NUMERICAL ANALYSIS OF BOVINE TRABECULAR BONE BY USING PHYSIOLOGICAL LOADS SPECIFIC TO NORMAL WALKING LOADS AND DOWN STAIRS LOADS.

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To my parents and family, thanks for patiently supports and courage during till
completion of master course…

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ABSTRACT

This project is containing of simulation on sectioned Bovine Trabecular Bone. The Bone was extracted from fresh bovine bone with interested section dimension for about 2 × 2 × 3.5 mm. After scanned process through µCT scanner, the bone was constructed via Mimics software. With preferred size of elements and consumed time per simulation, 774,996 elements were selected meshing number to use. Combination of 3 axes loads for both physiological movement specific to normal walking loads and downstairs loads, those presented one minute trends cycle completed both cycle as reliable applying loads in the consequent Trabecular Bone model. Simulation was conducted by fixed the model at the bottom and applying gait loads at the top, revealed most deflection of Trabecular Bone were occurred while down stairs activities. The most stress entire simulation also weighed to down stairs activities. From that, it composes young modulus for normal walking is 14.8Gpa. In the other hand, downstairs activities complies 14.9Gpa. Deviation on the experimental data of compressive test, could be translate on different of density model, besides, by doing only compressive stress could not represent on physiological loads on actual real situation.

ABSTRAK

Projek ini mengandungi simulasi Tulang Trabecular lembu yang telah disegmen. Tulang tersebut diekstrak dari tulang lembu segar dengan dimensi seksyen utama untuk 2 × 2 × 3.5mm. Selepas proses imbasan melalui pengimbas μCT, tulang telah dibina melalui perisian Mimics. Dengan saiz pilihan elemen dan masa yang digunakan setiap simulasi, 774.996 elemen dipilih bersirat nombor untuk kegunaan. Gabungan 3 paksi beban bagi pergerakan kedua-dua fisiologi spesifik kepada beban berjalan normal dan beban menuruni tangga, yang dibentangkan satu minit trend kitaran, ia tersebut menyempurnakan kitaran kedua-dua sebagai beban aplikasi dalam model Tulang Trabecular. Simulasi telah dijalankan dengan model berada pada posisi tetap disebelah bawah dan menggunakan beban di atas, ini telah mendedahkan pesongan yang paling pada Tulang Trabecular berlaku semasa aktiviti menuruni tangga. Keseluruhan simulasi yang paling tekanan juga ditimbangi kepada aktiviti-aktiviti menuruni tangga. Daripada itu, ia menghasilkan “Modulus young” untuk berjalan normal adalah 14.8Gpa. Selain itu, aktiviti-aktiviti menuruni tangga juga mematuhi 14.9Gpa. Sisihan pada data eksperimen ujian mampatan, boleh diterjemahkan pada model yang berbeza ketumpatan, selain dengan melakukan hanya kepada tegasan mampatan dan tidak boleh mewakili beban fisiologi sebagai menyamai keadaan sebenar sebenar

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CHAPTER 1

INTRODUCTION

This project with title Numerical analysis of Bovine Trabecular Bone by using physiological loads specific for 2 types of normal activities which are Gait loadings and Down Stairs loadings. In this first chapter, author will details the objectives, problem statements, scope of project and the significance of the project. As reflect of that, there are four objectives needs to achieve by through the concurrent problems over analysis hypothesis. However, this numerical project needs to follows scope and method constraint. Otherwise, it will be hardest to control in by taking all other environment consideration. End of this first chapter, author discussed the prolific significance of this project thorough expected findings result.

1.1 OBJECTIVES

- To analyses the parametric behavior of the Trabecular bone respect to physiological activity (Normal walking & Down Stairs).
- To study the relationship between bodyweight and stress distribution over Trabecular bone.
- To examine and compare the pre-location of crack initiation as due to cyclic gait loadings.

1.2 PROBLEM STATEMENTS

From previous researched approaches specifically on Trabecular bone, mostly researchers constructing alike model to representing the actual Trabecular bone. Since the existence of the bio-scanner, the technology was appreciates completely in other dimension specifically in numerical analysis. The capability of scanner neither dubious nor trustworthy, the technology brings easiness on constructing similar to an actual model with even in very complex 3D models. In the absent of human bone, there is still other alternative with similar mechanical properties to replace human bone. The bovine bone is the suitable bone to used by researchers during experimental. Readily available and cheap, has a similar mechanical properties brings this project forward.

Femur neck is said the second highest stress occurred during standing activity. They are also the only connected junction between legs and others organs which are implies a fury loads during physical activity. Understanding on stress distributions and reactions is such a helpful way as continuation study on femur neck of human bone. There were several studies on the reaction contact on hips by numerous researchers [1-3]. With those findings, it shall translate the reaction of internal stress bone behavior from basic physical movement loadings. In addition of that, pressure distribution over trabecular bone could easily analysis through stress contours. Furthermore, by using FE package features bone displacements with respect to stresses are able determines.

The intact of bodyweight and stress distribution is likely to give a linear assumption. For example, the person has weightier bodyweight is prone to have more local stresses on their hips. Simultaneously, the reactions on femur necks are equivalence to the exerted loadings. Through numerical simulation, mechanical properties will reveal the relation between bodyweight and the young modulus. Yet, it composed the suggestion risk of obese.

Normal walking and Down stairs act is of a common activities done by human. These simple activities had chaos assumption on which is contributes more stress during activity or which activity will more easily to jades for human task. In instance of that, both physiological activities have a second complete cycle. Thus, comparing between cycles is possible to make and realization. It is a different form of others activities such as slow walking, up stairs sitting down, standing on 2-1-2 legs or knee bend, all those activities had elapse more times in one completed cycles [2].

Fatigue failure is always referred to continuous cyclic loading [4]. Interestingly, human bones are always having cyclic loadings throughout any physical activities. Since the exposure of human bone against fatigue is risky. Knowing the signs of fatigue behavior under gait cycles are great achievement for future study. Practically, fatigue failure has to go through two phases of crack before failure occurred. The first is crack initiation and the second is crack growth. Location of crack initiation might sees if the crack is started. By that, the pressure contour and bone displacements could explain the situation.

1.3 SCOPE OF PROJECT

First scope of this project is to construct the Trabecular Bone structure. The model is constructed through scanning images from micro-CT scanner. The extension of the uses and advance technology brings easiness to examine any complex structure shape and design. Unlike other researcher approaches, mostly of them design their own Trabecular structure alike by composed a number of struts in definite ratio. First limitation is size, most of the FE package had a maximum numbers of elements. Thus, constructed Trabecular model will only considered in specimen dimension, shape of the specimen and meshing element size. All those consideration are important in getting an optimal finding result.

Second scope of this project is to perform static analysis by using FE package. Nowadays, numerical approaches seem to be very imperative in initial or preliminary study. That due to precision of numerical simulation brings draft taught of the simulation problem. In addition of that, stage of numerical study is far cheaper than constructing or setting apparatus for real experiment. Not repudiate on the experiment work, instance of that, hand-on experimental work is the real situation under a very minimal engineering assumption or constraint. Differently approaches on finite element simulation, the software is tends to excludes any external environment contact to the simulation models. That limitation concludes numerical simulation is just a tool to get a general problem solution near to the real situation.

Third scope of this project is to compares finding data result between physiological activities. Specific to this project, only two types of activities will be simulating thoroughly. The first is gait cycle and second is down stairs loadings. Both of them are the loads which have a direct contact between femur and tibia. By simply to understand the reaction involves in human hips during normal walking and down stairs. Data later should compares to the experimental result, even though applying physiological loads to the Trabecular Bone is novel. However, the comparison is possible by matching with uniaxial experimental data from various journals source in varies Trabecular bone samples.

1.4 SIGNIFICANCE OF PROJECT

In the first significance, exposing the actual physiological loadings on the 3D modeled Trabecular bone. The physiological loadings involved for this particular project is specific only for gait cycle and down stairs cycle loadings. Both cycles are referring to common activities for every human being. Thus, regain the understanding the mechanical properties of human bone (specify to Trabecular bone on femur neck) during involvement of physiological loadings. From that, the differentiation between physiological could be clearly stated in term of mechanical properties.

Second significance for this project is from the mechanical properties, the effect of bodyweight on the physiological activities capable to hypotheses as refer to stress-strain curve. The relation between bodyweight and physiological activities might important to obese generation and by hope finding result enable the risk of overweight body.

Prediction of bone life in fatigue study is the most preference. The prediction of fatigue life could employ in every angle of fatigue study. In order to manipulate the use of the Trabacular Bone application, estimation curve is a basic foundation of fatigue study as base on physical activities. The curve (S-N curve) is a reference to any cyclic human activity, same goes with the application of material S-N curve. As basic of the fatigue failure, crack initiation will start first before the development of crack till failure. By increasing two cycles of gait loadings, pre location of fatigue failure might appear through contour distribution on trabecular bone.

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REFERENCES

1. Duda, G.N., E. Schneider, and E.Y.S. Chao, *Internal forces and moments in the femur during walking.* Journal of Biomechanics, 1997. **30**(9): p. 933-941.
2. Bergmann, G., et al., *Hip contact forces and gait patterns from routine activities.* Journal of Biomechanics, 2001. **34**(7): p. 859-871.
3. Taylor, W.R., et al., *Tibio-femoral loading during human gait and stair climbing.* Journal of Orthopaedic Research, 2004. **22**(3): p. 625-632.
4. Schijve, J., *Fatigue of Structures and Materials*2009: Springer.
5. Keaveny, T.M., et al., *TRABECULAR BONE EXHIBITS FULLY LINEAR ELASTIC BEHAVIOR AND YIELDS AT LOW STRAINS.* Journal of Biomechanics, 1994. **27**(9): p. 1127-&.
6. Ryan, S.D. and J.L. Williams, *Tensile testing of rodlike trabeculae excised from bovine femoral bone.* Journal of Biomechanics, 1989. **22**(4): p. 351-355.
7. Morgan, E.F. and T.M. Keaveny, *Dependence of yield strain of human trabecular bone on anatomic site.* Journal of Biomechanics, 2001. **34**(5): p. 569-577.
8. Kopperdahl, D.L. and T.M. Keaveny, *Yield strain behavior of trabecular bone.* Journal of Biomechanics, 1998. **31**(7): p. 601-608.
9. Røhl, L., et al., *Tensile and compressive properties of cancellous bone.* Journal of Biomechanics, 1991. **24**(12): p. 1143-1149.
10. Bayraktar, H.H. and T.M. Keaveny, *Mechanisms of uniformity of yield strains for trabecular bone.* Journal of Biomechanics, 2004. **37**(11): p. 1671-1678.
11. Lindahl, O., *MECHANICAL PROPERTIES OF DRIED DEFATTED SPONGY BONE.* Acta Orthopaedica Scandinavica, 1976. **47**(1): p. 11-19.
12. Jee, W.S.S., *Principles in bone physiology.* J Musculoskel Neuron Interact, 2000. **1**: p. 11-13.
13. White, T.D. and P.A. Folkens, *The Human Bone Manual*2005: Elsevier Science.
14. Fajdiga, G. and M. Sraml, *Fatigue crack initiation and propagation under cyclic contact loading.* Engineering Fracture Mechanics, 2009. **76**(9): p. 1320-1335.
15. Clarke, B., *Normal Bone Anatomy and Physiology.* Clinical Journal of the American Society of Nephrology, 2008. **3**(Supplement 3): p. S131-S139.
16. Sherwood, L., *Human Physiology: From Cells to Systems*2012: Cengage Learning.
17. Lin, L., et al., *Prediction of trabecular bone principal structural orientation using quantitative ultrasound scanning.* Journal of Biomechanics, 2012. **45**(10): p. 1790-1795.
18. Seeman, E., et al., *Osteoporosis in men--consensus is premature.* Calcif Tissue Int, 2004. **75**(2): p. 120-2.
19. Hildebrand, T., et al., *Direct three-dimensional morphometric analysis of human cancellous bone: Microstructural data from spine, femur, iliac crest, and calcaneus.* Journal of Bone and Mineral Research, 1999. **14**(7): p. 1167-1174.
20. Mulder, L., et al., *Architecture and mineralization of developing cortical and trabecular bone of the mandible.* Anatomy and Embryology, 2006. **211**(1): p. 71-78.
21. A M Parfitt, C.H.M., A R Villanueva, M Kleerekoper, B Frame, D S Rao, *Relationships between surface, volume, and thickness of iliac trabecular bone in aging and in osteoporosis. Implications for the microanatomic and cellular mechanisms of bone loss.* J. Clin.Invest., 1983(72): p. 1396–1409.
22. Wolfram, U., H.J. Wilke, and P.K. Zysset, *Damage accumulation in vertebral trabecular bone depends on loading mode and direction.* J Biomech, 2011. **44**(6): p. 1164-9.

23. Homminga, J., et al., *Cancellous bone mechanical properties from normals and patients with hip fractures differ on the structure level, not on the bone hard tissue level.* Bone, 2002. **30**(5): p. 759-764.
24. Augat, P., et al., *Anisotropy of the elastic modulus of trabecular bone specimens from different anatomical locations.* Medical Engineering & Physics, 1998. **20**(2): p. 124-131.
25. Cory, E., et al., *Compressive axial mechanical properties of rat bone as functions of bone volume fraction, apparent density and micro-ct based mineral density.* Journal of Biomechanics, 2010. **43**(5): p. 953-960.
26. Goldstein, S.A., *THE MECHANICAL PROPERTIES OF TRABECULAR BONE DEPENDENCE ON ANATOMIC LOCATION AND FUNCTION.* Journal of Biomechanics, 1987. **20**(11-12): p. 1055-1062.
27. Linde, F., I. Hvid, and F. Madsen, *The effect of specimen geometry on the mechanical behaviour of trabecular bone specimens.* Journal of Biomechanics, 1992. **25**(4): p. 359-368.
28. Linde, F. and H.C.F. Sørensen, *The effect of different storage methods on the mechanical properties of trabecular bone.* Journal of Biomechanics, 1993. **26**(10): p. 1249-1252.
29. Prendergast, P.J., *Finite element models in tissue mechanics and orthopaedic implant design.* Clinical Biomechanics, 1997. **12**(6): p. 343-366.
30. Kim, H.S. and S.T.S. Al-Hassani, *A morphological model of vertebral trabecular bone.* Journal of Biomechanics, 2002. **35**(8): p. 1101-1114.
31. Seeman, E. and P.D. Delmas, *Bone Quality — The Material and Structural Basis of Bone Strength and Fragility.* New England Journal of Medicine, 2006. **354**(21): p. 2250-2261.
32. D. R. Carter, W.C.H., *The compressive behavior of bone as a two-phase porous structure.* The Journal of Bone & Joint Surgery, 1977. **59**(7): p. 954-962.
33. Choi, K. and S.A. Goldstein, *A comparison of the fatigue behavior of human trabecular and cortical bone tissue.* Journal of Biomechanics, 1992. **25**(12): p. 1371-1381.
34. Michel, M.C., et al., *Compressive fatigue behavior of bovine trabecular bone.* Journal of Biomechanics, 1993. **26**(4–5): p. 453-463.
35. Keaveny, T.M., et al., *Mechanical behavior of damaged trabecular bone.* Journal of Biomechanics, 1994. **27**(11): p. 1309-1318.
36. Dendorfer, S., H.J. Maier, and J. Hammer, *Effects of structural anisotropy on the fatigue behaviour of cancellous bone.* Journal of Biomechanics, 2006. **39, Supplement 1**(0): p. S17.
37. Dendorfer, S., H.J. Maier, and J. Hammer, *Fatigue damage in cancellous bone: An experimental approach from continuum to micro scale.* Journal of the Mechanical Behavior of Biomedical Materials, 2009. **2**(1): p. 113-119.
38. Dendorfer, S., et al., *Anisotropy of the fatigue behaviour of cancellous bone.* Journal of Biomechanics, 2008. **41**(3): p. 636-641.
39. Haddock, S.M., et al., *Similarity in the fatigue behavior of trabecular bone across site and species.* Journal of Biomechanics, 2004. **37**(2): p. 181-187.
40. Moore, T.L. and L.J. Gibson, *Fatigue microdamage in bovine trabecular bone.* Journal of biomechanical engineering, 2003. **125**(6): p. 769-776.
41. Moore, T.L., F.J. O'Brien, and L.J. Gibson, *Creep does not contribute to fatigue in bovine trabecular bone.* Journal of biomechanical engineering, 2004. **126**(3): p. 321-329.
42. Moore, T.L.A. and L.J. Gibson, *Fatigue of Bovine Trabecular Bone.* Journal of biomechanical engineering, 2003. **125**(6): p. 761-768.

43. Topoliński, T., et al., *Study of the behavior of the trabecular bone under cyclic compression with stepwise increasing amplitude.* Journal of the Mechanical Behavior of Biomedical Materials, 2011. **4**(8): p. 1755-1763.
44. Bowman, S.M., et al., *Creep Contributes to the Fatigue Behavior of Bovine Trabecular Bone.* Journal of biomechanical engineering, 1998. **120**(5): p. 647-654.
45. Rapillard, L., M. Charlebois, and P.K. Zysset, *Compressive fatigue behavior of human vertebral trabecular bone.* Journal of Biomechanics, 2006. **39**(11): p. 2133-2139.
46. Moore, T.L.A. and L.J. Gibson, *Microdamage Accumulation in Bovine Trabecular Bone in Uniaxial Compression.* Journal of biomechanical engineering, 2002. **124**(1): p. 63-71.
47. AI Pearce, R.R., S Milz, E Schneider and SG Pearce, *Animal Models for Implant Biomaterial Research in Bone: A Review.* European Cells and Materials, 2007. **13**: p. 1-10.
48. Keaveny, T.M., et al., *Trabecular bone exhibits fully linear elastic behavior and yields at low strains.* Journal of Biomechanics, 1994. **27**(9): p. 1127-1136.
49. Logical Information Machine, I., *Mimic User guide*, 1995: Chicago.
50. Runkle, J.C. and J. Pugh, *The micro-mechanics of cancellous bone. II. Determination of the elastic modulus of individual trabeculae by a buckling analysis.* Bull Hosp Joint Dis, 1975. **36**(1): p. 2-10.
51. Ashman, R.B. and R. Jae Young, *Elastic modulus of trabecular bone material.* Journal of Biomechanics, 1988. **21**(3): p. 177-181.
52. Hardinge, M.G., *Determination of the strength of the cancellous bone in the head and neck of the femur.* Surg Gynecol Obstet, 1949. **89**(4): p. 439-41.
53. Keller, T.S., *PREDICTING THE COMPRESSIVE MECHANICAL-BEHAVIOR OF BONE.* Journal of Biomechanics, 1994. **27**(9): p. 1159-1168.
54. Szabo, M.E., M. Taylor, and P.J. Thurner, *Mechanical properties of single bovine trabeculae are unaffected by strain rate.* Journal of Biomechanics, 2011. **44**(5): p. 962-967.
55. Ducheyne, P., et al., *The mechanical behaviour of intracondylar cancellous bone of the femur at different loading rates.* Journal of Biomechanics, 1977. **10**(11–12): p. 747-762.
56. Kelly, N. and J.P. McGarry, *Experimental and numerical characterisation of the elasto-plastic properties of bovine trabecular bone and a trabecular bone analogue.* Journal of the Mechanical Behavior of Biomedical Materials, 2012. **9**(0): p. 184-197.
57. Gupta, A., et al., *Constitutive Modeling and Algorithmic Implementation of a Plasticity-like Model for Trabecular Bone Structures.* Computational Mechanics, 2007. **40**(1): p. 61-72.
58. Hakim, A.A., et al., *Effects of Walking on Mortality among Nonsmoking Retired Men.* New England Journal of Medicine, 1998. **338**(2): p. 94-99.
59. Guillén, T., et al., *Compressive behaviour of bovine cancellous bone and bone analogous materials, microCT characterisation and FE analysis.* Journal of the Mechanical Behavior of Biomedical Materials, 2011. **4**(7): p. 1452-1461.