for Tibia 1, and main part of device

According to Figure 5, cut Tibias (1, 2 and 3) will be tested separately. Method of test is that Tibia locates in the machine vertically along of loading and it is fixed of mandible and movable head, moves to the down with a definite speed to do the fracture completely. Distance of two jaws has adjusted according to Tibia main length. In monitor machine, speed of maxilla has given instantly and ratio of force to the extension has been determined in different time of loading and in computer, changes graph of it has been brought. Next, obtained results of test will be examined through stress-strain graph for each three Tibia.

4.1. Final test

According to the mentioned descriptions in the previous section, each three parts of Tibia has tested in turn and separately .in Figure 6 three stages of compressive test time have been shown (primary loading time, loading time to fracture moment, complete fracture stage). Done test was conducted quickly and Tibia resistance was obtained 1, 2 and 3 in the shape of force-extension changes graph. Fracture behavior is similar to the viscous behavior in bone and after passing of yield stress extent, it breaks quickly and it doesn’t show a plastic and elastic behavior.

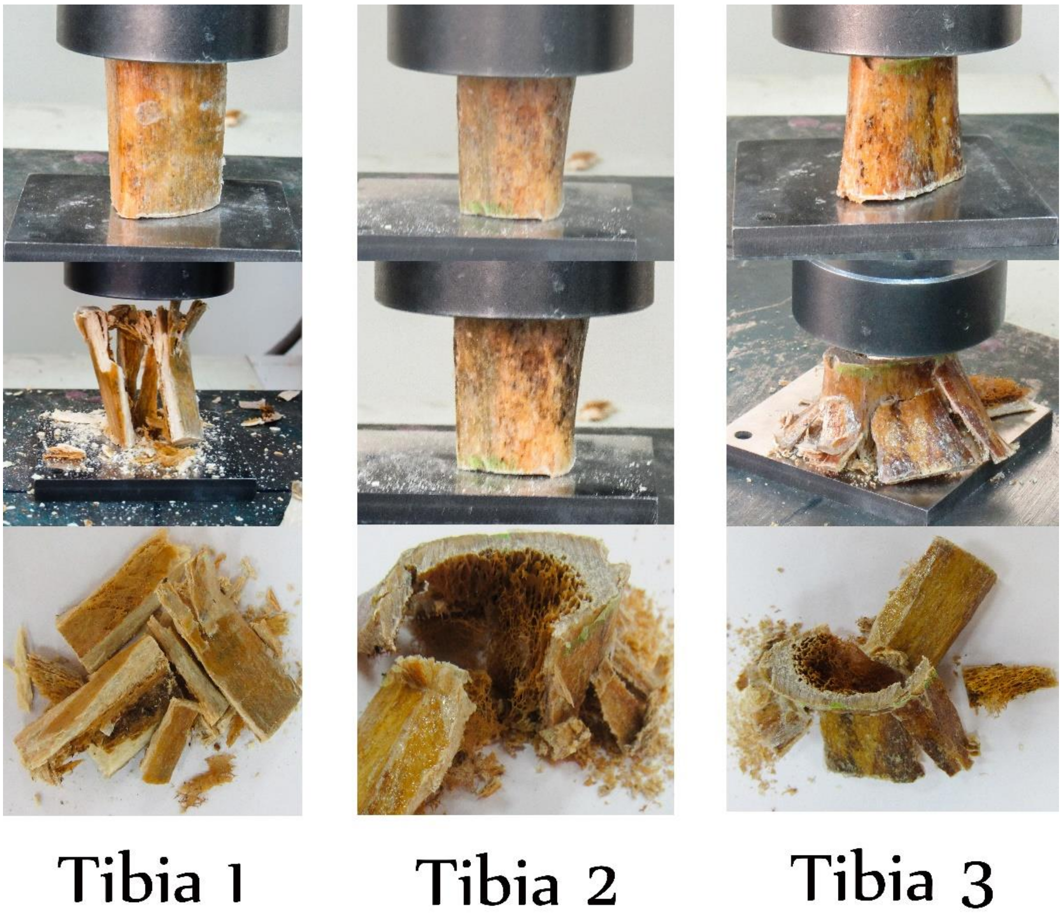


Fig. 6. Three stages of the Tibia compressive strength test. In the upper image pre-loading and loading up the stage in the second breakage and the end of figure, Tibia fractures has been shown. Compressive test on the Tibia component. Stages of loading to the point of complete failure of the Tibia.

5. Results

5.1. Failure analysis

After done loading in compressive test on Tibia 1, 2 and 3 and after passing of yield stress in bone, Tibia enters the fracture area quickly and it has been done completely. Bone behavior is like viscous material and shape change is not seen in the loading time and fracture like Figure 7 makes once and afterwards fracture does completely.

Plastic area in viscous material is not like the behavior of soft materials and like shown bone, constant changes do once and remaining tensions do not make inside of element bone. As it was said before, Tibia bone has different cross sections and main hole in Tibia length is not the same. This factor causes that resistance and length in bone change and shown fractures don't make in similar time in press test. The place of beginning fracture in the exterior and interior surface of bone depend on the different factors and they are not predictable in advance.

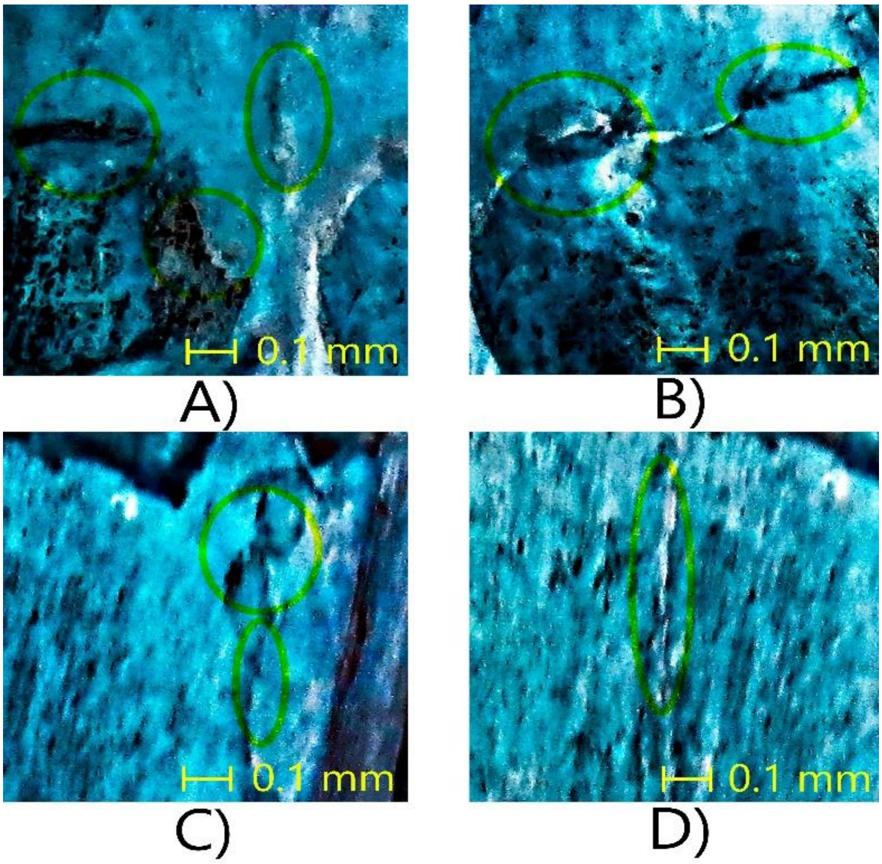


Fig. 7. The time of beginning fracture in the exterior surfaces of the Tibia 1 and 2 in the pressure test - Pictures A and B are in different areas of the exterior surfaces of the Tibia 1 and pictures C and D are include of the Tibia 2.

5.2. Stress analysis

According to the previous section, three areas of Tibia 1, 2 and 3 have been tested and press test machine based on the low of maxilla (with a definite speed) shows extension amount in the test by mm unite. Whatever extension is more, force increases for tested sample (Extension=0 means maxilla is tangent to the upper surface of Tibia). It is done to the time that tested sample of Tibia breaks completely. We can see the force exert in different extension-force changes based on extension draws in a force-extension graph for each tested sample. All of the results have been shown in graphs of Figure 8. Tibia 1 has been increased to reach to the max force, and force is followed by severe drop. This force drop is when Tibia 1 breaks completely, but in this test after a complete fracture of sample, loading continuous that it has been shown by error but it is not examined in this paper.

In right graph of figure, we can see stress-strain graphs for each three parts of Tibia 1, 2 and 3 which they have a similar graph with force-extension graph. In this graphs, yield stress extent has been obtained approximately.

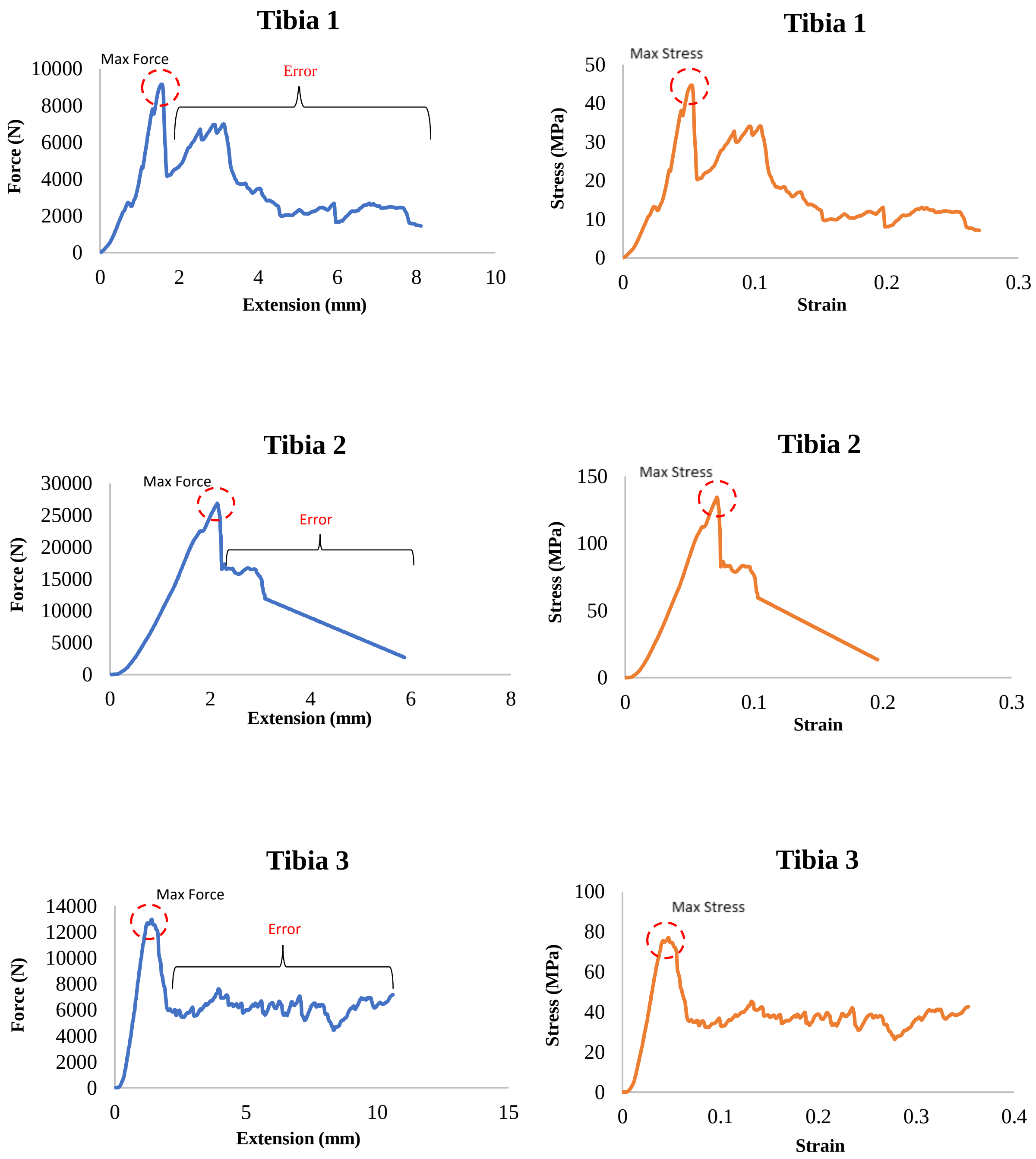


Fig. 8. Force-Extension and Stress-Strain graphs for Tibia 1, 2 and 3

In graph of Figure 11, all of errors have removed and three Tibia have compared to each other.

5.3. Failure algorithm by FEM

In this part, Tibia 1, 2 and 3 have analyzed separately through components method. Analysis method is in this way that at first each three Tibia is meshing and then the way of test loading on each three Tibia has exerted. From the down side, mentioned Tibia has fixed and from upside, one plate with a constant and definite speed comes down to press on Tibia (according to the maxilla speed in press test). In this analysis, according to the geometry of each Tibia, one break algorithm has obtained and analysis results have extracted. According to the Figure 9, you see that Tibia 2 has mashed from upside but Tibia 1 and 3 have passed from yield stress and they have less resistance than Tibia 2.

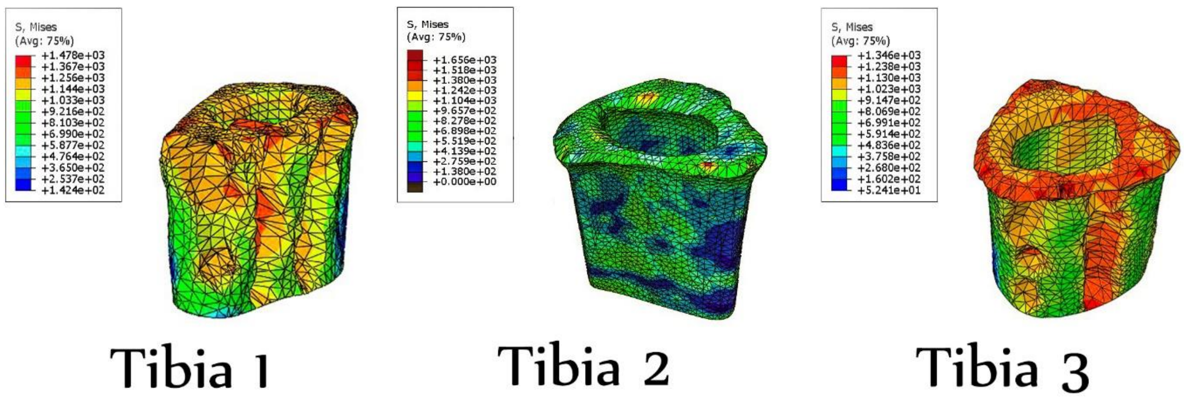
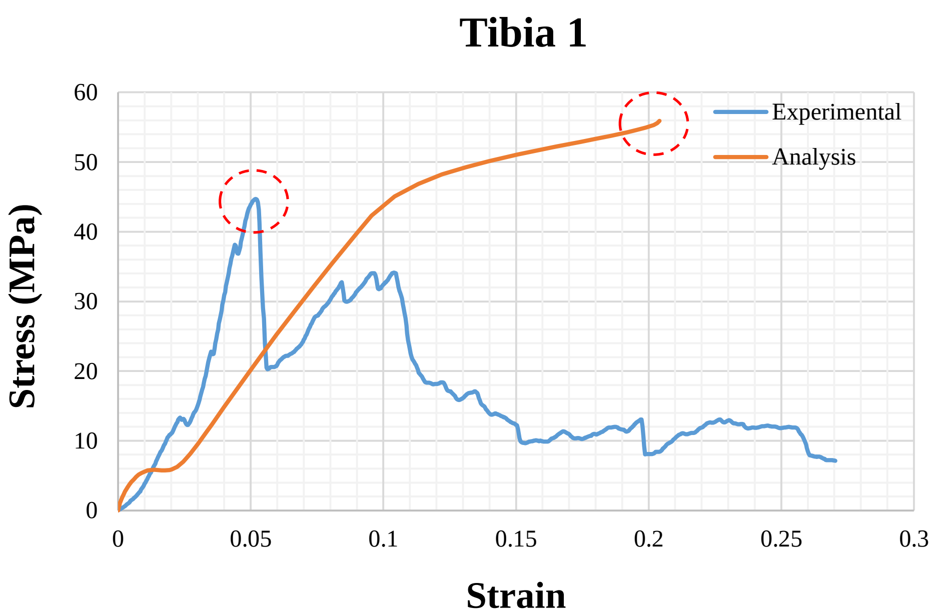


Fig. 9. Stress contours for Tibia 1, Tibia 2, and Tibia 3

In stress-strain graph in Figure 10, it has shown that stress changes on strain has brought for two experimental and analytical states. Differences derived of bone decay and relative errors of machine and operator leads to 10 to 15 percent error in analysis result in yield stress of each Tibia. In practical test, only sheer press has considered but in analysis, besides pressure, break and stress focus have considered which this factor causes changes in strain-stress curve after yield stress point in Tibia.



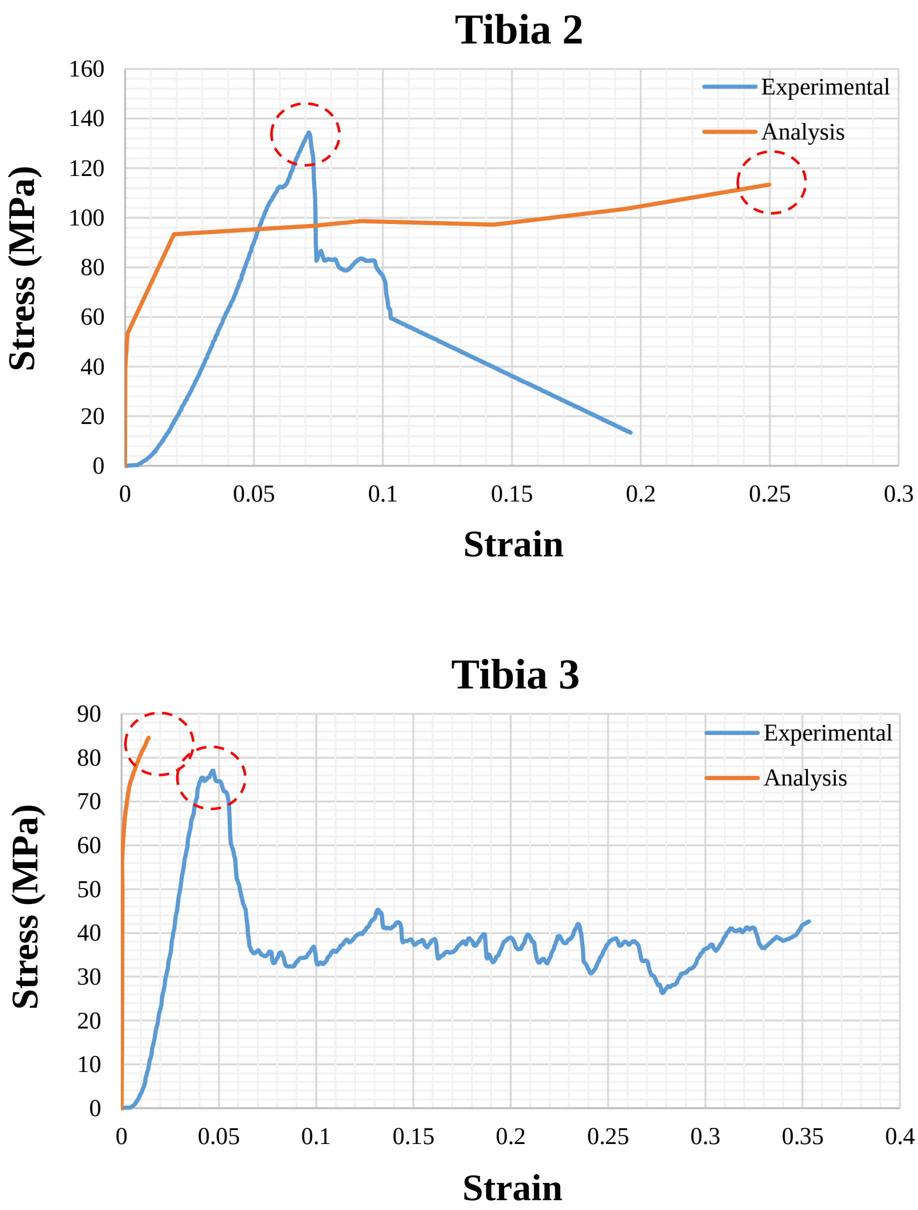


Fig. 10. The comparison of stress-strain changes for Tibia 1, 2, and 3 in experimental and analytic state.

Conclusion

The aim of this paper was to examine the strength of three upper, middle and terminal parts of human Tibia bone. After compressive test on three mentioned areas, according to the result of stress-strain graph, we have resulted that Tibia bone has the most strength in the middle area but it has the least strength in the upper area. In this paper, two big parts of Tibia joints have not been examined and the results are related to the main part of Tibia bone. Presented results in this paper have a direct relation with the cross sections and bone central hole. The cause of low strength of Tibia 1 is cross section reduction and rising of central hole and thin-walled of bone casing than other areas. Yield stress in Tibia 2 (middle area) is 136.75 MPa (Tibia 2 is strongest area in Tibia bone). If we regard the errors of test like machine errors and operator and approximate decay for bone, so test data has been obtained with the existence of error.

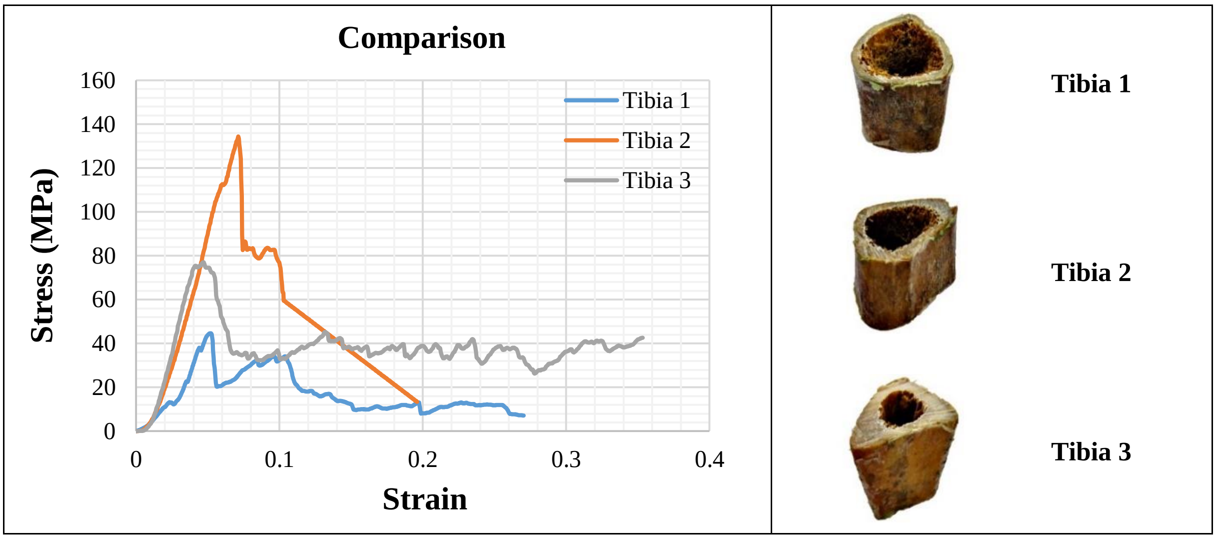


Fig. 11. Comparison between Tibia 1, Tibia 2 and Tibia 3 in stress-strain graph

Acknowledgments

We would like to thank "Strength of Materials Laboratory" at Isfahan University of Technology Faculty of Mechanical Engineering and "Anatomy" and "Autopsies" Laboratory at Najafabad Branch, Islamic Azad University.

References

E. Dall'Ara, R.Eastell, M. Viceconti, D. Pahr and L. Yang. (2016). Experimental validation of DXA-based finite element models for prediction of femoral strength. Journal of the mechanical behavior of biomedical materials. 63 (2016) 17–25

Hassan Mehboob and Seung-Hwan Chang. (2014). Evaluation of healing performance of biodegradable composite bone plates for a simulated fractured tibia model by finite element analysis. Composite Structures. 111 (2014) 193–204

V. Filardi and D. Milardi. (2017). Experimental strain analysis on the entire bony leg compared with FE analysis. Journal of Orthopaedics. 14 (2017) 115–122

Fuhao Mo, Pierre Jean Arnoux, Jean Jaques Jure and Catherine Masson. (2012). Injury tolerance of tibia for the car–pedestrian impact. Accident Analysis and Prevention. 46 (2012) 18– 25

C.M.E. Avery, Péter Bujtár, János Simonovics, Tamás Dézsi, Károly Váradi, George K.B. Sándor and Jingzhe Pan. (2013). A finite element analysis of bone plates available for prophylactic internal fixation of the radial osteocutaneous donor site using the sheep tibia model. Medical Engineering & Physics. 35 (2013) 1421–1430

Walter Rabl, Christian Haid and Martin Krismer. (1996). Biomechanical properties of the human tibia: fracture behavior and morphology. Forensic Science International. 83 (1996) 39-49

Luca Cristofolini, EvaAngeli, JanM.Juszczyk and MateuszM.Juszczyk. (2013). Shape and function of the diaphysis of the human tibia. Journal ofBiomechanics. 46(2013)1882–1892

M. A. Kumbhalkar, Umesh Nawghare, Rupesh Ghode, Yogesh Deshmukh and Bhushan Armarkar. (2013). Modeling and Finite Element Analysis of Knee Prosthesis with and without Implant. Universal Journal of Computational Mathematics 1(2): 56-66, 2013

Richard L. Drake, A. Wayne Vogl and Adam W. M. Mitchell. (2010). Gray´s Anatomy for Students (2nd Ed.). pp. 558–560. ISBN 978-0-443-06952-9

G. Nelson, P. Kelly, L. Peterson and J. Janes. (1960). Blood supply of the human tibia. J Bone Joint Surg Am. 42–A: 625–36. PMID 13854090

Finn Bojsen-Møller, Erik B. Simonsen and Jørgen Tranum-Jensen. (2001). Bevægeapparatets anatomi [Anatomy of the Locomotive Apparatus] (12th Ed.). pp. 364–367. ISBN 978-87-628-0307-7

Vincenzo Filardi. (2015). the healing stages of an intramedullary implanted tibia: A stress strain comparative analysis of the calcification process. Journal of orthopaedics xxx (2015) I-II