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

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ABSTRACT

This study is containing of simulation on sectioned bovine trabecular bone. The aim of this research is to determine the prediction of the compressive fatigue behavior on cancellous bone specimens as a function of density, porosity and volume fraction. The specimen was extracted from fresh bovine bone with interested section dimension for about $2 \times 2 \times 3.5$ mm. After scanned process through μCT, the bone was constructed using Mimics. With preferred size of elements and consumed time per simulation, optimum meshing yield 774,996 elements number was used. Combination of 3 axes loads for both physiological movements specific to normal walking and downstairs presented as one minute trends cycle completed during stance phase was applied on trabecular bone 3D model. Simulation was conducted with the bottom of the model fixed while gait loads applied at the top. Most deflection with highest stress occurred during downstairs simulated condition. Young modulus for normal walking and downstairs loading condition are 14.8 GPa and 14.9 GPa respectively. Differences of the compressive experimental data compared to present result could be influenced by density model. Compressive stress alone could not represent any actual physiological loads during daily activities.

Keywords: *Numerical Analysis, Trabecular Bone, Cancellous bone, multi-axial load, physiological loads.*

1.0 INTRODUCTION

Every movements of our body create stresses along bones, joints and muscles. The stress histories created on particular portion of bone are unique depend on activities. Taylor et al (2001), [1] recorded on basic forces and moments in two distal femoral during gait, resulted successive constant trend cycles for every pace. Differently approached and resulted from Duda et al (1997), [2], they studied the reaction on joint between femur and hip. The study was extended by Bergman et al (2001), [3] which suggested three axial plane forces produced. The result recorded that, nine types of consecutive activities base on daily basis actions that contributes to high focal loads especially on hip joint. These

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three findings emphasized the phrases on the second line that, stresses loads are depend on data taken position and activities.

Osteoporotic fracture is the fracture that due to excessive loads exerted on bone [4]. Most of the osteoporotic fracture accidents are referring to fall [5-6], while in mechanics point of view that fall incidents are normally generated from the high localize stress in damage sites would reduced bone strength to resist fracture. Other than that, osteoporosis is also defined as lagging of bone mineral density, BMD [7]. Apart from that, the BMD will tend to lessen during increasing of age [7-8]. As referred to previous general agreement, elderly were the most suffered from osteoporotic fracture [7-9]. Knowing that, the unknown relation of gait loads during daily activities in reflected to elderly could be the main cause of these problems arises.

Insufficient supply of human bone in this study brings to other alternatives which could be replaced to other bone species. Through bone properties classification, a number of suitable bones replacement mainly from mammalian animal as favor to this experiment. The bone properties classes branched to macrostructure, microstructure, bone composition and bone remodeling. AI Pearce et al (2007), [10] summarized four types of animal bones which are canine, sheep, pig and rabbit. However, they found nothing out of four animals is completely similar with human bone physiology. In bone structure division point of view AI Pearce et al (2007), [10] recorded, sheep had a most similar macrostructure to human bone. Meanwhile, the pig or porcine is likely close to bone composition and bone remodeling cycles. However, only canine and pig bone had a moderate similar microstructure to human bone.

In the practical and more realistic approach in Malaysia focusing to Muslim, encompassing canine and pig bone into testing is not a good practiced. To deflect the deficient on result testing, another substitute bone could replace sample experiment. With referred to bone availability, bone structure composition and other advantages. The suitable substitute bone is bovine bone. Bovine bone indicates slightly similar mechanical properties to human bone. Kopperdahl et al (1998), [11] grouped from eight different authors in one summary table of yield and ultimate strains between human bone and bovine bone. Most of them found bovine bone had a slightly higher in yield and ultimate strain than human bone for about 1% deviation. Microstructure, macrostructure, bone composition and bone remodeling are somehow slowly degrade after their reach of the bone maturity [10]. Thus, visibility of age in the Kopperdahl et al (1998), [11] table is limited due to limitation of information gathered from others journal researchers.

Mechanical properties of trabecular bone related to its importance in the development of bone regenerative solution and development on bone analogous materials as an alternative for *in vitro* biomechanical tests substrate, bonegraft and implants. This development requires to the greatest extend of knowledge in material properties of trabecular bone acquire from experimental techniques and/or computational method.

The mechanical properties of trabecular bone were dependent on bone density, volume, morphology of micro-architectural parameter and tissue properties [12]. Measurement of these properties has been performed non-destructively after preconditioned sample preparation and testing. Method and techniques used for such studies should not alter the initial stated properties of bones if compared to fresh bone. Previous studies have shown mechanical properties of bones influences towards its behavior when being analyses. Goldstein et al (1987), [13] reported the extensive variation on mechanical properties of trabecular bone is a function of anatomic location and physiology. Later studies by Linde et al (1992 and 1993), [14-15] demonstrated that the mechanical properties of trabecular bone are affected by different storage method and specimen geometry would have affected its properties. In order to quantify accurate materials properties for trabecular bone, constant and consistent method of measurement must be designed to eliminate variation of error in results. There are two main objectives of this project. Firstly is to analyze the deformation behavior of the trabecular bone with respect to normal walking loads and down stairs loads. Second objective is to investigate the relationship between bodyweight and stress distribution over trabecular bone structure.

2.0 MATERIAL AND METHOD

A bovine bone as discussed is the most suitable bone to replace due to the scarce of human bone supply. However, the similarity characteristic between human bone and bovine are falls closed by view of mechanical properties. In the other hand, in term of bone composition, human bones are more similar with pig bones rather than mechanical properties. Hence, bovine bone is much more preferable to be appreciated in this kind study. Most of the specimens are prepared in very cautions and cares condition in order to avoid of specimen defective. At the first, the leg of bovine bones is separated in parts by parts.

The next process is to clean up the *in-situ* marrow on the trabecular bone. The raw bone materials are taken from fresh bovine bone within age ranges in between 2 to 3 years old. Initially, the bovine bones were stored in -20°C to keep the raw bone in fresh condition. After removing the wrapped muscles left on the bone, the trabecular bone than through precision machine (Allied Techcut, USA) being extracted cylindrically following method from literatures [16-17]. The extracted specimen's region was purposely followed and aligned with base on the bone structure. With those condition, it will brings a standardize specimens between bone samples. The specimens then been stepwise removed the in-situ marrow by submerged with (Pumicized, Gent-1-kleen, USA) for a day. Secondly, pressurize air was applied onto the specimens to flush away the excessive marrow. Original dimension of extracted trabecular bone specimens was r = 20mm, l = 60mm before kept its back in the frozen state. All these subsequent steps are necessary in order to remain the freshness of specimens.

2.1 Meshing

The 3D model of trabecular bone was constructed in Mimic software from stacked micro-computed tomography (μCT) image file for finite element simulation. The step of converting file to natural file type is a common method to transfer a 3D model from difference CAD processor or FE processor. This method allows any types of CAD software have live interaction between FE software. In COMSOL finite element processor, the maximum number of elements allows are one million elements. In the exporting process, 3D model was unable to progress for meshing as due to insufficient memory. This unexpected error needs a correction loops by reducing size of 3D model. The loop correction needs has done in Mimics software. With some modification, thorough 3D view and satisfaction of accuracy shape, the current cubical shape resized dimension change to $2.5 \times 2.5 \times 3.0$ mm. Accounting on memory computer limit, ideal meshing shape and size the maximum number of elements created were 774,996 elements as shown in Figure 1.

2.2 Basic Material Properties

Most of the FE packages are depends on user input on the list, boundary condition, loading applies and a lot more. Usually, FE package will provide a material library that integrated in the package. Laterally, basic material properties for compression test for all types of FE packages are yield strength, Young's modulus and a Poisson's ratio. These three combinations of material properties are completely enough to initiate the numeric calculation. For trabecular bone, specific and exact value of material properties is indeed different for every experiment performed. The collected data from published papers with specific related title to trabecular bone as express in Table 1.

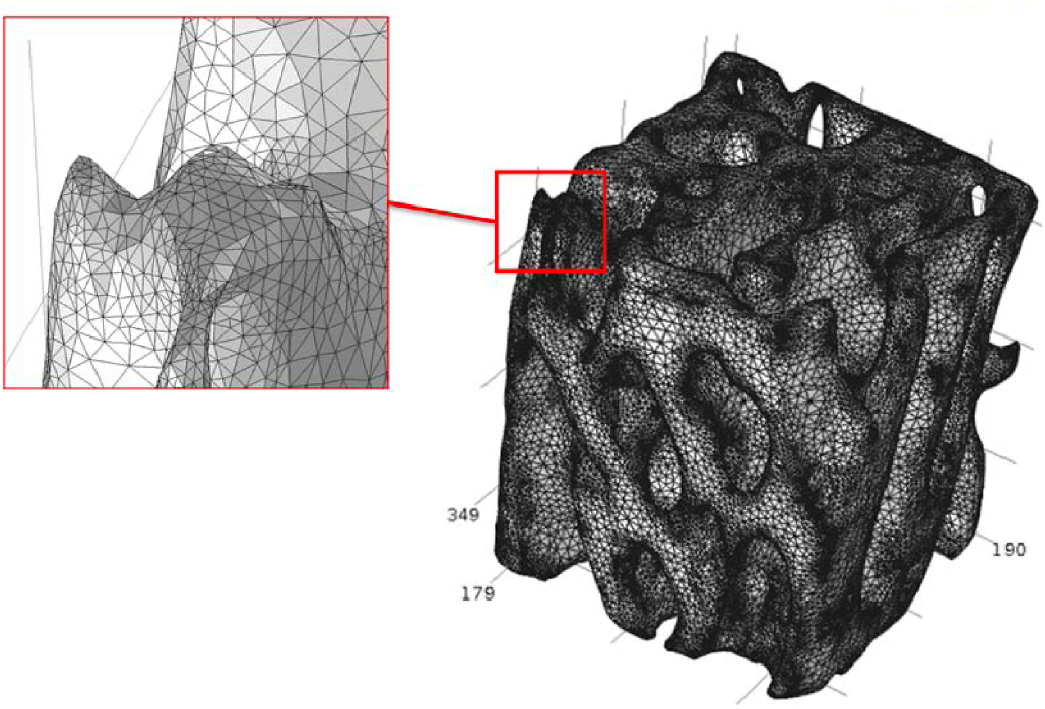


Figure 1: Meshed specimen with 774,996 numbers of elements created to satisfy finding in converged region.

For this particular study, as tabulated value in table, selected material properties are referred to the most cited among published papers. Yield strength is 17.45 MPa, Young's modulus is 18 GPa and a Poisson's ratio of 0.3. All the constituted parameters clearly cited as in Table 1. Although the data were taken from previous researchers, several engineering assumption has been made to simplify this study. On the whole, the finding and methodology are possible to be applied as it's followed the same method of the analysis preceded.

Table 1: Basic Trabecular Bone material properties

Type of Bone	Elastic Modulus (Gpa)	Yield Strength (Mpa)	Test Method	Ref.
Distal Femur	8.69 $\pm$ 3.17	NA	Buckling	[18]
Femur & Tibia	5.3 $\pm$ 2.6	NA	FEM	[19]
Proximal Femur	0.049 - 0.572	16.2 - 17	Uniaxial Stress	[20]
Human Femoral	0.172 - 0.176	0.39 – 5.98	Uniaxial Stress	[21]
Bovine Femoral	1.13 – 16.46	NA	Bending Test	[22]
Bovine Femoral	0.4 – 3.6	NA	Uniaxial Stress	[23]
Distal Femur	0.0588 – 2.942	0.98 – 22.5	Uniaxial Stress	[24]

2.3 Elasto-Plastic Material Properties

Trabecular bone is spongy structure as were reported in detail before. The bone behaves differently as ferrous, non-ferrous or metallic materials. Most near related to the bone structure properties is composite behavior such honeycombs structure or foam. However, recent study revealed that trabecular bone had similar properties to elasto-plastic material [25]. This type of material properties explained trabecular bone has two phases of region before fracture occurred. The first phase interprets the material will return to its initial position right before stresses applied are below yield stress. Begin after stresses are applied exceeded yield point, the bone will not return to its original position called irreversible state. Elasto-plastic material properties in FE package provided two types of plastic hardening. Firstly called isotropic hardening and the second one is kinematic hardening. Both types of hardening play different in yield surface depending on loadings given. Simple annotations on both of types of hardening are, isotropic hardening is easily described brittle-plastic-like behavior and then kinematic hardening gives better agreement with the actual behavior on cyclic loadings [25]. A good research from Gupta et al (2007), [26] which was provided the differential trend of fully perfectly plastic, kinematic hardening, isotropic hardening and the combination of both hardening.

2.4 Loadings

Bergmann et al (2001), [3] had figured the trend of hip contact, which represented the data of average cycle for normal walking condition. First rapid raise before Peak Force (FP) is indicated the concentrated force on hip right before heel touchdown to the floor. FP is the force exerted by hipbone where every pace cycles of first time heel land on the floor. That force showed the highest force absorbed by the hip. After reached peak force, the force on hip degraded as regard of transition from heel to toe. Second peak explained force acting on hip is again rising due to Metatarsals and Phalanges land on the floor. This gait cycle is representing one step of walking normal condition.

There are three axes loading exerted to form one completed gait cycle. For constructing those three equations by using Matlab function and commanding a potential coding to extract the nearest polynomial function as presented in Figure 2a. Since the genuine graph of gait cycle trend is in body weight percentages, thus, author presented the polynomial equations were base 60 kg person. Which means it is representing the averages weight among adult person. In addition of that, to have a better curve fitting on the gait cycles, highest orders were employed to get the best representative of curves. However, the contra of using high order polynomials is the curve is starting to scatter at both tips of the trends. Furthermore, heuristic method on the nearest polynomial equations is getting more complicated to match.

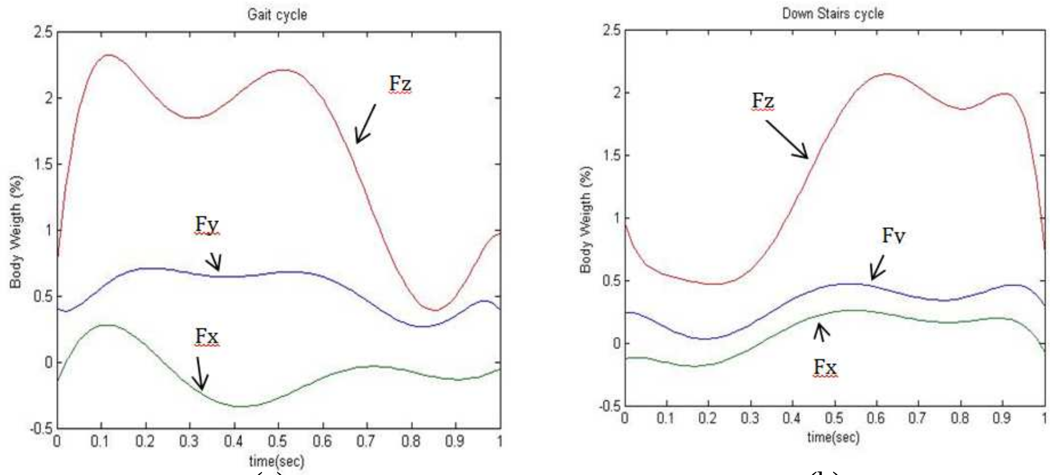
Responding to the software requirement, loadings in parametric study needs a special equation to represent as loadings in the calculation of element matrixes. Harnessing on the technology, three equations as reflect on finding from Bergmann et al (2001), [3] capable to extract through Matlab software. Figure 2b shows the plotted graph on femoral neck base on downstairs activity. The process of extracting three polynomial graphs is using a similar way as previous on extracting method. In spite of that, previously in excerption gait cycle equations, the polynomial order is up to seven for closest presenting trends. Contrary to this extracting approach, polynomial has to be in different orders as followed to trend requirements. Trends with fewer curves that are F_x and F_y loading were engaged with polynomial to the power of six. While loading in z direction, F_z was coded to extend in polynomial to the power of 7. This is to impose the nearest trend could mimic from the original down stairs trend as well as the smoothness of the trends.

3.0 RESULTS AND DISCUSSION

3.1 Convergence study

Numerical study has been done in approximation of loading method applied in trabecular model. Convergence study also was performed in order to obtain optimum size and number of elements which hope to yield an accurate result. Thus, it’s explained the approximation of finite numbers of elements in the generic numbers. Interestingly, the mores of number of elements creates in particular model design its will simultaneously optimize the best approximation results. In all such instances, this computational simulation had run varies number of elements against specific Von Misses. For Comsol

FE package, the maximum numbers of elements are able to generate for about 1,000,000 elements. That features explain the software is fit for complex structure. Deciding to use small meshing size means the number of elements increased and such that closely related to simulation time. More elements generated through the mesh setting are believed to increase the computational time to run an analysis. Particularly in optimizing the best number of elements, result findings and time consuming in this study, a same one model with six different numbers of elements has been analyzed.



(a) (b)

Figure 2: a) A mimic of normal walking loads trends by Matlab software
b) A mimic of downstairs loads trends by using Matlab software

Referred to Figure 3, three samples of different number of elements show a nice precise von misses value. The number of element ranges for the first three samples is in between 70,000-98,000 elements. In the forth sample, the value data start to converge until number of elements applied for about 922,224 which is closed to maximum number of elements. However, using high number of elements in simulation will consume a lot of times. Thus, author decided to uses the optimum number of elements in varies analysis for the sake of saving time analysis. The selected optimum number of elements was 774,996 elements. Through this, it costs author a day for a sample to simulate the result. 24 hours for a test sample is much worth to wait rather than waiting for two weeks finding result for 922,224 numbers of elements. Since, the result in that region seems to be in settling down region.

3.2 Specimen Displacement

Focusing Figure 4 show Gait analysis loads, from started of cycle, a displacement was already occurred for about 2.9117×10^{-7} m. At time 1 s, the specimen had displaced for about 4.3573×10^{-7} m. With referring to the normal walking activity curve, the specimen was experienced three ranges of displacement range. First half from the top specimen surface, the displacement occurred in between $(40 – 50) \times 10^{-7}$ m. Meanwhile, the rest bottom half specimen was displaced in between $(20 – 30) \times 10^{-8}$ m. The most critical displacement occurred on the trabecular bone specific for walking is at 0.2 s. Recorded at 6.8377×10^{-7} m displacement took place and that covered a quarter of the top bone surfaces. That gives the highest displacement across 1 s period. The minimal displacement occurred at the time 0.8 s. Mostly for the entire bone, the specimen was dominated with two displacement contour phases. The first range is in between $(20 – 30) \times 10^{-8}$ m and the second range is in between $(0 – 20) \times 10^{-8}$ m. At 0.5 s, the specimen started to return into the initial position gradually with respect to the given loads in function of time. Observing through the specimen, the bone deflection is toward on minus x-axis direction.

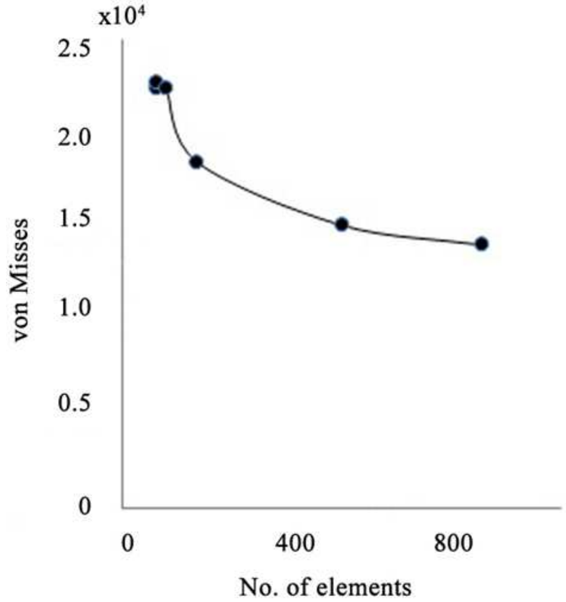


Figure 3: Plotted graph of von-Misses against number of elements, indicated in the region of 700,000 to 800,000 considered as optimum numbers

For down stairs loads, in the first 4 steps, from 0 to 0.4 s, the specimen displacement shows in very minimal value as reflect to low contacts from three major axis loadings. The specimen shows major differences during time 0.6 s, that magnifies the highest deflection across down stairs cycle occurred, with value 1.1281×10^{-6} m. From closed looks, only 4 steps from 0.6 s to 0.9 s gave distinct impacts on the trabecular section. In comparison with both down stairs and the gait cycle, the displacements are completely opposite. For gait cycle, first six steps are the most impact period to the specimen. And differently occurred for down stairs cycle, the physiological impact seems begin in period before at the end of cycles.

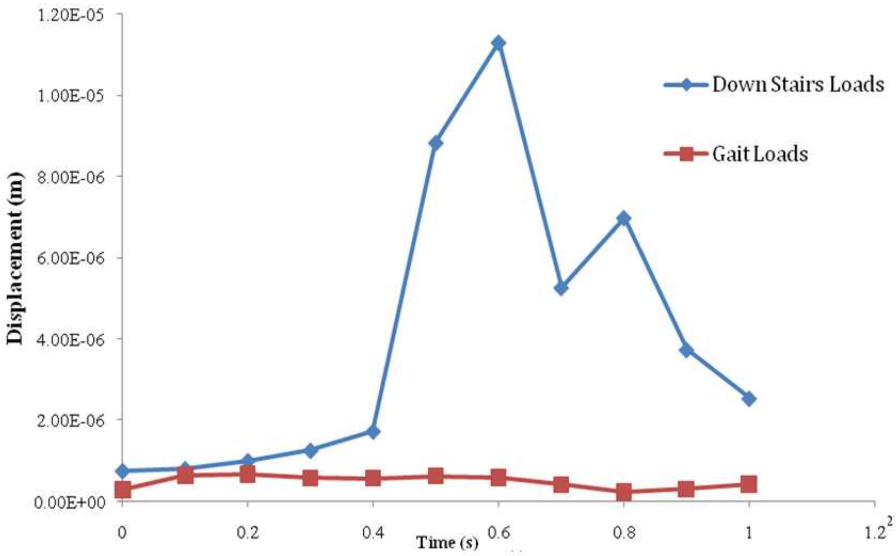


Figure 4: Deflection data between Gait Loads and Down Stairs loads

3.3 Stress-Strain curves

In Figure 5, appointing on one specific location on specimen, stress and strain data were extracted at time 1s. Three bundles of data had been plotted together in stress-strain graph as shown. Started with 60 kg bodyweight, the trend shows in the Figure 5 in blue line with triangular marking line. Apparently, the trend for gait loadings (60 kg) plotted linearly in the lowest stress and strain ranges. The middle ranges follow by gait loadings with bodyweight 80 kg and the highest ranges of stress-strain is from 100 kg bodyweight gait loadings. The Young's modulus of these three loadings produces equal value as expected. Since, all three trends is linear, hence the Young's modulus$E = \Delta\sigma/\Delta\varepsilon$ is equal for all and yield 14.8 GPa

Down stairs loadings initially had been setup with person has 60 kg bodyweight. Dealing with the comparison between down stairs loadings and gait loadings, the correlation will only solid through plotting the same loadings weight. In Figure 6, red marking line presenting gait loadings with 60 kg bodyweight and blue trend composed from down stairs loadings. Prior to down stairs loading first, the strain started while gait loadings reach maximum at strain. That developed strain highest through the end which is strain, Ɛ about 0.017%. That elongation occurred at 7504 Pa of down stairs loadings. From the plot gives the Young's modulus of the down stairs loadings is yield approximately 14.7 GPa.

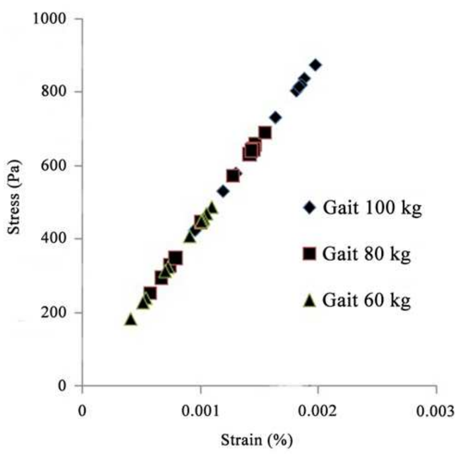


Figure 5: Stress-Strain curves for three level of bodyweight

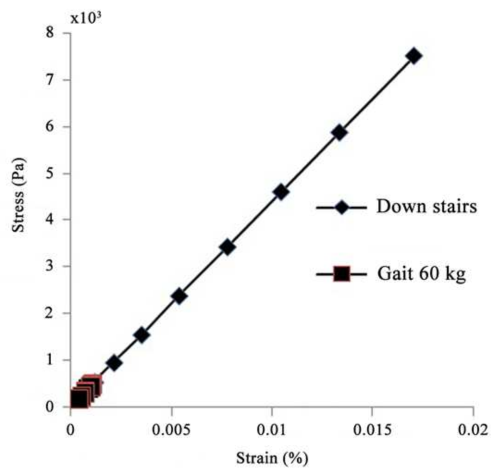


Figure 6: Down stairs Loadings and Gait Loadings for bodyweight 60kg

Refer to Figure 7, density of the specimen giving slightly change to the numerical data provided by software. There are huge different for a small deviation of density. The deviation value is only 0.262g/cm^3, however the difference in mechanical properties is obviously literate for the experimental data is integrated with compressive data alone. While the gait goadings and down stairs loadings are the combination of three axes furthermore its inclusive tensile and compressive movements together.

Gait loadings from Bergmann et al (2001), [3] consist of three axes loadings. Integrated to section 3.1 to 3.3, it is resembled from a minute of cycle for every gait. Displacement is seems to be the one of important output to initiate the study of mechanical properties. Furthermore, in physical wise, any given stress subjected to particular object will react to squeeze, swell, deflect and other behaviors depending on material properties and applied loads. Through that, the resultant trend shows Figure 8, the tallies of displacement occurred on the specimen. Thus, elasto-plastic properties induce to play as big roles in adapting the applied gait loads. Guillen et al (2011), [27] in his recent study suggested that the similarity of porous material and trabecular bone as reflect to their elasto-plastic mechanical behavior. Recently, Gupta et al (2007), [26] suggested the immerged better ratio for isotropic hardening and kinematic hardening for elasto-plastic mechanical properties.

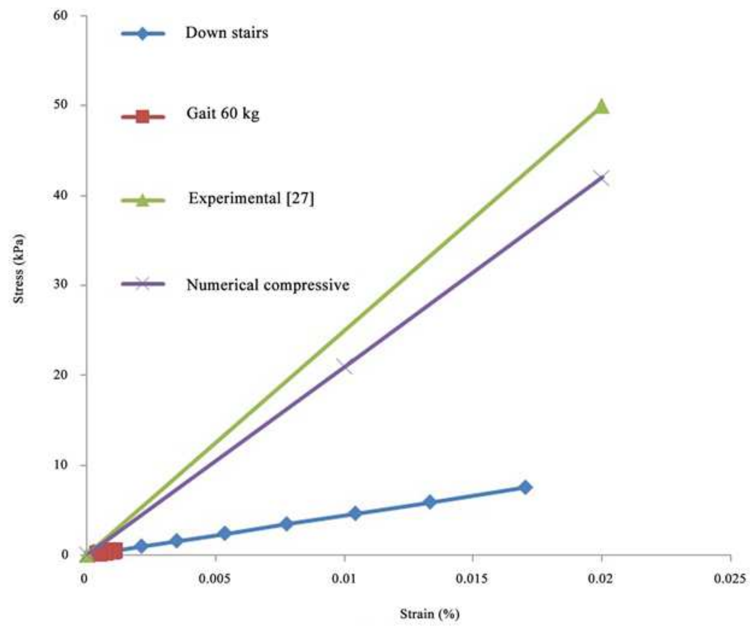


Figure 7: Density effect of stress-strain curve vs experimental data

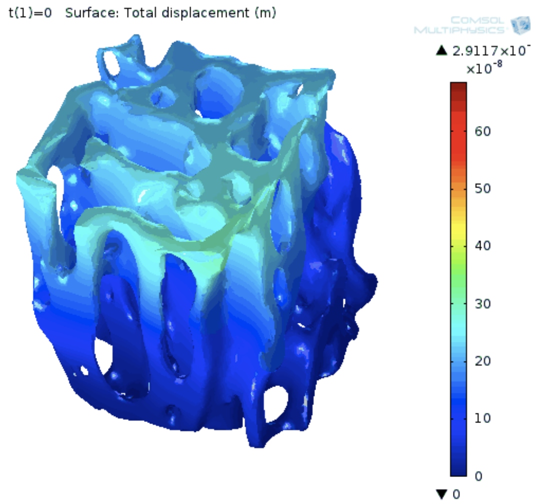


Figure 8: Total displacement of normal walking with 60 kg bodyweight load

4.0 CONCLUSION

The total displacement between two particular activities, which are normal walking and down stairs, the worst case is suggested go to down stairs activity. This is because our bodyweight are more focal in intact during simulation. In addition, the effect of elevation height will indeed considering speed of gravity to bodyweight during activity. The femur bone in normal walking gait is having less impact on stress as well as strain during gait compared to down stairs. Most of the Trabecular Bone fatigue analysis is known to be failure when secant modulus value in every cycle gives sudden abrupt change. Most of the researchers indicates their own experimental in decreasing of 10% secant modulus. However, through our observation, crack initiation will started in “V” shape all the way through middle of the specimen. This is due to half top and half bottom give different big gap of displacement. Considering the whole bone structure, according to distribution of color in deflection, distortion will occur near to the femur neck for about 1 mm from cortical surfaces. That suggestion implies on real situation happened on the osteoporosis patients.

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