Journal of Biomedical and Bioengineering
ISSN: 0976-8084 & E-ISSN: 0976-8092, Volume 3, Issue 1, 2012, pp.-67-70.
Available online at http://www.bioinfo.in/contents.php?id=87

BIOMECHANICAL ANALYSIS OF HUMAN FEMUR: A REVIEW

AMRITA FRANCIS[1]*, ASHWINI SHRIVASTAVA[1], CHETNA MASIH[1], NIDHI DWIVEDI[1], PRIYANKA TIWARI[1], RAJI NARELIYA[3] AND VEERENDRA KUMAR[2]

[1]Government Engineering College, Jabalpur-482004, MP, India.
[2]Department of Mechanical Engineering, Government Engineering College, Jabalpur-482004, MP, India.
[3]Hitkarni College of Engineering and Technology, Jabalpur-482004, MP, India.
*Corresponding Author: Email- amrita.francis21@gmail.com

Received: June 19, 2012; Accepted: June 28, 2012

Abstract- The main objective of this review paper is to analyze the behavior of human femur subjected to various forces and conditions. Forces normally experienced by humans during daily living activities, also in uncertain cases like accident, twist, etc causing femur deformation or failure. Thus, it is necessary to analyze the material properties, structure, load resistance and chance of failure of human femur. The present study includes description of the structure and the mechanical properties of the cortical and cancellous bone of the femur, the analysis of joint and muscle forces acting on the femur, the mathematical methods, Finite Element Analysis, vibrational behavior of human femur, the experimental methods using strain gauges, Wilcoxon test, Mann-Whitney test and the compression, tension, bending and torsion test resulting strength analysis of human femur from the point of view of fracture mechanism which is arranged in the chronicle order.
Key words - Human Femur, Finite Element Analysis, Material Properties, Mechanical Test, Composite Synthetic Femur.

Citation: Amrita Francis, et al. (2012) Biomechanical Analysis of Human Femur: A Review. Journal of Biomedical and Bioengineering, ISSN: 0976-8084 & E-ISSN: 0976-8092, Volume 3, Issue 1, pp.-67-70.

Introduction

Femur is thigh bone, extending from the hip to the knee. It is the largest, longest and strongest bone of the human skeleton. Its head fits into a pelvis socket called the acetabulum to form hip joint. The femur head is joined to the bone shaft by a narrow piece of bone known as the neck of the femur. The lower end of femur hinges with the tibia to form the knee joint. At the lower end, the bone is enlarged to form two lumps called the condyle that distribute the weight-bearing load on the knee joint. On the outer sides of the upper end of the femur are protuberance called greater trochanter and lesser trochanter. Macroscopically structure of femur consists of two types: cortical or compact bone which is a dense outer layer mainly resists bending, Cancellous or spongy or trabecular bone present in the interior of mature bones, this structure mainly resists compression and bone elements place or displace themselves in the direction of functional pressure according to Wolff's Law [1].

The neck of the femur is a point of structural weakness and a common fracture site in elderly people, especially in women suffering from osteoporosis and is usually associated with a fall and with age of 65 or above. This causes severe pain in the hip and legs cannot bear any weight. Occasionally, the broken ends of the bone become impacted i.e. wedged together, thus lesser pain and makes walking still possible but delay reports fracture and injury. Fracture of the shaft of the femur occurs when subjected to extreme force such as in a road traffic accident. It causes severe pain, tenderness, swelling and blood loss from bone. Many issues of health as well as disease, injury and their treatment in both humans and animals are addressed under biomechanics. Biomechanics is the development, extension and application of mechanics for the purpose of understanding better the influence of mechanical loads on the structure, properties and function of living things. Biomechanics focuses on design and analysis, each of which is foundation of engineering.

Literature Review

The shape of the femur is asymmetric and curved in all three planes. Hence, a three-dimensional model is required for a quantitative stress analysis. Thus the left femur is used to provide data for FE model and another is experimented with thirty four rosette strain gauges to determine its data experimentally. The femoral head is loaded by a single force parallel to the shaft axis for stress study of its diaphysis. Its deflection, principal stresses are determined and compared. The upper one third and the diaphysis of the femur are differently affected in their state of stress, by different modes of loading including simulation of the abductor muscles and the iliotibial tract [2]. Koch is the first who gave a complete and thorough description of the structure of the femur and demonstrated the relations which exist between the structure and the function as well as between the external and internal architecture of the femur [3]. Mechanical properties of cortical and cancellous bone of eight human specimen aging between 45 to 68 years are determined using computerized tomography (CT), values obtained from scans of the bones in water is corrected to Hounsfield Units. The correlations between CT numbers and mechanical properties are commonly used to parameterize finite element models of the skeletal system. Relationships estimated for cortical bone are found to be low, while these for cancellous bone are found to be higher, where as modulus in the anterior-posterior direction or medial-lateral direction and modulus in the Strength Index (SI) direction for cancellous bone are found to be good [4]. The mechanical behavior of the whole bone composite model is studied and compared to human fresh-frozen and dried-rehydrated specimens for different loading conditions and experimentally validated. The viscoelastic behavior of the models under simulated single leg stance loading, the head deflection under a single vertical load, the strain distribution under a single vertical load, the bending stiffness in different plane and the torsional stiffness are investigated [5]. For better understanding of femoral loading forces exerted by the soft and hard tissues of the thigh together are considered, a three dimensional model is created taking into account all thigh muscles, body weight, contact forces at the hip, patellofemoral and knee joints based on [6] and hence the internal loads on the bone are calculated [7]. A program is developed to read a CT data set as well as the FEA mesh generated from it and to assign material properties to each element of the mesh which is derived from the bone tissue density at the element location. As CT images are capable of providing accurate information about the bone morphology and tissue density, if calibrated correctly. This program is tested on phantom data sets and is adopted to evaluate the effects of the discrete description of the bone material properties [8]. Frequency analysis of long bones has been investigated as a tool to assess bone quality or integrity. A three-dimensional finite element model of a fresh human femur with geometrical and mechanical properties is derived from quantitative computer tomography images. This model is exercised and the results are compared to those obtained from a vibration analysis technique [9]. Methods for automating mesh generation (AMG) used to mesh a human femur are evaluated. The five AMG methods are: mapped mesh, which provides hexahedral elements through a direct mapping of the element onto the geometry, tetra mesh, which generates tetrahedral elements from a solid model of the object geometry, voxel mesh, which builds cubic 8-node elements directly from CT images and hexa mesh, that automatically generate hexahedral elements from a surface definition of the femur geometry. The various methods are even tested against two reference models: a simplified geometric model and of a proximal femur model [10]. The influence of muscle action on horizontally constrained femoral head within the intact femur is analyzed and the strain distribution is measured for three loading configurations: joint reaction force only, joint reaction force plus abductors and joint reaction force plus the abductors, vastus lateralis and iliopsoas, using twenty uniaxial strain gauges placed on the medial, lateral, anterior and posterior aspects of the proximal femur [11]. This study compares the structural properties of a new versus established design of composite replicate femurs and tibias. The new design has a cortical bone analog consisting of short-glass-fiber-reinforced (SGFR) epoxy, rather than the fiberglass-fabric-reinforced (FFR) epoxy in the currently available design. The hypothesis is that this new cortical bone analog would improve the uniformity of structural properties between specimens, while having mean stiffness values in the range of natural human bones. The composite replicate bones are tested under bending, axial and torsional loads. In general, the new SGFR bones are significantly less stiff than the FFR bones, although both bone designs reasonably approximated the structural stiffnesses of natural human bones [12]. The role of anteversion in transferring the load from implant to bone and its influence on total hip arthroplasty (THA) is determined. Also loading of the proximal femur during daily activity i.e. walking and stair climbing is determined. Experimental and analytical approaches are used to determine the in-vivo loading of the hip joint. A numerical muscular skeleton model is validated against measured in-vivo hip contact forces [13]. Mechanical properties from four locations in the human distal femur is determined by compression testing over twenty eight cylindrical specimens which are removed perpendicular to the press-fit surface after the surgical cuts on ten human cadaveric is made. The bone mineral apparent density (BMAD), apparent modulus of elasticity, yield and ultimate stress and yield and ultimate strain are measured, each property significantly differed in the superior and inferior locations [14]. Material properties of femur bones are evaluated to facilitate further study of total hip joint and replacement of joint in Indian subjects, as these properties are needed before finite element analysis of indigenized hip joint to study its stability in the bone. Orthotropic behavior of cancellous portion of cadaveric femur bone is determined through theoretical approach and experimental test for mechanical properties, which comprise of tensile testing, compression testing and shear testing on the specimens. Experimental data stated here include tensile strength, compressive strength, yield strength, modulus of elasticity, torsion strength and shear modulus, which can reflect the complex material behavior of femur bone which establishes orthotropic nature of femur bone as expected [15]. Von Meyer (1867) presented a drawing of the trabecular bone structure that he had observed in the human proximal femur and interestingly, his drawing had strong similarities with what of Culmann (1866) drew for the principal stress trajectories in a crane like curved bar. In 1892, Julius Wolff suggested that the fine structure within bones is governed by the lines of tension that result from the applied loads and Wolff gave the law of bone remodeling. He also suggested that the bone obtains “maximum” mechanical efficiency with ‘‘minimum’’ mass, many scientists and engineers have often cited a bone as an example of ‘‘optimal’’ structures [16]. Wolff's law is validated using topology optimization in the human proximal femur. A two-dimensional micro-FE model with 50 μm pixel resolution is used to represent the full trabecular architecture in the proximal femur and perform topology optimization to study the trabecular morphological changes under three loading cases in daily activities i.e. one-legged stance, extreme ranges of motion of abduction and adduction [17,18]. The simulation results are compared to the actual trabecular architecture in previous experimental studies [16,19]. Relationships between CT density (ρ_{CT}) and ash density (ρ_{ash}), between ash density and apparent density (ρ_{app}) for bone tissue, are evaluated and experimental-numerical study is done which shows their influence on the accuracy of strain prediction of subject-specific FE models of human bones. The ρ_{CT} is obtained from CT dataset calibrated with ESP phantom and Data Manager software is used to measure the average HU value for each specimen [20], the ρ_{app} is measured as in [21] and ρ_{ash} is measured experimentally. A regression analysis is performed for ρ_{CT} versus ρ_{ash}, both splitting the data for tissue type and for pooled data. Distribution of absolute residual values for trabecular, cortical and pooled groups is compared by means of a Mann-Whitney test. Finally, the regression lines of the pooled groups and the quadrant bisector are compared by the analysis of covariance (ANOVA). FE models are created using ANSYS and homogeneous material properties are assigned to the FE models using the Bone Mat software. Strain gauge is used for measurements, reference study is finally compared using a Wilcoxon test for paired samples on the error distribution between the two studies and results are obtained [22]. CT-based FE model under dry and wet condition are generated [23] and compared the experimental observations. This study shows that the environment in which the bone is immersed during the CT scans has minor influence on the FE results [24]. The boundary detection algorithm shows to be insensitive to CT scans environment. With minor modifications CT scans FE models can be used to generate reliable subject-specific FE models [25]. A mathematical model is developed to simulate three-dimensional femur bone and femur bone with implant in the femoral canal, taking into account stress distribution and total displacement during horizontal walking. The equilibrium equations are used in the model. Realistic domain is created by using CT scan data. Different cases of static loads and different boundary conditions are used in the simulation. The Finite Element Method is utilized to determine total displacement and Von Mises stress. The influences of human weight during horizontal walking are investigated. The results show that higher weight provides higher total displacement. And it is found that the Von Mises stress affects the lateral femur [26]. Numerical-experimental results are compared i.e. FE-predicted surface strains with strain-gauge measurements. Thirty-six major cadaveric long bones i.e. humerus, radius, femur and tibia, which cover a wide range of bone sizes, are tested under three-point bending and torsion. The FE models are constructed from CT scans and the segmented bone images are corrected for partial-volume effects. The material properties are calibrated by minimizing the error between experiments and simulations among all bones [27]. A subject- specific Finite Element models of bones are created using CT data that accurately predicts strains in quasi-axial loading configurations, also when applying low magnitude loads in sideways configurations using hyper mesh, bone mat, digitizer, ANSYS. Finite Element predicted strains are compared with strain measured from three cadaver proximal femurs instrumented with sixteen strain rosettes when tested non-destructively fewer than twelve loading configurations, spanning a wide cone of sideways fall scenarios. The results showed satisfactory agreement between experimentally measured and predicted strains and displacements [28].

Conclusion

The human femur has been subjected to numerous investigations like physical test yielding knowledge on apparent whole-bone properties, digitized and modeled in many different Finite Element programs even mathematically both at the tissue level and at the whole-bone macroscopic level. Much work has been done to ascertain the femur bone tissue constituents' linear and non-linear material properties by methods ranging from mechanical and acoustic testing to more theoretical means. The more accurate FE models of the femur whole-bone, or separately, the bone tissues, include material models that describe some degree of material anisotropy, or unique directional behavior, as well as strain rate dependence and remodeling of femur under muscle loading and vibration. All these investigation have lead to great advancement in the issues and problems faced by the orthopedic surgeons during hip implant and these bone data available will be major parameter in design of hip joint prosthesis for patients. Still more research is required to overcome the problems which are still present like grain orientation along the bone length, reduction in bone minerals due to high heat formation during cutting and finishing which ultimately tends to reduce strength of bone and dynamic analysis of femur under biological loading. Preservation of samples and amount of hydration influenced even determination of alignment error and shrinkage of bone during experimental test need to be evaluated.

Conflict of Interest

The authors have no conflicts of interest. The authors hereby declare that with regard to the submission of this article there are no financial and personal relationships with other people and organizations.

References

[1] Nather Aziz, Ong H.J.C. and Aziz Zameer, *Structure of bone*, 5.

[2] Rohlmann A., Mossner U., Bergmann G. and Kolbel R. (1982) *Journal of Biomedical Engineering*, 4, 242-246.

[3] Gdoutos E.E., Raftopoulos D.D. and Baril J.D. (1982) *Journal of Biomaterials*, 3, 2-8.

[4] Rho J.Y., Hobatho M.C. and Ashman R.B. (1995) *Medical Engineering & Physics*, 17(5), 347-355.

[5] Cristofolini Luca, Viceconti Marco, Cappello Angelo Toni Aldo (1996) *Journal of Biomechanics*, 2(4), 525-435.

[6] Brand R.A., Crowninshield R.D., Wittstock C.E., Pederson D.R., Clark C.R. and Krieken Van F.M. (1982) *Journal of Biomechanics*, 104, 304-310.

[7] Duda Georg N., Schneider Erich, Edmund Y.S. Chao (1997) *Journal of Biomechanics*, 30(9), 933-941.

[8] Zannoni Cinzia, Mantovani Raffaella and Viceconti Marco (1998) *Medical Engineering and Physics*, 20, 735-140.

[9] Couteau Beatrice, Hobatho Christine Marie, Darmana Robert, Brignola Claude Jean and Arlaud Yves Jean (1998) *Journal of Biomechanics*, 31, 383-386.

[10]Viceconti Marco, Bellingeri Luisella, Cristofolini Luca, Toni Aldo (1998) *Medical Engineering and Physics*, 20, 1-10.
[11]Simoes J.A., Vaz M.A., Blatcher S. and Taylor M. (2000) *Medical Engineering and Physics*, 22, 453-459.
[12]Anneliese D. Heiner and Thomas D. Brown (2001) *Journal of Biomechanics*, 34, 773-781.
[13]Heller Markus O., Bergmann Georg, Deuretzbacher Georg, Claes Lutz, Haas Norbert P. and Duda Georg N. (2001) *Clinical Biomechanics*, 16, 644-649.
[14]Burgers Travis A., Mason Jim, Niebur Glen, Ploeg Heidi L. (2008) *Journal of Biomechanics*, 4, 1077-1085.
[15]Kulkarni Mrudula S. and Sathe S.R. (2008) *Trends Biomaterial & Artificial Organs*, 22(1), 9-15.
[16]Jang Gwun In and Kim Yong Il (2008) *Journal of Biomechanics*, 41, 2353-2361.
[17]Beaupre G.S., Orr T.E. and Carter D.R. (1990a) *Journal of Orthopedic Research*, 8, 651-661.
[18]Tsubota K., Adachi T. and Tomita Y. (2002) *Journal of Biomechanics*, 35, 1541-1551.
[19]Bitsakos, Kerner J., Fisher I. and Amis A.A. (2005) *Journal of Biomechanics*, 38, 133-139.
[20]Viceconti M., Taddei F., Montanari L., Testi D., Leardini A., Clapworthy G. and Jan Sint Van S. (2007) *Computer Methods and Programs in Biomedicine*, 87, 148-159.
[21]Morgan E.F., Bayraktar H.H., Keaveny T.M. (2003) *Journal of Biomechanics*, 36, 897-904.
[22]Schileo Enrico, Ara Enrico Dall, Taddei Fulvia, Malandrino Andrea, Schotkamp Tom, Baleani Massimiliano and Viceconti Marco (2008) *Journal of Biomechanics*, 41, 2483-2491.
[23]Yosibash Z., Padan R., Joscowicz L. and Milgrom C. (2007b) *ASME Journal of Biomechanics Engineering*, 129(3), 297-309.
[24]Yosibash Z., Trabelsi N., Milgrom C. (2007a) *Journal of Biomechanics*, 40, 3688-3699.
[25]Trabelsi Nir, Yosibash Zohar, Milgrom Charles (2009) *Journal of Biomechanics*, 42, 234-241.
[26]Amornsamankul Somkid, Kaorapapong Kamonchat Wiwatanapataphee Benchawan (2010) *International Journal of Mathematics and Computers in Simulation*, 4(4), 171-178.
[27]Varghese Bino, Short David, Penmetsa Ravi, Goswami Tarun and Hangartner Thomas (2011) *Journal of Biomechanics*, 44 (7), 1374-1379.
[28]Grassi L., Schoileo E., Taddei F., Zani L., Juszczyk M., Cristofolini L. and Viceconti M. (2012) *Journal of Biomechanics*, 45, 394-399.