# INFLUENCE OF MECHANICAL STIMULATION ON BONE TISSUE ELASTICITY WITH FEM

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**ABSTRACT**

Mechanical stimuli have a significant influence on the growth of bone. Osteocytes of canaliculi can communicate with osteoblasts. Furthermore, osteoblasts communicate with cells in the bone marrow with projecting it cells into endothelium, thus forms new bone cells. The aims of this research are to determine the effect of mechanical stimuli on the static and dynamic of stress, strain, and strain rate on the bone tissue and the influence of differences in bone properties (Young's modulus). In this research, a linear elastic material model was chosen for bone tissue modelling and analysis. The strain and stress of the modelling bones were calculated using finite element method of the derivation harmonic oscillator for bone, then to use the finite element method calculation. The results showed that the static force results maximum strain rate 20.986/s, furthermore, due to the different properties of the bone (reduction is 6% of Young's modulus of 17.9 GPa to 16.92 GPa ) resulted in the increase strain rate 0.238/s. The decrease bone properties (reduction is 6% of Young's modulus) decreases the tension 2.36%, raise the strain 14.536% or every decrease 2% (the increase is one decade of age) will decrease tension 0.78667% and the increase the strain 4.485%. The results of this study can be used to calculate the bone density by using the equations of V. Klika and F. Marsik.

**Keywords:** Remodelling Bone; Voltage; Strain; Rate Strain; Bone Density

## Introduction

Bone is a complex tissue that is constantly damaged and forming through the biological remodelling process. The main component of bone consists of cortical bone, and trabecular bone (Fig. 1).[1] Cortical bone is composed of collagen filaments are arranged parallel to the shaft of the femur. Cortical bone mechanical stimuli are biggest since being on the outer layer of the bone.

Bone remodelling is the process of formation and damage continuously in the bone. The process of bone remodelling influences by osteoblasts and osteoclasts cells. Osteoblast cells are responsible for bone formation while cells osteoclasts responsible for bone destruction.[2] Due to the destruction of bone remodelling, bone density changes gradually to explains how the process of osteoporosis occurs. The release of bone due to osteoporosis will be greater than the formation so that bones become thin, brittle, fragile, and easily broken bones.[3] Addition can also occur due to mechanical stimuli that exceed the elasticity bone.[4]

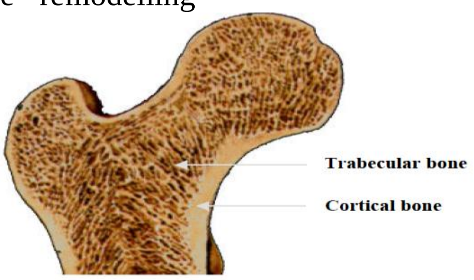


**Figure 1.** Pieces longitudinal of the femur which shows that trabecular bone is covered by cortical bone.[5]

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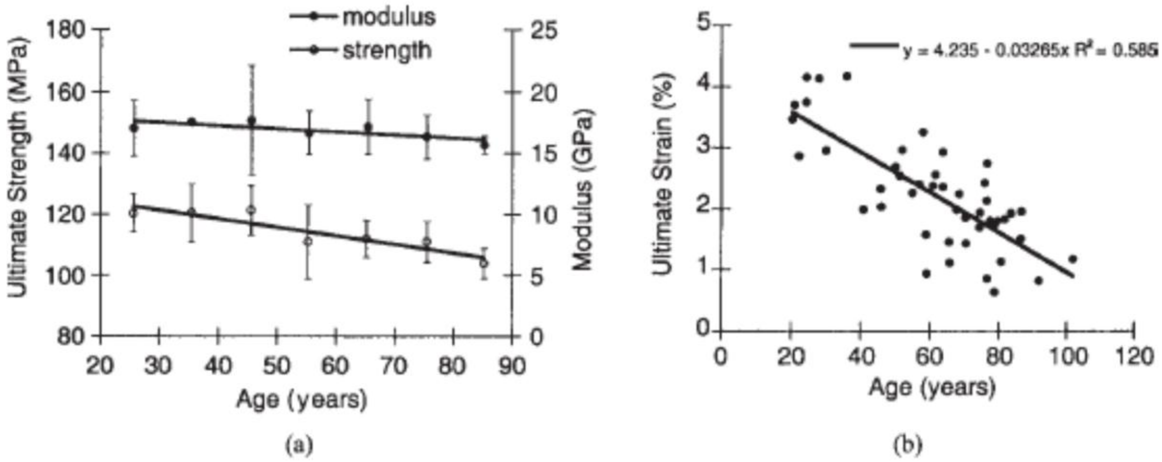



**Figure 2.** Reduction of the mechanical properties of human cortical bone with age. (a) the rate reduction of tension about 2 percent every ten years. (b) The reduction of strain rate approximately 10 percent every ten years.[6]

Cortical and trabecular bone remodelling is influenced by mechanical stimuli. Mechanical stimulation affects the activity of osteoblasts and osteoclasts.[7] Due to mechanical stimuli, osteocytes can communicate with osteoblasts. Furthermore, osteoblast cells will communicate with cells in the bone marrow cells with projecting it cells into endothelium.[8]

Research on mechanical stimulation of bone remodelling has been done by several researchers. However, can not explain the mechanical stimuli and strain rate in full. V. Klika and F. Marsik in 2006 using a model of RANK-RANKL-OPG to lower the differential equations remodelling bone.[9] Followed in 2010, they examined the thermodynamic model of bone remodelling that can explain the process of osteoblast activity by modifying the previous equation yet. Analysis of these studies can not explain the distribution of strain and strain rate on bone.[10]Whereas in 2013 Idhammad Ahmad et all have calculated the density of the bone due to mechanical stimuli however the mechanism of osteoblasts, osteoclast, and osteocytes cells facilitate adaptive alterations in bone mass and architecture is not yet completely understood.[11] This problem becomes an impetus for authors to be able to calculate tension, strain and strain rate on the bone due to mechanical stimuli. This research aims to calculate the distribution stress, strain, and strain rate due to different physiological activities (force) and due to differences in bone properties (Young's modulus).

A different analysis of stress, strain and strain rate of bones will be obtained as a result of different physiologic activities, as well as due to the different properties of the bone.

Strain distribution is calculated with Equation relationships displacement, strain, and stress as well as differences in bone material properties (Young's modulus) using *the finite element method.*

### Cortical Bone Properties

Bone tissue macroscopically is divided into two parts. The first is the bone cortical or compact that is dense tissue. The second is cancellous or trabecular bone, and the bone is more porous and soft. Located outside the cortical bone covers the trabecular bone tissue,[5] Whereas the mechanical stimuli originating from the junction of the femur with the pelvis (Figure 1).[12]

The cortical bone microstructure is anisotropic, elastic and strong. Cortical bone is stronger and stiffer in the longitudinal direction than the direction of the radial or circumferential direction. With increasing age affects the mechanical properties of human cortical bone. Ultimate stress declines by about 2 percent every decade (Figure 2 (a)). While the ultimate strain decreases to about 10 percent every decade (Figure 2 (b)).[13]

Fig. 3 shows the sensitivity of the strain rate. It describes the influence of external forces (loading rate) on strength and Young's modulus. Thus it should be explained, as the loading rate is increased by 6 orders of magnitude, the modulus increase by factor 2 and strength increase by factor 3. Loading rate (strain rate) at 0.01-1/sec is the strain rate in daily activity which at very high strain rate, ultimate strain decrease results in a ductile to brittle on cortical bone.[13]

### Influence of Mechanical Stimuli

Osteocytes are osteoblast that is the buried of lacunae in the mineralized bone matrix and serves as the nervous system. Osteocytes amount ten times the number of osteoblasts. Osteocytes throughs the plasma membrane protrusion (length is 5-30 mm) in the canaliculi can communicate with osteoblasts. Furthermore, osteoblasts communicate with cells in the bone marrow cells projecting it cells to endothelium in sinusoid.

Osteocytes also can change detection interstitial fluid flow in the canaliculi that is generated by mechanical loading and detection of changes in levels of the hormone estrogen. Therefore outage in osteocytes can increase bone density (figure 4).[14]

## Methods

Bone remodelling is a highly complex process that is very difficult to set up mathematical equations. It takes the right approach to be able to explain the process. In this study, the author uses bone mechanics approach to Elastic material models. Mechanical approach is used to explain the stress, strain and strain rate in bone tissue.

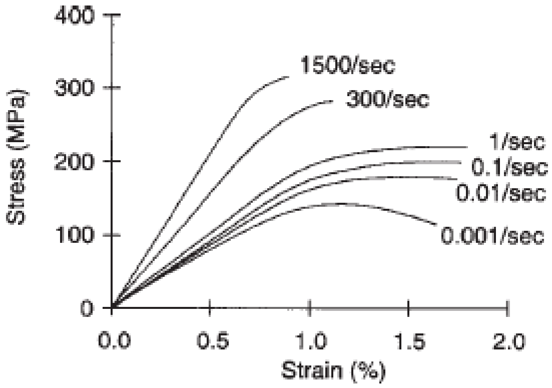



**Figure 3.** The sensitivity of strain rate on cortical bone in the direction longitudinal[13]

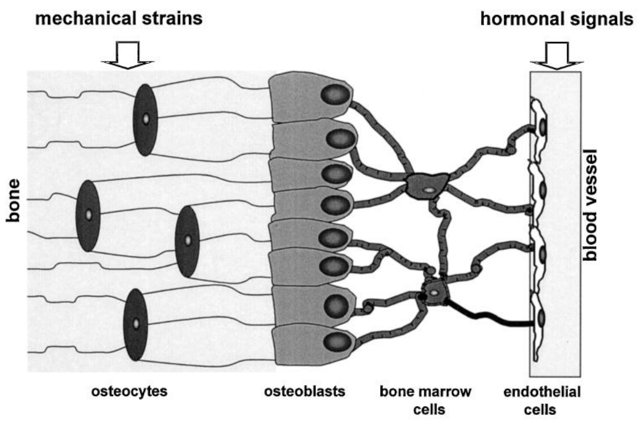



**Figure 4.** functional syncytium comprising osteocytes, osteoblasts, bone marrow stromal cells, and cell endothelium[15]

**Equations of the Elastic Material**

At the time of standing up, the most body weight is accepted by the femur bone, so caused static pressure on the bone. However, not all weight is concentrated on the femur bone. Damien et al. described body mass is concentrated between two hips. In this study, the body weight is assumed to be received by the bones of 1200 N. Static pressure and strain relationships in the femur bone is given by equation (1).

$$F = kd \quad \text{dan} \quad \sigma = D\varepsilon \tag{1}$$

The above equation showed that the force on the bone $(F)$ resulting from the multiplication properties of bone stiffness $(k)$ and displacement $(d)$. The pressure on the bone $(\sigma)$ producted of properties of the bone $(D)$ (i.e., Young's modulus and Poisson's ratio) and strain (ε). Equation (1) described in a matrix by the method of *weighted residuals* then calculated using the *finite element method (*FEM). Properties of bone in the form of Young's modulus $(E)$ and Poisson's ratio $(v)$ is given by equation (2). While stress and strain decomposed into three directions $(x, y, xy)$ namely the equation (3-4)

With the *weighted residual*, it available equation of bone stiffness matrix, force and strain relations (equations (5-7)). Equation (6) showed that each element of the matrix (bone tissue) in the FEM.

$$[D] = \frac{E}{1-v^2}\begin{bmatrix} 1 & v & 0 \\ v & 1 & 0 \\ 0 & 0 & \frac{1-v}{2} \end{bmatrix} \tag{2}$$

$$\{\sigma\} = \{\sigma_x \ \sigma_y \ \tau_{xy}\}^T \tag{3}$$

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} \tag{4}$$

$$\int_\Omega \begin{Bmatrix} \frac{\partial \omega_1}{\partial x} & 0 & \frac{\partial \omega_1}{\partial y} \\ 0 & \frac{\partial \omega_2}{\partial y} & \frac{\partial \omega_2}{\partial x} \end{Bmatrix} [D] \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} d\Omega = \int_\Omega \begin{Bmatrix} \omega_1 f_x \\ \omega_2 f_y \end{Bmatrix} d\Omega + \int_{r_n} \begin{Bmatrix} \omega_1 \bar{\Phi}_x \\ \omega_2 \bar{\Phi}_y \end{Bmatrix} dr \tag{5}$$

$$[K^e] = \int_{\Omega^*} [B]^T [D][B] d\Omega = [B]^T [D][B] A \tag{6}$$

$$[B] = \frac{1}{2A}\begin{bmatrix} (y_2 - y_3) & 0 & (y_3 - y_1) & 0 & (y_1 - y_2) & 0 \\ 0 & (x_3 - x_2) & 0 & (x_1 - x_3) & 0 & (x_2 - x_1) \\ (x_3 - x_2) & (y_2 - y_3) & (x_1 - x_3) & (y_3 - y_1) & (x_2 - x_1) & (y_1 - y_2) \end{bmatrix} \tag{7}$$

***Dynamic Voltage Mechanics Equations***

The different physiological activity (walking, running) give rise to different mechanical stimuli on the femur. In addition, the stress and strain occur every bone tissue dynamic that occurs when external pressure is very quickly going to happen superposition of strain and strain rate of each network.[13]

$$F(t) = A_0 + \sum_{n=1}^{\infty} \left( A_n \cos \frac{2n\pi t}{2T} + B_n \sin \frac{2n\pi t}{2T} \right) \tag{8}$$

$$F(t) = \frac{1}{2T}(F_1 T + F_2 T) + \frac{1}{n\pi}[-F_1 \cos n\pi + F_1 - F_2 \cos 2n\pi + F_2 \cos n\pi] \sin \frac{2n\pi t}{2T} \tag{9}$$

$$\ddot{\varepsilon} + \frac{b}{\rho}\dot{\varepsilon} + \frac{E}{\rho}\varepsilon = \frac{1}{2T}(P_1T + P_2T) + \frac{1}{n\pi}[-P_1\cos n\pi + P_1 - P_2\cos 2n\pi + P_2\cos n\pi]\sin\frac{2n\pi t}{2T} \quad (10)$$

For the high physiological activity of the external force occurs continuously with a different factor. The dynamic external force derived from Fourier series with equation (8-9). For a state of static pressure (supporting the body) is $P_1$ and the dynamic pressure $P_2$, $P_1$ given conditions to style for $0 < t < T$ and $P_2$ for $T < t < 2T$ given equation (9). Every tissue in the bone interconnected that cause damping on strain and strain rate can be assumed that the dynamic processes that occur as a force *driven harmonic* oscillator (equation (10)).

### *Runge-Kutta* Orde 4

*Runge Kutta method* is one of the algorithms solved differential with the principle of Taylor series. Runge-Kutta orde4 required an initial value to begin with ($x_0$, $y_0$) and a piece of the four calculations Taylor series. The calculation is given in the following equation.

$$k_1 = f(x_i, y_i)$$

$$k_2 = f\left(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_1h\right)$$

$$k_3 = f\left(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_2h\right)$$

$$k_4 = f(x_i + h, y_i + k_3h)$$

$$y_{i+1} = y_i + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)h$$

## Result and Discussion

Femur bone geometry is described by using FEM with triangular elements with broad $10^{-5}$ m. In this geometry, the femur has 1458 elements (Fig. 5). Linkage pelvic bone and femur are given external force due to support body weight 1200 N and due to walk normally 2700 N.[15]

Both the external force applied to the bone with different bone properties are $E = 17.9\ Gpa$ with a Poisson's ratio $v = 0.4$ and $E = 16.92\ GPa$ with $v = 0.344$.[1] The static force is given at the junction of the femur and pelvis bone giving rise to the bone strain rate of cortical bone as shown in Fig. 6. Bone with a smaller Young's modulus has a greater strain rate (Fig. 6). In addition, both the strain rate properties of bone have a very small difference in clinical outcome as 1998 Hill PA.[1]

The distribution of strain rate shows that the strain rate increases in the point of origin static external force and shaft of the femur. Strain rate is proportional to the density of bone as a result by V. Klika and F. Marsik in 2010.[11] It shows the correspondence between the distribution of bone density simulation with clinical outcomes as a result of mechanical stimulation research Ahmed Idhammad 2013.[10]

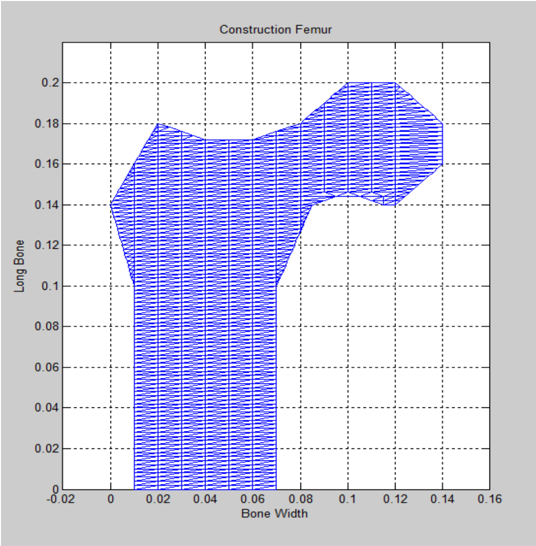



**Figure 5.** Femur geometry construction

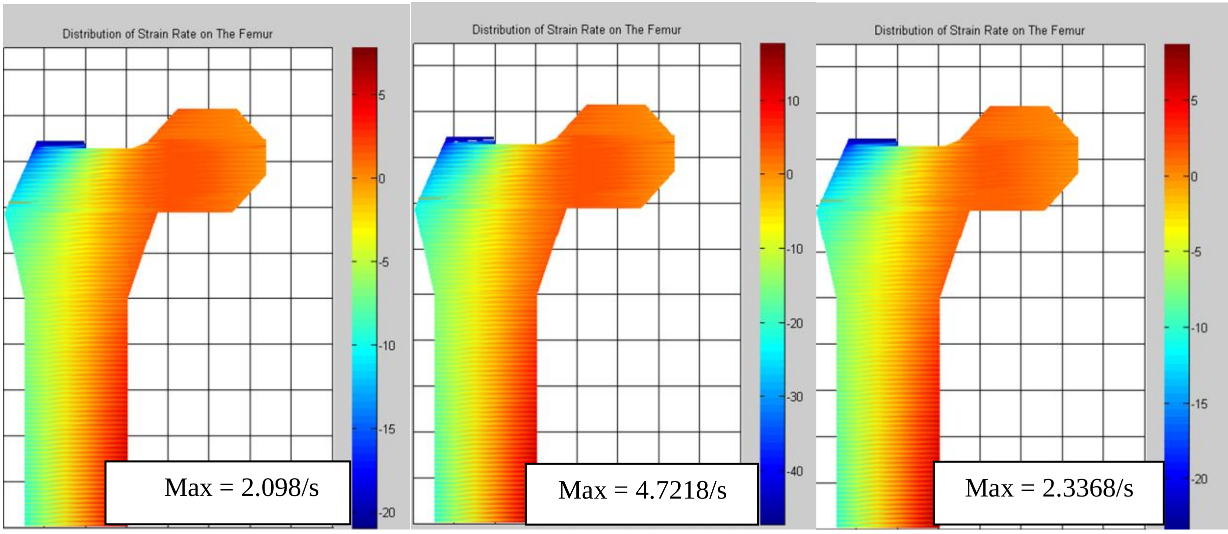
The static force results strain rate 20.986/s. Whereas, due to changes in Young's modulus can change the strain rate 0.238/s.

The bone elasticity $E = 17.9\ GPa$ is given static force 1200 N is obtained 4.2350 x $10^5$ Pa maximum tension, maximum strain 0.0015685% and strain rate 2.0986/s. Whereas, static force 2700 N obtained

9.5287 x $10^5$ Pa maximum tension, maximum strain 0.0035292%, and strain rate maximum 4.7218/s (Fig. 7-8).

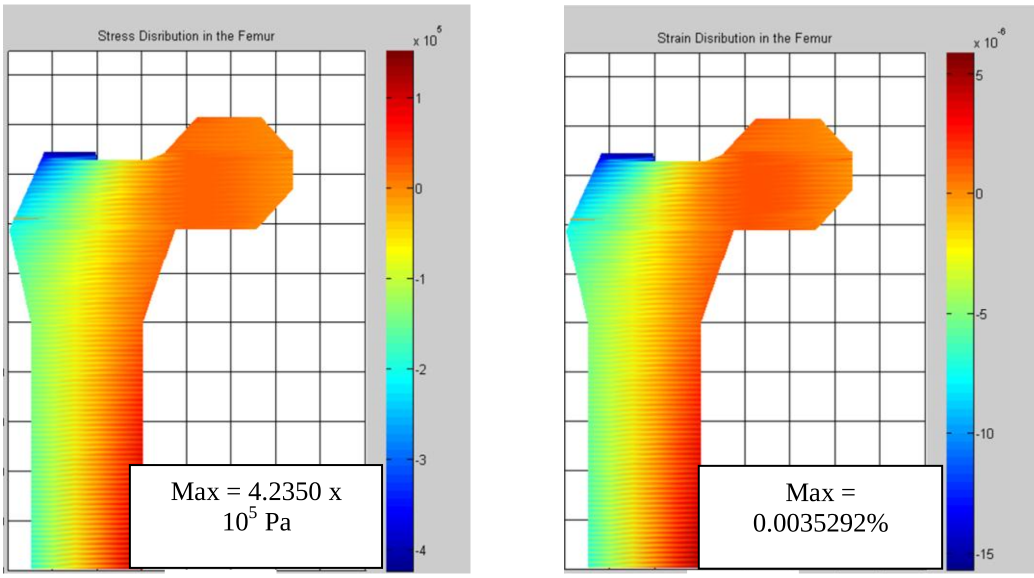
While on the bone with elasticity $E = 16.92\ GPa$ at 1200 N force obtained 4.0787 x $10^5$ Pa maximum stress, maximum strain 0.0017965%, and the maximum strain rate 2.3368/ s. For style 2700 N obtained 9.1772 x $10^5$ Pa maximum voltage, maximum strain 0.0040421% (Figure 9-10).

The calculations show that the increase in stress, strain, and strain rate is proportional to the increase in the given external force. In addition, due to the decrease in Young's modulus by 6% tension reduction 2.36%, raise the strain 14.536% or every decrease 2% (the increase is one decade of age) decrease stress 0.78667%, and strain increases 4,485%.



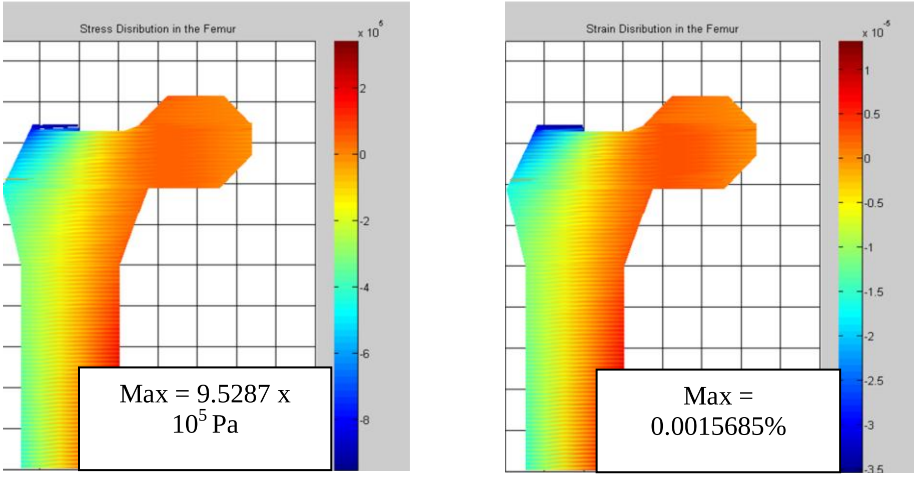

(a) (b) (c)

**Figure 6**. Distribution of strain rate: (a) the static force 1200 N and Young's modulus = 17.9 $Gpa$, (b) the static force 2700 N and Young's modulus ($E = 16.92\ Gpa$), (c) the static force 1200 N and Young's modulus ($E = 16.92\ Gpa$)



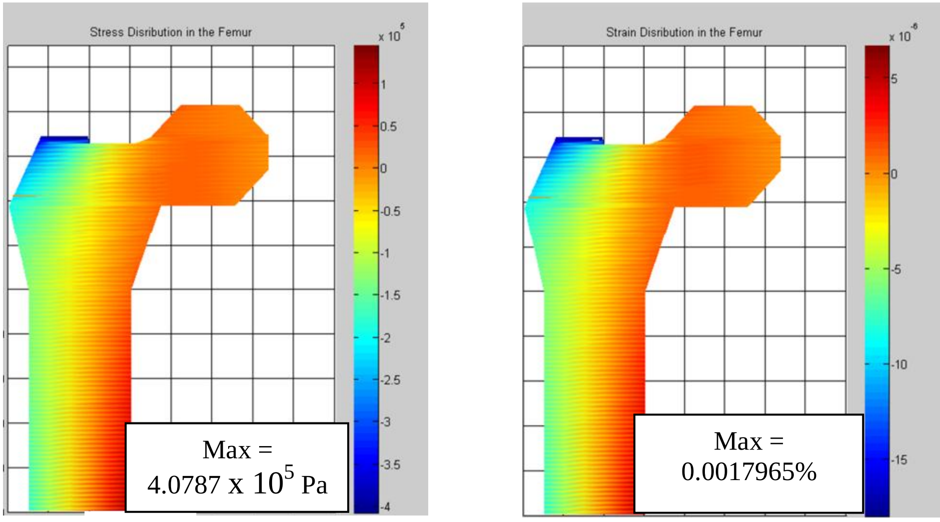

(a) (b)

**Figure 7.** External force 1200 N is given bone in the cortical bone of the femur ($E = 17.9\ GPa$)



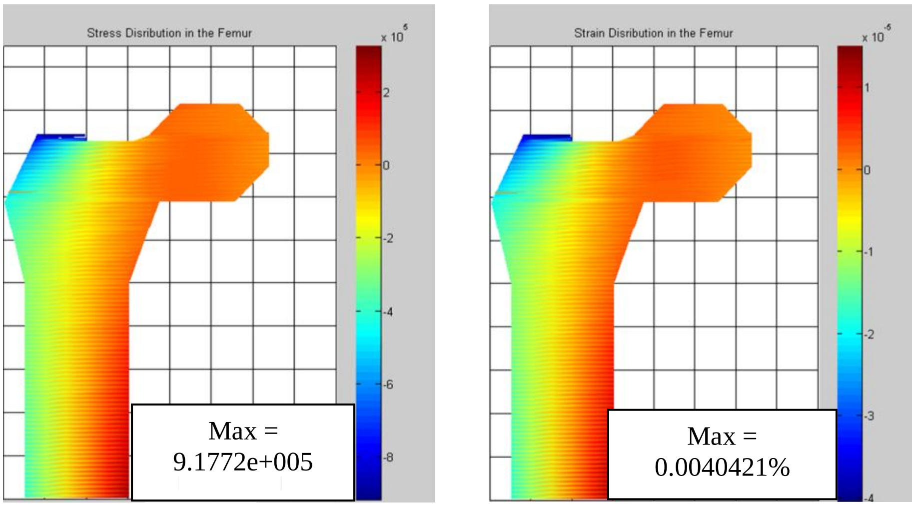

(a) (b)

**Figure 8**. External force 2700 N is given bone in the cortical bone of the femur ($E = 17.9\ GPa$)




(a) (b)

**Figure 9.** External force 1200 N is given bone in the cortical bone of the femur ($E = 16.92\ GPa$)




(a) (b)

**Figure 10.** External force 2700 N given bone in the cortical b one of the femur ($E = 16.92\ GPa$)

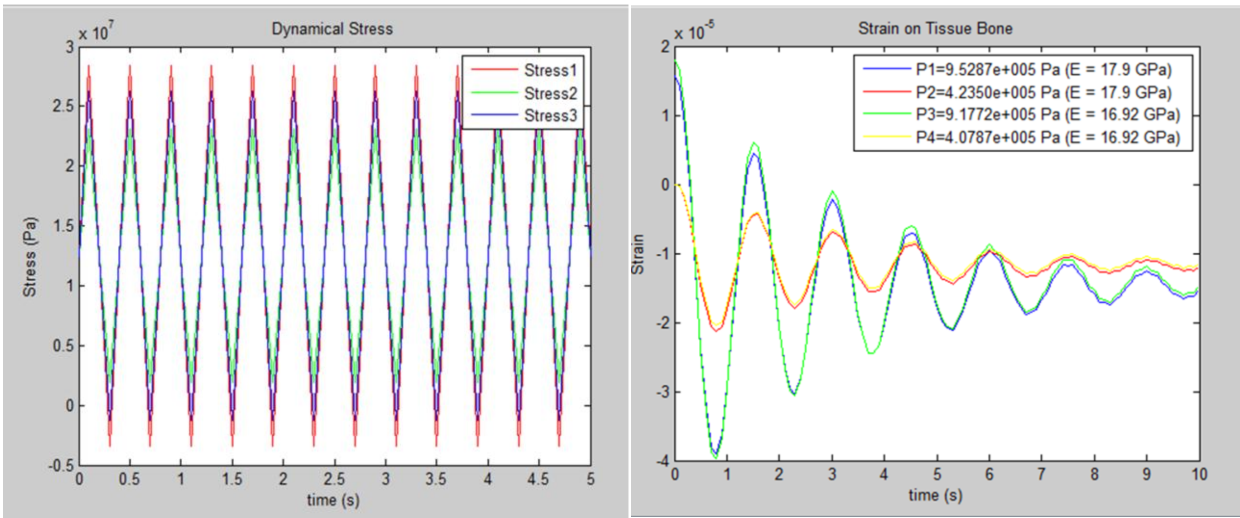
Figure 10 (a) shows the stress with different values due to an external force that is constantly received by bone. Using Fourier series, equation (10) and simulated in figure 11 (a) shows the three pressure as limitations in this research.

The varies tress in bone tissue continue to happen as long as the same physical activities. The total stress on the bone tissue is not the sum of all the incoming stress on bone tissue. However, the total stress is the superposition of different stress values (Fig. 11 (a)).

Equation (10) shows an infinite index of Fourier series. The index explains the number of incoming stress on each bone tissue. The stress up is calculated with use equation (1) and changed be a matrix (equation (6)) for each element.

The relations force and displacement may be likened to relations stress and strain. In this relationship, the constant stiffness springiness can be replaced with Young's modulus as elasticity material. Finally obtained equation (11) that can be used to calculate strain dynamic every element by inserting value elasticity material (17,9 Gpa and 16,92 Gpa) and the constant damping 0.9. The value stress is obtained from the ordinal fig. 7, 8, 9, 10 (a).

The dynamic strain calculation results that the time it takes a stretch to balance depending on the external force. The smaller external force is given the fast stretch to balance. These are not discussed in the research time needed for bone tissue strain oscillation to balance because there is no reference to clinical outcome. In addition, in fig 11 (b) shows that the strain on each bone tissue strain is not entirely exhausted, however towards certain equilibrium value depends from the stress of it. The greater pressure on it then more strain oscillation equilibrium on the element.




(a) (b)

**Figure 11.** (a) Dynamical stress model of tissue bone, (b) Dynamical strain influences stress and young's modulus is different

**Discussion**

Remodelling bone in every cortical is resorption and formation continuously. The process of remodelling bone caused by the mechanical stimuli originating from the external form of support is due to the heavy body, muscular contraction, and fats. This research using the femur as a model observation.

The results of geometry bones show a form resembling bone of the femur. Then, an external force is given derived from connection bone of the femur and the hip bone. Although stimuli mechanical also derived from muscle contraction and connection with the patella, stimulation was neglected because of stimuli mechanical largest derived from junction the hip bone and the femur.

Bone gets different mechanical stimuli depend on physiological activity. The bigger external force received by bone the result physiological activity such a high climbing and run. Whereas, properties of bone was a form of age bone demonstrated by Young's modulus.

Stress on bone tissue comparable with external force and properties of bone (i.e., Young's modulus and Poisson's ratio) that shows on similarities (equation (1)). The bigger external force, the larger also pressure any bone tissue. Beside, strain any bone tissue also got as we get external force as shown in the fig. 9 and 11.

An external force that occurs in the bone there is analyzed two styles of external static and dynamic external force. A static external force is a result of the support body weight assuming a force of 1200 N is obtained strain rate distribution in Figure (8). As a result of static force raises the maximum strain rate 20.986/s, while the result of changes in bone properties (Young's modulus) is 0.238/s. Distribution changing the strain rate is proportional to the density of bone as research V. Klika and F. Marsik[10] so that the distribution of strain rate can also indicate the femur bone density due to mechanical stimuli. Due to the dynamic mechanical stimulation, bone obtains external force constantly to produce pressure and harmonic strain on any bone tissue. In this study, mechanical stimuli every bone tissue is considered continuous and limited to three external pressure. Due to continuous external pressure will arise superposition of strain and pressure that results in strain rate.

The result shows the maximum strain and strain rate as a result of dynamic mechanical stimulation increase with increasing external force as shown in the fig. (9)-(12). As equation (1) shows, the stress and strain relations are linear, as well as to the force and pressure so that all three have a linear relationship. Whereas, due to the changing properties of the bone in the form of Young's modulus decrease of 6% increase bone strain until 14.536% as shown in fig. (9) and (11). This result indicates that with increasing age of someone ten years lose 2% of the Young's modulus[13] will raise approximately 4.485% strain. Due to the increase in the strain, the strain limit bone destruction due to the addition of age will be small.[6]

External pressure on every bone tissue dynamic has a value different, so it is possible there be the destruction of bone tissue if the vibration frequency approaches the natural frequency of bone. Model of the superposition of the external pressures derived from Fourier series is illustrated in Fig. 13(a). The calculations show that the strain and strain rate rise along with increasing external pressure ($P_1$). This result indicates that the higher activity of the human physiological strain and strain rate increase, but not the sum of each strain and strain rate caused by any pressure, but the superposition of each strain and the strain rate. In addition, the amount of pressure determines the time it takes the strain reaches continuity. The smaller the stress, the shorter the time required to achieve continuity strain (Fig. 13(b)). This result indicates that the strain reaches balance before followed by the new strain.

## Conclusions

Bone remodelling occurs by the process of bone resorption and formation happens continuously. In the process, the process is responsible for osteoclasts and osteoblasts. Osteoclasts are responsible for bone resorption while osteoblasts are responsible for bone formation. Activity rate of bone destruction and formation is influenced by mechanical stimuli such as strain rate. As research V. Klika and F. Marsik that bone density was comparable to the rate of mechanical.

The strain rate is proportional to the pressure caused by an external force. The calculations show that the force due to the static result strain rate of 0.238/ s and Young's modulus increase due to a decrease in strain rate 0.238/s in accordance with the results experiment.[14] As a result of the increase in dynamic external force is obtained an increase in strain and strain rate is linear. Due to a decrease in bone properties (Young's modulus) of 17.9 GPa be 16.92 GPa, down 6% strain resulted in an increase of 14.536% or every 2% decrease (the increase is 1 decade of age) decrease the stress 0.78667%, while the strain increases to 4.485%.

Results vary the pressure on each bone tissue result in a superposition of strain and strain rate. The calculations show that the magnitude of the pressure affects the time it takes the strain to continue circumstances. The smaller the stress, the faster strain toward equilibrium. However, if the stress is continuous, then the superposition of strain also occurs continuously until these physiological activities cease.

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## References


1. Ruimerman. Modelling and Remodelling in bone tissue. Technische Universiteit Eindhoven; 2005.
2. Väänänen HK, Horton M. The osteoclast clear zone is a specialized cell-extracellular matrix adhesion structure. Journal of cell science. 1995 Aug 1;108(8):2729-32.
3. Rouhi G. Biomechanics of osteoporosis: the importance of bone resorption and remodeling processes. InOsteoporosis 2012. InTech.
4. Ritchie RO, Kinney JH, Kruzic JJ, Nalla RK. A fracture mechanics and mechanistic approach to the failure of cortical bone. Fatigue & Fracture of Engineering Materials & Structures. 2005 Apr;28(4):345-71.
5. Hill PA. Bone remodelling. Br J Orthod. 1998; 25:101-7.
6. Keaveny TM, Morgan EF, Oscar C. Bone mechanics. California(AS): McGraw-Hill; 2004.
7. Wolff J: Das Gesetz der Transformation der Knochen. Berlin A. Hirchwild (1892) Translated as: The Law of Bone Remodelling. Maquet P. & Furlong R., Springer-Verlag: Berlin; 1986.
8. Manolagas SC. Birth and death of bone cells basic regulatory mechanisms and implications for the pathogenesis and treatment of osteoporosis. Endocrine Reviews 2000;21(2):115-37.
9. V. Klika and F. Marsik. 2006. Mathematical and numerical analysis of differential equations of bone remodelling. Czech technical university Faculty of nuclear science and physical Engineering Department of mathematics.
10. Klika V, Marsik F. A thermodynamic model of bone remodelling: the influence of dynamic loading together with biochemical control. J Musculoskelet Neuronal Interact. 2010 Sep 1;10(3):220-30.
11. Idhammad A, Abdali A, Alaa N. Computational simulation of the bone remodeling using the finite element method: an elastic-damage theory for small displacements. Theoretical Biology and Medical Modelling. 2013 Dec;10(1):32.
12. Pacioga A, Palade DD, Comsa S. Computational Simulation Of Bone-Personalized Hip Prosthesis Assembly. University "Politehnica" of Bucharest Scientific Bulletin, Series D: Mechanical Engineering. 2011;73(2):249-62.
13. Tony M. Keaveny, Elise F. Morgan, dan Oscar C. Yeh. Bone mechanics. California: McGraw-Hill; 2004.
14. Plotkin LI, Weinstein RS, Parfitt AM, Roberson PK, Manolagas SC, Bellido T. Prevention of osteocyte and osteoblast apoptosis by bisphosphonates and calcitonin. The Journal of clinical investigation. 1999 Nov 15;104(10):1363-74.
15. Damien P. Et all. Anatomy and Biomechanics of the Hip. Medicine Journal. 2010, 4, 51-57