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Simulation of mechanical stimulation effect on bone density changes due to age-based finite element method (FEM)

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Abstract. The getting older of people age, the density of bone will be further reduced. The process speed of bone formation decreases progressively after reaching peak bone mass in the age range 25-30 years. The reduction in bone density is known as osteoporosis. This phenomenon occurs due to an interruption on remodelling bone due to some conditions. Therefore, this study is going to simulate the effect of mechanical stimuli on femur bone density using walking and standing mechanical stimuli. In this study, there are four stages passed. First, build the femur bone construction which consists of two layers (cortical and trabecular). Then input the properties of bone based on age (Young's modulus and Poisson's ratio). Then calculate the stress, strain and strain rate and calculate the bone density using thermodynamic equation of V. Klika and F. Marsik with Runge-Kutta method of 4th orde. The bone density given standing mechanical stimuli (1290 N) for age 25 is 0.7963 g/cm^2 and walking mechanical stimuli (1741.5 N) is 1.0698 g/cm^2. Then the bone density given standing mechanical stimuli (1200 N) for age 51 is 0.7703 g/cm^2 and walking mechanical stimuli (1620 N) is 0.9885 g/cm^2.

1. Introduction

Bone is really important role in supporting the body skeleton, have properties that are rigid, hard and its ability to regenerate and repair themselves [1]. Many abnormalities that occur in bone and influencing factors, one of which osteoporosis. Until now, osteoporosis remains a problem throughout the world, it's such a data report from WHO explains that throughout the world there are approximately 200 million people suffer from osteoporosis. Osteoporosis may result in broken bones, according to a report from the WHO indicate that 50% of fractures due to osteoporosis are femur fracture above that can cause lifelong disability and death [2].

One of the factors that influence bone strength is of age. The increasing age of the human bone strength is also weakened. In the age range 20-30 years bone density has reached the maximum (peak bone mass) so that the risk of fracture is very low. Meanwhile, over the age of 30 years, bone density will decrease causing bones more brittle [3].The more dense the bones before the age, the less the possibility of osteoporosis [4].

Osteoporosis is a condition characterized by low bone mineral density and deterioration of bone tissue microstructure [5]. The damage is caused by several conditions among which the reduction in the mechanical stimulus (inactive) in the bone, reduced estrogen, side effects of some medications, smoking and so on. As a result of some of these conditions, the bone remodeling process becomes unbalanced.

Bone remodeling is a continuous process in which old bone matrix is destroyed by osteoclasts and always replaced by new bone matrix formation by osteoblasts. When the activity of osteoclasts is greater than the osteoblast cells can cause bone loss which gradually becomes osteoporosis [6].

Osteoporosis is a disease that is difficult to diagnose early, a new osteoporosis symptoms usually appear after the age of 50 years [2]. Osteoporosis can be diagnosed using a tool that has a high degree of accuracy, the tool is the Dual Energy X-ray Absorptiometry (DEXA). However, these tools can not explain the process of formation and destruction of bone. In addition, examination using DEXA quite expensive, so not many people who do a bone density examination.

Based Rouhi Gholamreza research shows that bone integrity is determined by mechanical stimuli. Bone density may decrease or increase depending on the size of the received mechanical load [7]. When someone does not do much physical activity, then there is a lot of stimulation received by osteoblasts. While osteoblasts will work to form bone when it gets enough stimulation. Mechanical stimuli such as walking can be used as an alternative to increase bone density, because it is easy to do, does not require expensive and without side effects.

Bone mass and change its construction follows an external mechanical environmental changes in order to adapt to the new mechanical environment. Nowadays, with the development of computing technology that rapidly, it is possible to quantitatively simulate the process of adaptation to the bone in order to predict and explain the formation and maintenance of bone architecture under the influence of different mechanical by combining algorithm bone remodeling quantitative element analysis [8]-[9]. Simulation modeling in computation can be used to diagnose osteoporosis without having to incur the cost is quite expensive.

The influence of mechanical stimuli on bone remodeling process has been studied by several scientists. As with previous studies, in 2006, using a model of RANK-RANKL-OPG (receptor for activation of nuclear factor-kappaB ligand Osteoprotegerin), V. Klika and F. Marsik lower the differential equation of bone remodeling. This study only describes the mechanical stimuli can activate osteoblasts to bone mineral formation is greater than resorption [10]. Then continued in 2010, V. Klika and F. Marsik researching bone remodeling thermodynamic models can only explain the process of osteoblast activity by modifying the previous [11].

Whereas previous research in 2012, Ahmad Idhammad & Abdelmounaim has done a simulation study of the femur bone remodeling due to mechanical stimuli. Modeling used in this study is the finite difference method in the one-dimensional bone structure of n-element model of the unit. Thus, the analysis of this study can not explain the effect of mechanical stimuli on bone density in the form of two-dimensional simulation [12].

Based on the above explanation, the authors conducted a study entitled "Simulation Mechanical Stimulus Effect on Bone Density Changes Due to Age-Based Finite Element Method (FEM)". This study aims to simulate the distribution of forces on bone and calculate bone density. Strain distribution equation was made with relation displacement, strain and stress as well as bone material properties (Young's modulus and Poisson's ratio) using the Finite Element Method (FEM) in a 2-dimensional bone structure. Furthermore, the strain rate as a result of mechanical stimulation will be calculated based on the equation of thermodynamics bone density of V. Klika and F. Marsik, using RungeKutta method of 4th orde.

2. Literature Review

2.1. Mechanical stimulation

Activity the physical human body can provide mechanical stimuli. In this case, due to the different physical activity will give different mechanical stimuli. According to the study Damien, et al. the differences of mechanical stimuli received by the bone by physical activity can be seen in Table 1 [13].

Table 1. Contact pelvis force measured in vivo [13].

Activity	Style (Body Weight)
Walking, slowly	1.6 - 4.1
Walking, normal	2.1 - 3.3
Walking, fast	1.8 - 4.3
Jogging, running	4.3 - 5.0
Climbing up the stairs	1.5 - 5.5
Down the stairs	1.6 - 5.1
Stand up	1.8 - 2.2
Sit	1.5 - 2.0
Knee bend	1.2 - 1.8

When someone does a physical activity, it will stimulate the activity of osteoblasts. Osteoblasts is produced by osteocytes buried deep within the lacunae and mineralized bone matrix.As a result of mechanical stimulation and detection of changes in levels of the hormone estrogen, osteocytes have the ability to detect changes in the interstitial fluid flow generated canaliculi, therefore osteocytes stimulation on the network can increase bone density [14].

2.2. Bone

The bones in the human body and other mammals are generally classified into two types, namely the cortical bone, also known as compact bone and trabecular bone is known as spongy bone or bone concellous. Both types are classified based on porosity and microstructure [15].

Cortical bone. Cortical bone is the largest part (80%) making up the human skeleton. In this case, cortical bone has a low porosity compared to trabecular bone porosity is 5-10%. This has led to the composition of tissue in cortical bone dense and hard. This bone has a high elastic modulus, so as to withstand the mechanical stresses such as bending and torsion loads are heavy[16]. Reduction of the mechanical properties of human cortical bone with age can be observed by Keaveny et al [17]. The result experiment Keaveny, modulus not reduced much if silent, while the power is reduced more, with a rate of about 2% per decade, and strain declined sharply with age, at a rate of about 10% per decade from a young age [17].

According Keaveny et al., (2004), in cortical bone microstructure is anisotropic, elastic and strong. Based on some experiments have been conducted, cortical bone has a Young's modulus of 17.9 MPa with a Poisson's ratio of 0.4. And the elastic properties of cortical bone strength will change with age. In infancy, the bones in humans will grow dense and growing longer to reach maximum density at the age of 30 years. After age 30, bone density will decrease this may even lead to a decrease in height [17].

2.2.1. Trabecular Bone. Trabecular bone has a smaller elasticity and it shows that the mineral content is lower than cortical bone. In addition, experienced trabecular bone resorption process is faster than the cortical bone [18]. Trabecular bone mechanical strength of about 1.5 to 3.8 MPa, whereas cortical bone has mechanical strength of about 200 MPa. Mechanical power difference is caused by differences in bone density [19].

Trabecular bone compressive strain produces approximately 1%. Area larger strain due to compression rather than tension. Maximum strain due to the linear compression range 1 to 2.5%. Elasticity and strength of the trabecular bone declines with age, ie over 10% per decade. Young elastic modulus of trabecular bone ranged from 0.1 to 30 MPa, whereas the Poisson ratio of between 0.03 to 0.6[17].

2.3. Finite Element Methods(FEM)

Finite element methods (FEM) is a numerical technique to solve the problems described by partial differential equations or can be formulated as a functional minimization[20]. Finite element method

(FEM) requires domain division problem into many subdomains, and each subdomain called finite elements. Therefore, the problem domain is composed of many pieces of the finite element[21]. Pieces of these elements have a variety of forms, some form of two-dimensional elements are described as follows:

2.3.1. Element Triangle. Bone considered isotropic material means to have the same behavior if given the treatment of a variety of directions. Using the relationship of stress and strain obtained constitutive equation,$\{\sigma\} = [D]\{\varepsilon\}$where for the triangular element shows stress and is a stretch. The matrix material properties become$\{\sigma\} = \{\sigma_x \sigma_y \tau_{xy}\}^T \{\varepsilon\} = \{\varepsilon_x \varepsilon_y \varepsilon_{xy}\}^T [D][21]$ [21]:

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

Finite element formulation for the elasticity of the material, given by the method of Weighted Residual method for material elasticity equations obtained the following equation [21]:

$$\int_{\Omega} \begin{Bmatrix} \frac{\partial \omega_1}{\partial x} & 0 & \frac{\partial \omega_1}{\partial y} \\ 0 & \frac{\partial \omega_2}{\partial y} & \frac{\partial \omega_2}{\partial x} \end{Bmatrix} [D] \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} d\Omega = \int_{\Omega} \begin{Bmatrix} \omega_1 f_x \\ \omega_2 f_y \end{Bmatrix} d\Omega + \int_{r_n} \begin{Bmatrix} \omega_1 \bar{\Phi}_x \\ \omega_2 \bar{\Phi}_y \end{Bmatrix} dr \tag{2}$$

The result of this weighted function provides the finite element domain integral form.

$$\int_{\Omega^*} [B]^T [D][B] d\Omega \{d\} \tag{3}$$

WhereΩ^* indicates the domain elements. Thus, the stiffness matrix elements for elasticity can be formed as follows:

$$[K^e] = \int_{\Omega^*} [B]^T [D][B] d\Omega \tag{4}$$

So we get the finite element equation for the elasticity of the material is as follows.

$$[K^e]\{d^e\} = \{f^e\} \tag{5}$$

2.3.2. The rectangular elements. Characteristics rectangular element represented by the node i, j, k and m as shown in Figure 1. Element rectangle bounded by four vertices where ij side, and km parallel to the y-axis then jk and noodle side parallel to the x axis. Parameter Φ expressed displacement component in the direction of the x or y. So that the rectangular element shape functions can be expressed in the form of a global coordinate system (x, y) [22].

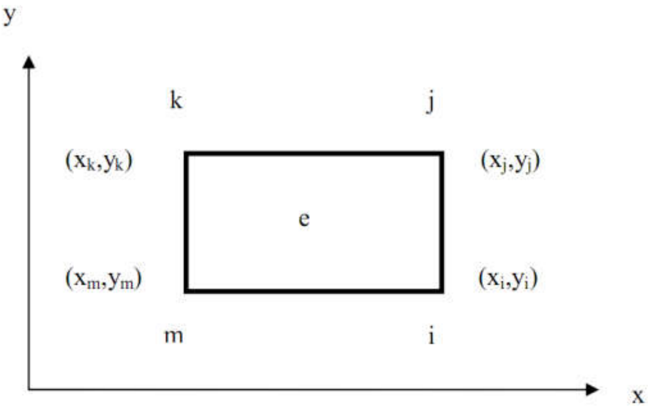


Figure 1. Rectangular elements in global coordinates [22].

Shape functions for elements of the rectangle can be derived from the following interpolation equation [21]:

$$u = a_1 + a_2x + a_3y + a_4xy \tag{6}$$

Using the stress and strain relationship equation obtained konstitutiv $\{\sigma\} = [D]\{\varepsilon\}$. Where to rectangular elements indicate stress and is a stretch. So that the matrix material properties become$\{\sigma\} = \{1\ \sigma_x\sigma_y\tau_{xy}\}^T\{\varepsilon\} = \{1\ \varepsilon_x\varepsilon_y\varepsilon_{xy}\}^T[D]$ [21][21]:

$$[D] = \frac{E}{(1+v)(1-2v)}\begin{bmatrix} 1-v & v & v & 0 \\ v & 1-v & v & 0 \\ v & v & 1-v & 0 \\ 0 & 0 & 0 & \frac{1-2v}{2} \end{bmatrix} \tag{7}$$

2.4. Bone remodeling

Bone remodeling outline occurs in two steps: osteoclasts attach to bone surfaces, dissolving minerals, and then the organic phase of bone, opening a hole that was filled by a number of osteoblasts, which produce collagen matrix and secrete proteins that stimulate the deposition of calcium phosphate[23]. The whole cycle takes 4 to 8 months but can last at least 3 months or even 2 years. Rapid resorption process only takes 4-6 weeks, while the process of new bone formation was slow take up to 2 months for each remodeling cycle [24].

Osteoclasts and osteoblasts are closely collaborating in the process of bone remodeling and called Basic multicellular unit (BMU). BMU cortical bone in the form a cylinder about 2000 μm channel length and 150-200 μm wide. Gradually the hole formed in the bone at a speed of 20-40 μm / day. After arriving at the end, on the order of ten osteoclasts dig a circular tunnel (cones) in the direction of loading dominant. Then followed by several thousand osteoblasts fill the tunnel (closing cone) to produce (secondary) new bone osteon [25]. In this process, approximately 2-5% of the cortical bone renovated every year [26].

Trabecular bone remodeling process in the majority in the surface layers. Due to a much larger surface to volume ratio, the more active renovated from cortical bone, with a level of remodeling that can be up to 10 times higher. Osteoclasts travel throughout the trabecular surface at a speed of about 25 μm / day, dig ditches instead of tunnels, with a depth of 40-60 lm. As in cortical bone they are followed by osteoblastic bone formation. Active remodeling sites include areas of various sizes from as small as 50 × 20 μm up to 1000 × 1000 μm[25].

In 2010, V. Klika and F. Marsik researching bone remodeling thermodynamic models to explain the process of osteoblast activity by modifying the previous research (Table 2). Here is the equation of kinematics of cell mononucleoid, old bone, osteoblasts, osteosyte, and new bone[11].

$$\frac{dn_{MCELL}}{d\tau} = -\delta_1(\beta_1 + n_{MCELL})n_{MCELL} + J_3 + J_{New\_B} - D_1$$
$$\frac{dn_{Old\_B}}{d\tau} = -(\beta_3 - n_{MCELL} + n_{Old\_B})n_{Old\_B} - D_2 + J_{New\_B}$$
$$\frac{dn_{OB}}{d\tau} = \delta_3\left(\beta_6 - n_{Old_B} - (n_{OB} + n_{Osteoid} + n_{New_B})\right)\left(\beta_8 - (n_{OB} + n_{Osteoid} + n_{New\_B})\right)\dots$$
$$- \delta_4(\beta_{11} - (n_{Osteoid} + n_{New\_B})n_{OB}) + D_3 - D_4$$
$$\frac{dn_{Osteoid}}{d\tau} = \delta_4\left(\beta_{11} - (n_{Osteoid} + n_{New\_B})\right)n_{OB} - \delta_5(\beta_{14} - n_{New\_B})n_{Osteoid} + D_4 - D_5$$
$$\frac{dn_{New\_B}}{d\tau} = \delta_5(\beta_{14} - n_{New\_B})n_{Osteoid} - J_{New\_B} + D_5 \quad (8)$$

Table 2. Mathematical equations thermodynamic parameters of bone remodeling**.**

Parameter	Unit	Information
$\boldsymbol{n_{MCELL}}$	[1]	Changes in cell concentration mononucleoid
$\boldsymbol{n_{Old\_B}}$	[1]	Changes in the concentration of old bone
$\boldsymbol{n_{OB}}$	[1]	Changes in the concentration of osteoblast
$\boldsymbol{n_{Osteoid}}$	[1]	Changes in the concentration of osteoid
$\boldsymbol{n_{New\_B}}$	[1]	Changes in the concentration of new bone
$\boldsymbol{\beta_i}$	[1]	Total normalization of the starting substance
$\boldsymbol{\delta_\rho}$	[1]	The ratio of the rate constant to-reaction to the reaction rate constant of the secondρ
$\boldsymbol{D_\rho}$	[1]	Dynamic stimulus influence on the rate of chemical to-equationρ
$\boldsymbol{J_i}$	[1]	Flux to-substance$i$

The parameters used in this study is based on the calculation of V. Klika and F. Marsik shown in Table 3. The ratio of the reaction rate constant of all of the rate constant of the reaction shown by equation (9), whereas the effect of dynamic stimuli at a rate of to the chemical equation shown by equation (10) [11]. Bone density used for the calculation of equation (11).

$$\delta_\alpha = \frac{k_{+\alpha}}{k_{+2}} \quad (9)$$

$$D_\alpha = \frac{l_{\alpha v} d_{(1)}}{k_{+2}[Bo]^2} \quad (10)$$

$$\rho(I) = \rho_0\left(N_{Old_B}(I) + N_{New_B}(I)\right) \quad (11)$$

Table 3. The constant value of the mathematical equations of bone remodeling.

Constants	Score	Unit	Constants	Score	Unit
$[\boldsymbol{Old\_B_0}]$	input	mol/l	δ_1	4	1
$[\boldsymbol{B_0}]$	$22\ 10^{10}/N_A$	mol/l	δ_3	2	1
$[\boldsymbol{New\_B_0}]$	Input	mol/l	δ_4	1/7	1
$[\boldsymbol{Osteosid_0}]$	0	mol/l	l_{1v}	$-1.22\ 10^{-14}$	mol/l
$[\boldsymbol{OB_0}]$	$1.1\ 10^{10}/N_A$	mol/l	l_{3v}	$-3.49\ 10^{-17}$	mol/l
$\boldsymbol{\beta_6}$	1:05	1	l_{2v}	$3.09\ 10^{-19}$	mol/l
$\boldsymbol{\beta_3}$	1/2000	1	l_{4v}	$-1.39\ 10^{-17}$	mol/l
$\boldsymbol{\beta_1}$	0.6	1	l_{5v}	$-5.44\ 10^{-19}$	mol/l
$\boldsymbol{\beta_{11}}$	1	1	k_{+2}	$6\ 10^7$	$l/mol.s$
$\boldsymbol{\beta_{14}}$	1/20	1	J_{Old_B}	$2.6\ 10^{-4}$	1
$\boldsymbol{\beta_8}$	1/10	1	J_{New_B}	$2.6\ 10^{-4}$	1
			J_3	$0.416\ 10^{-4}$	1

2.5. Runge Kutta Order-4

Runge-Kutta methods is the method a step that provides greater accuracy of results and does not require derivative of the function. Runge-Kutta methods are often used in the completion Orde4 differential equation because it can resolve complex mathematical problems more efficiently. In addition, the Runge-Kutta method orde4 have a level of error that is smaller than the Runge-Kutta method of order underneath. In general, the equation in order RungeKutta order-4 is[27]:

$$k_1 = hf\ (t_i, \omega_i) \tag{12}$$

$$k_2 = hf\ (t_i + \frac{h}{2}, \omega_i + \frac{1}{2}k_1) \tag{13}$$

$$k_3 = hf\left(t_i + \frac{h}{2}, \omega_i + \frac{1}{2}k_2\right) \tag{14}$$

$$k_4 = hf\ (t_{i+1}, \omega_i + k_3) \tag{15}$$

3. Methods

Simulation modeling study was conducted on May 7th, 2019 until September 30th, 2019. This study was held at Computing Laboratory of Physics Department of Islamic State University of Maulana Malik Ibrahim Malang. This research was conducted by the following steps:

3.1. Make Femur Geometry Construction

Construction of femur bone geometry is created in MATLAB software. Bone geometry consists of 1337 elements for rectangular element with size of each element has width and height $0.7.10^{-2}$ x $1.43.10^{-3}$. Then bone geometry for triangular element consists of 1580 elements which has width of each element is 1.10^{-2} and height 2.10^{-3}. Femur bone construction is made of two layers where the inner layer have the shape of trabecular bone while the outer layer have the shape of cortical bone.

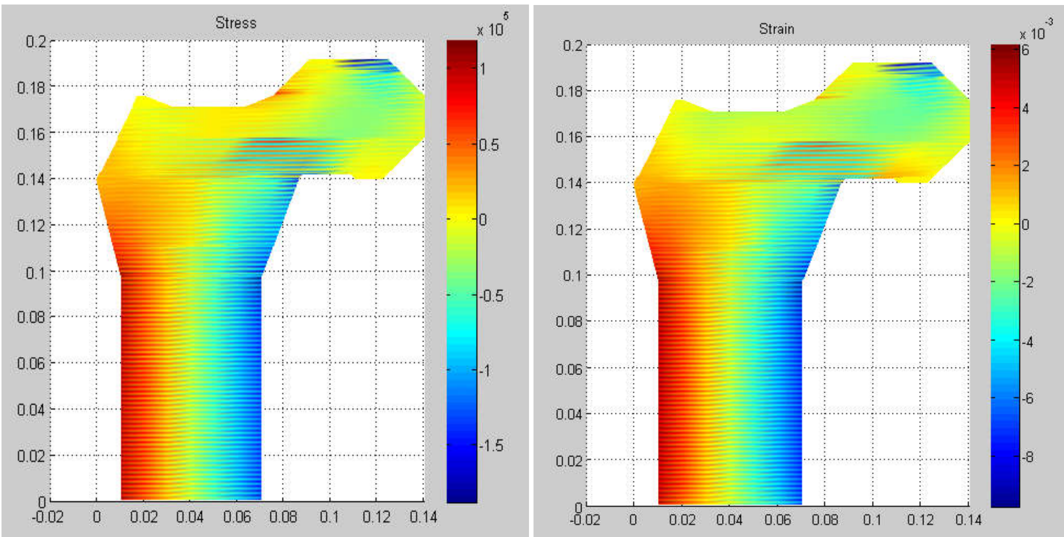
3.2. Input properties of bone

Femur construction is treated bone age that is 25 years old and 51 years old. For 25 years old, cortical bone has Young's modulus of 17.9 MPa with Poisson ratio of 0.4, while the trabecular bone has Young's modulus of 13 MPa with Poisson's ratio of 0.5. Then for 51 years old, cortical bone has Young's modulus of 16.9692 MPa with Poisson ratio 0.53, while the trabecular bone has Young's modulus of 9.62 MPa with a Poisson's ratio is 0.63.

3.3. Simulation Distribution of stress, strain and strain rate
The pressure simulation is done by providing a compressive force on the femur. Boundary conditions for this simulation is to provide a zero limit at the end of the stem lower part of bone construction. The force applied in accordance with weight and standing activity in the amount of 1 290 N (25 years old) and 1200 N (51 years) as well as activity goes in the amount of 1741.5 N (25 years old) and 1620 N (51 years old). Then the force is applied at the point of 2984 and 2986 for rectangle element, then at te point of 1812 for three elements located at the top of the bone construction. Equation (5) is used to calculate the stress, strain and static strain rate on bone tissue. The simulation was performed using finite element method with MATLAB software 2008.

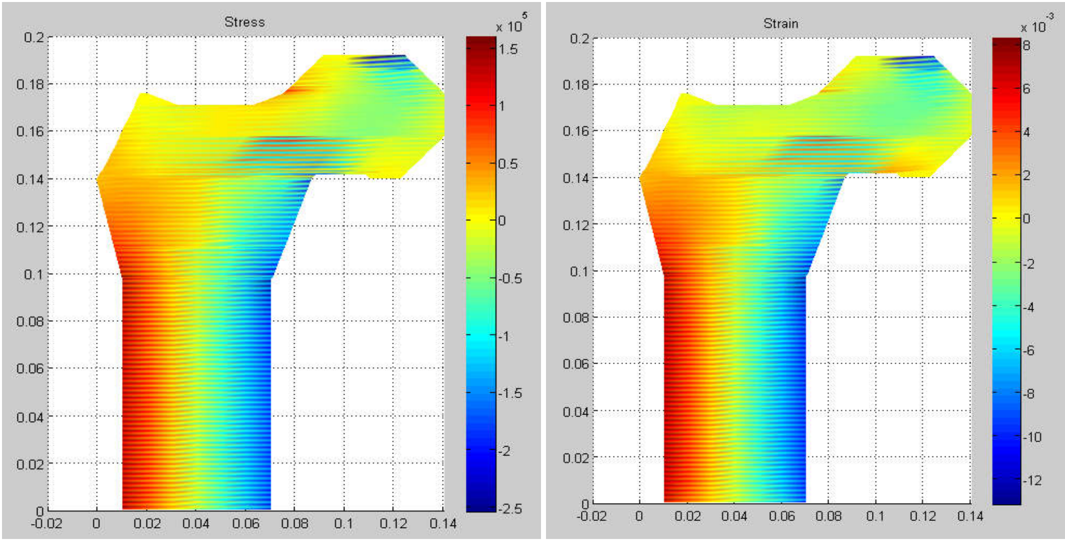
3.4. The calculation of Bone Density
The calculation of bone density to mechanical stimuli due to differences in bone age is based on the Equation (7) by the Runge-Kutta method orde4 using MATLAB software 2008. Strain rate variableis obtained from simulation phase of deployment stress and strain used to calculate bone density. Bone density calculations is done at some point that are femur neck including trabecular bone and right rod and left rod including cortical bone. After that, the calculation results are matched with the data results of the Bone Mineral Density (BMD) of the patients who had weight loss of 64.5 kg for ages 25 years and 60 kg to ages 51 years.

4. Results and Discussion
Distribution of stress and strain in this study were obtained based on different mechanical stimuli and age using a different form element. The simulation results of stress and strain on the elements of the triangle as shown in Figure 2 and 3.



(a) (b)

Figure 2. (a) Stress distribution and (b) Strain distribution to the age of 25 years standing activity.



(a) (b)

Figure 3. (a) Stress distribution and (b) Strain distribution to age of 25 years with walking activity.

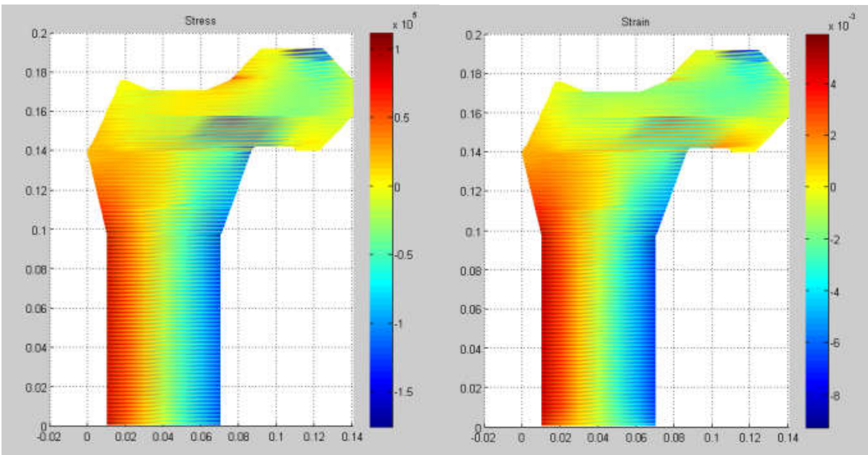
Mechanical stimuli in the form of force of 1290 N at the age of 25 years is an activity-based mechanical load stands, where twice the weight of patients in this study amounted to 64.5 kg and multiplied by the force of gravity. While walking activity, 2.7 times the weight. Once the force is applied on the y-axis direction on the bone as mechanical stimuli will be formed strain and stress. Where stress and strain is positive for stretching (as drawn) in the image shown in red and negative for compression (like a button) on the image shown in blue. Data distribution of stress and strain at the age of 25 years is shown in Table 4.

Table 4. Stress changes, strain and strain rate on the mechanical stimulation Due to age 25 years.

Observation point	Standing (1290 N)			Walking (1741.5 N)		
	Stress (MPa)	Strain	Rate strain (/ sec)	Stress (MPa)	Strain	Rate strain (/ sec)
Trunk Left	1.1313e + 005	0.0061	0.1924	1.5273e + 005	0.0083	0.4156
Right Trunk	-1.4800e + 005	-0.0081	0.2538	-1.9980e + 005	-0.0109	0.5483
femoral neck	-1.0587e + 005	-0.0045	0.1403	-1.4293e + 005	-0.0060	0.3030
head of the femur	2.5804e + 004	4.9057e-004	0.0154	3.4835e + 004	6.6228e-004	0.0333

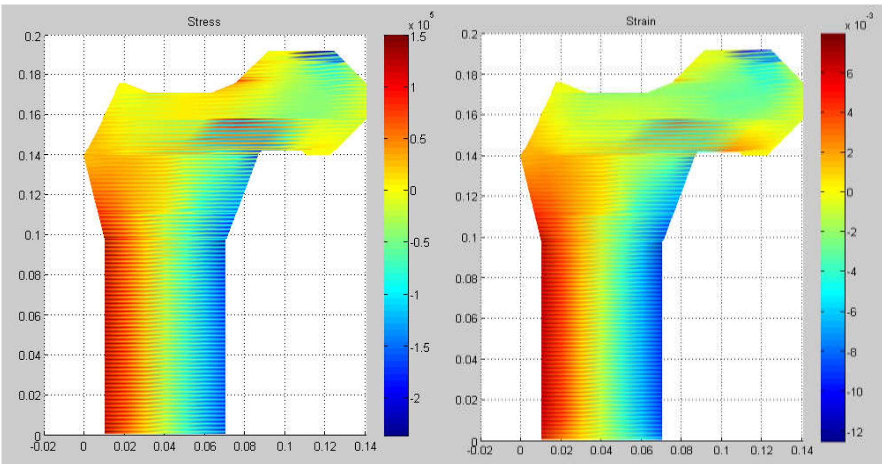
Rated stress and large strain is directly proportional to the force applied. Bone by a larger force has a value high enough stress and strain. Stress and strain on the right side of the rod has a value greater than the left side of the trunk. That's because the bones in the right part undergo stem compression due to bending of the bones on the right side so that the force is more pressing on the right side of the bone. While the bone on the left side of the rod to stretch as it gets a bit of pressure. Values obtained from a strain strain rate, multiplied by the frequency of bone cells to the different activities, when dynamic 8 Hz and to static 5 Hz. So the value of the strain rate is proportional to great strain, and the greater the activity of walking.

In addition influenced by the mechanical stimuli, stress and strain on the bones is also influenced by age. When compared with the value of stress and strain in older age, then its value will decrease, as shown in Table 5 with the simulation results as in Figure 4 and 5.



(a) (b)

Figure 4. (a) The distribution stress and (b) the distribution of strain at the age of 51 years for activities stand.



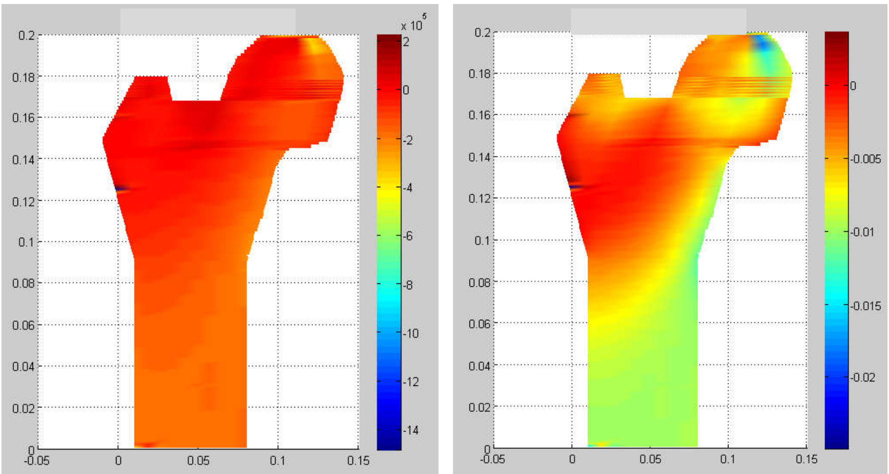
(a) (b)

Figure 5. (a) The distribution stress and (b) the distribution of strain at the age of 51 years for walking activities.

Distribution of stress, strain and strain rate at the age of 51 years look smaller than when the age of 25 years. The nature of the bone elasticity decreases with age, because the bone remodeling process that is not balanced due to estrogen continues to decline. The stress will decrease when the modulus of elasticity of bone also declined, but not so for the rectangular element. The simulation results of stress and strain by using a rectangular form element to the age of 25 years is shown in Figure 6 and 7. Result of distribution of stress and strain for age of 51 years is shown in Figure 8 for standing activities and Figure 9 for walking activities.

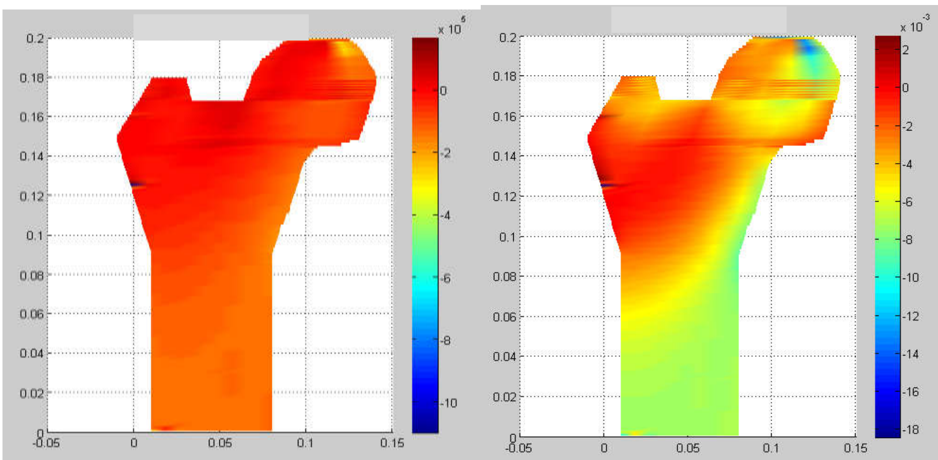
Table 5. Changes in stress, strain and strain rate due to mechanical stimuli at the age of 51 years.

Observation point	Standing (1200 N)			Walking (1620 N)		
	Stress (MPa)	**Strain**	**Rate strain (/ sec)**	**Stress (MPa)**	**Strain**	**Rate strain (/ sec)**
Trunk Left	1.0656e + 005	0.0059	0.1851	1.4385e + 005	0.0080	0.3999
Right Trunk	-1.3888e + 005	-0.0078	0.2454	-1.8749e + 005	-0.0105	0.5302
femoral neck	-1.0201e + 005	-0.0038	0.1209	-1.3771e + 005	-0.0052	0.2612
head of the femur	2.3464e + 004	1.3119 e-004	0.0041	3.1676e + 004	1.7711 e-004	0.0089



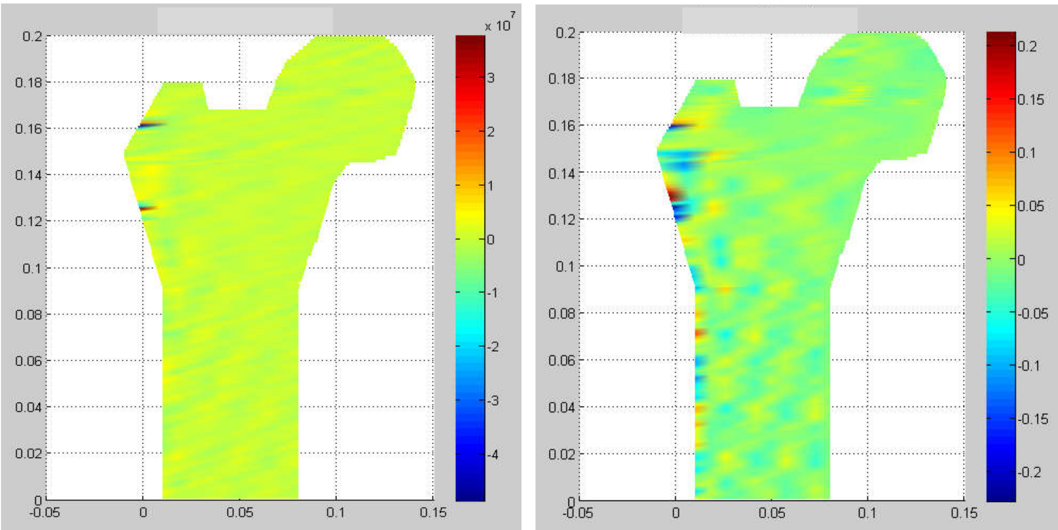
(a) (b)

Figure 6. (a) The distribution stress and (b) the distribution of strain at the age of 25 years for walking activities.



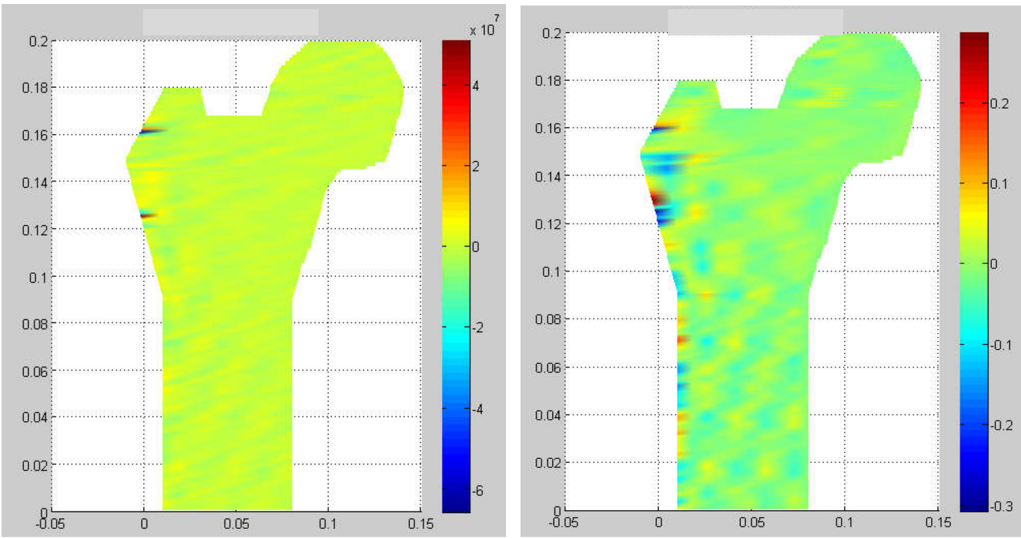
(a) (b)

Figure 7. (a) The distribution stress and (b) the distribution of strain at the age of 25 years for activities stand.



(a) (a)

Figure 8. (a) The distribution stress and (b) the distribution of strain at the age of 51 years for activities stand.



(a) (b)

Figure 9. (a) The distribution stress and (b) the distribution of strain at the age of 51 years for walking activities.

Based on the image simulation results of stress and strain on the rectangular elements, has not been able to show the relationship between styles with stress and strain. Value of stress and strain does not display the compression and stretching as the triangular elements. Data stress, strain and strain rate for rectangular elements shown in Table 6 and 7.

Table 6. Changes in stress, strain and strain rate due to mechanical stimuli at the age of 25 years.

Observation point	Standing (1290 N)			Walking (1741.5 N)		
	Stress (MPa)	**Strain**	**Rate strain (/ sec)**	**Stress (MPa)**	**Strain**	**Rate strain (/ sec)**
Trunk Left	-1.1980e + 005	-0.0054	0.1692	-1.6173e + 005	-0.0073	0.3655
Right Trunk	-1.3942e + 005	-0.0074	0.2340	-1.8821e + 005	-0.0101	0.5055
femoral neck	-1.3826e + 005	-0.0039	0.1230	-1.8665e + 005	-0.0053	0.2657
head of the femur	-2.3413e + 004	-0.0022	0.0678	-3.1607e + 004	-0.0029	0.1464

Table 7. Changes in stress, strain and strain rate due to mechanical stimuli at the age of 51 years.

Observation point	Standing (1200 N)			Walking (1620 N)		
	Stress (MPa)	**Strain**	**Rate strain (/sec)**	**Stress (MPa)**	**Strain**	**Rate strain (/sec)**
Trunk Left	3.1850e + 006	-0.1017	3.1964	4.2997e + 006	-0.1374	6.9043
Right Trunk	6.6017e + 005	-0.0082	0.2581	8.9123e + 005	-0.0111	0.5575
femoral neck	-1.6284e + 005	-0.0015	0.0481	-2.1984e + 005	-0.0021	0.1039
head of the femur	1.3848e + 006	-0.0064	0.2000	1.8695e + 006	-0.0086	0.4319

Rated stress, strain and strain rate generated did not show any influence of age on the deterioration in the value of the three. Even from these data show the opposite, that with age the stress, strain and strain rate increases. It contradicts existing theories, according to Tandra (2009) when old age bone density decreases, a low density have a low stress and strain as well. Construction with rectangular-shaped element can not interpret the distribution of stress and strain because its structure is too dense, so that the surface area is too large. As the stress equation which states that the smaller the surface area, the greater the stress spread [3].

Rated stress, strain and strain rate can predict bone density. So far for the triangular element in accordance with the existing theory, so the strain rate results obtained using triangular elements can be used to calculate bone density. The result of the calculation of bone density as shown in Table 8 below.

Bone density at age 51 years lower than in bone density at the age of 25 years. In old age, the bones have a high porosity on the inside, but the cortical bone part, still has a density of about 1.9 g/cm^2 in general for normal bone. This leads to reduced bone in terms of strength as it becomes thinner and the density decreases. Bone density in the right hand is the cortical bone when the age of 25 years for walking activities amounted to 1.8186 g/cm^2. Then at the femoral neck bone density of 1.0698 g/cm^2. It shows that the bone under normal circumstances.

Bone density in the femoral head is smaller than the femoral stem that is equal to 0.6657 g/cm^2. The femoral head has a layer of very thin cortical bone and most of its constituent is trabecular bone. Mechanical stimuli received by the femur can be optimized in this section. Because the pressure is inversely proportional to the area, which when given the force on the upper end of the femur would happen propagation force to the lower end of the bone. The smaller the surface area at the head of the femur, the greater the pressure to be distributed.

Table 8. Bone Density Calculation Results Age 25 and 51 Years.

Mechanical stimulation	Observation point	Bone Concentration (g / cm2)	Experiment (g / cm2)	The accuracy (%)
Stand 1290 N (25 years old)	Trunk Left	0.8723	-	-
	Right Trunk	0.9750	-	-
	femoral neck	0.7963	1.18	67%
	head of the femur	0.6466	-	-
Walk 1741.5 N (25 years old)	Trunk Left	1.3425	-	-
	Right Trunk	1.8186	-	-
	femoral neck	1.0698	1.18	91%
	head of the femur	0.6657	-	-
Stand 1200 N (51 years old)	Trunk Left	0.8611	0.926	93%
	Right Trunk	0.9600	0.926	96%
	femoral neck	0.7703	0.615	94%
	head of the femur	0.6349	-	-
1620 Walk N (51 years old)	Trunk Left	1.2988	0.926	60%
	Right Trunk	1.7397	0.926	12%
	femoral neck	0.9885	0.615	64%
	head of the femur	0.6399	-	-

Bone by a larger force had greater bone density as well. It was due to the mechanical stimulation that will create a disturbance in the osteocytes that can activate osteoblasts to form bone. Greater stimulus will increase the activity of osteoblasts to bone formation will also increase. The process of increasing bone formation can increase bone density.

Bone density obtained from these simulation results have a high enough accuracy when compared with existing experimental data. BMD is an advanced data comparison is the data of patients aged 25 and 51 years. For data of patients aged 25 years, according to the simulation results for the activity of walking. While the data of patients aged 51 years according to the simulation results for the activity stands.

5. Conclusion

Based on this study, the distribution of greatest stress and strain contained in the bone that gets the greatest mechanical load and when the age of 25 years. Bone density when age 25 is greater than bone density at age 51 years, It shows that age becomes one of the factors that affect bone density. In addition, a large mechanical load received by the bones are also factors that affect bone density. Bones receive greater mechanical load had greater bone density. Data from the research and data BMD have a fairly high degree of accuracy. The simulation results showed that the age of 25 years have bones that are still in the normal state. While the age of 51 years have a bone in abnormal conditions or begin to show symptoms of osteoporosis.Based on simulation results, we can conclude that mechanical stimuli can improve bone density that can slow down the loss of bone mineral. And bone density will decrease with age. In this case, the elements of the triangle represents a better result than the quadrilateral element.

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References

[1] Taichman RS 2005 *Blood* **105** 2631-2639
[2] Kemenkes RI 2015*Pusat Data dan Informasi Kementrian Kesehatan RI: Data & Kondisi Penyakit Osteoporosis di Indonesia* (Jakarta Selatan: Kementrian Kesehatan RI)
[3] Tandra Hans 2009 *Osteoporosis: Mengenal, Mengatasi dan Mencegah Tulang Keropos* (Jakarta: PT Gramedia Pustaka Utama)
[4] Corwin and Elizabeth 2009 *Buku Saku Patofisiologi* (Jakarta: EGC)
[5] Seeman E and Delmas PD 2006 *The New England Journal of Medicine* **354**(21) 2250-2261
[6] Usha, Kini and NandeeshB N 2012*Physiology of Bone Formation, Remodeling and Metabolism* (India: Springer–Verlag Berlin Heidelberg)
[7] Rouhi, Gholamreza 2014 Biomechanics of Osteoporosis: The Importance of Bone Resorption and Remodeling Processes*Osteoporosis* 60-72
[8] Huiskes R, Ruimerman R, Van Lenthe G H and Janssen J D 2000 *Nature* **405** 704–706
[9] Ruimerman, Ronald., Van Rietbergen B, Hilbers P, Huiskes R 2003 *Biotheology* **40** 315–320
[10] Klika V and Marsik F 2006 *Mathematical and numerical analysis of differential equations of bone remodelling* (Praha: Czech technical university Faculty of nuclear science and physical Engineering Department of mathematics)
[11] Klika V and Marsik F 2010 *J Muscul Neur Inter.* **10**(3) 220-230
[12] Idhammad A, Abdali A, Alaa N 2013 Computational simulation of the bone Remodeling using the finite element method: an elastic-damage theory for small displacements *Theor Biol Med Model* 10:32
[13] Damien PB, Kevin M and Joseph FB 2010 *Op. Sport Med J.* **4** 51-57
[14] Manolagas SC 2000 *Endocrine Reviews* **21**(2) 115-37
[15] Martin R B and Burr D B 1989 *Structure Function and Adaptation of Compact Bone* (New York: Raven Press)
[16] Ott, Susan M 2012 *American Journal of Nephrology* **47** 373-375
[17] Keaveny, TM, Morgan EF, Oscar C 2004 *Bone mechanic* (California: McGraw-Hill)
[18] Guo X E and Goldstein S A 1997 *Forma* **12** 3-4
[19] Guo X E 2001 *Bone Mechanics* **10**1-10
[20] Nikishkov G P 2004 *Introduction in the Finite Element Method* (Japan: University of Aizu)
[21] Kwon, Young W and Hyochoong Bang 1996 *The Finite Element Method Using Matlab* (New York: CRC Press)
[22] Susmikanti, Mike and Utaja 2005 *Risalah Lokakarya Komputasi dalam Sains dan Teknologi Nuklir XVI* 169-187
[23] Teitelbaum S L and Ross F P 2003*Nature Reviews Genetics* **4**(8) 638–649
[24] Noviyana, Muji 2011 *Asupan Zat Gizi, Aktivitas Fisik dan Kepadatan Tulang Penari* (Semarang: Universitas Diponegoro)
[25] Ruimerman, Ronald 2005 *Modeling and remodeling in bone tissue* (Eindhoven: Technische Universiteit Eindhoven)
[26] Lee C Aand T A Einhorn 2001 *Osteoporosis* 3-20
[27] Triatmodjo B 2002 *Metode Numerik Dilengkapi dengan Program Komputer* (Yogyakarta: Beta Offset)

Appendix 1
Static bone elasticity equation

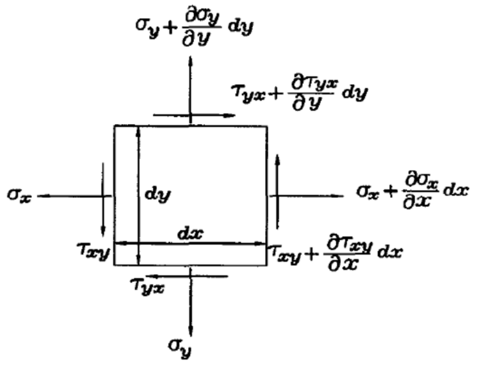

Figure A1. field in two dimensions.

Based on the pictures in addition, the amount of force in the horizontal and vertical directions given by the following equation.

$$\sum F_x = \left(\sigma_x + \frac{\partial \sigma_x}{\partial x} dx\right) dy - \sigma_x dy + \left(\tau_{xy} + \frac{\tau_{xy}}{\partial y} dy\right) dx - \tau_{xy} dx + f_x dxdy = 0$$

$$\sum F_y = \left(\sigma_y + \frac{\partial \sigma_y}{\partial y} dy\right) dx - \sigma_y dx + \left(\tau_{xy} + \frac{\tau_{xy}}{\partial x} dx\right) dy - \tau_{xy} dy + f_y dxdy = 0$$

Where and are the force on the object per unit area (or per unit volume is assumed to be small unit that is perpendicular to the field) in the x direction and yyang assumed to be positive when given along the positive axis. All the stresss in Figure A1 indicates a positive value. In a simple form of a simple equation is given as follows.$f_x f_y$

$$\frac{\partial \sigma_x}{\partial x} + \frac{\tau_{xy}}{\partial y} + f_x = 0$$
$$\frac{\partial \sigma_y}{\partial y} + \frac{\tau_{xy}}{\partial x} + f_y = 0$$

Next is to determine the constitutive equations. This equation linking between stress and strain. For isotropic materials, konstitutiv equation becomes:

$$\{\sigma\} = [D]\{\varepsilon\}$$

Where the form of stress and is a stretch. The matrix material properties and is a kinetic equation.$\{\sigma\} = \{\sigma_x \sigma_y \tau_{xy}\}^T \{\varepsilon\} = \{\varepsilon_x \varepsilon_y \varepsilon_{xy}\}^T [D]\{\varepsilon\}$

$$[D] = \frac{E}{1 - v^2} \begin{bmatrix} 1 & v & 0 \\ v & 1 & 0 \\ 0 & 0 & \frac{1 - v}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix}$$

Then to the rectangular elements are:

$$[D] = \frac{E}{(1 + v)(1 - 2v)} \begin{bmatrix} 1 - v & v & v & 0 \\ v & 1 - v & v & 0 \\ v & v & 1 - v & 0 \\ 0 & 0 & 0 & \frac{1 - 2v}{2} \end{bmatrix}$$

Equilibrium, konstitutiv equations and kinetic equations obtained eight (three stress, three strain, and two displacement) for eight equations (two equilibrium, three konstitutiv, and three kinetic).

The boundary conditions there are two kinds of essential (geometry) or natural (appeal). Conditions indicated by the displacement geometry and boundary conditions are reflected in the appeal indicated by the following equation.

$$\Phi_x = \sigma_x n_x + \tau_{xy} n_y = \overline{\Phi}_x$$
$$\Phi_y = \sigma_y n_y + \tau_{xy} n_x = \overline{\Phi}_y$$

Where is the direction cosine out the unit normal vector at the boundary; and provide value appeal.$n_x n_y \overline{\Phi}$

Based on the development of finite element formulation for elasticity problem, given the Galerkin method. Energy method is used to get the finite element formulation in the subsequent discussion. Application of Weighted Residual method for material elasticity equation is:

$$\int_{\Omega} \begin{Bmatrix} \omega_1 \left(\dfrac{\partial \sigma_x}{\partial x} + \dfrac{\partial \tau_{xy}}{\partial y} \right) \\ \omega_2 \left(\dfrac{\partial \sigma_y}{\partial y} + \dfrac{\partial \tau_{xy}}{\partial x} \right) \end{Bmatrix} d\Omega + \int_{\Omega} \begin{Bmatrix} \omega_1 f_x \\ \omega_2 f_y \end{Bmatrix} d\Omega - \int_{r_x} \begin{Bmatrix} \omega_1 \Phi_x \\ \omega_2 \Phi_y \end{Bmatrix} dr = 0$$

Where the boundary conditions are essential and integral berat.Diberikan function with an integral part of the equation in the first$r_e \omega_i (i = 1,2)$

$$-\int_{\Omega} \begin{Bmatrix} \dfrac{\partial \omega_1}{\partial x} \sigma_x + \dfrac{\partial \omega_1}{\partial y} \tau_{xy} \\ \dfrac{\partial \omega_2}{\partial y} \sigma_y + \dfrac{\partial \omega_2}{\partial x} \tau_{xy} \end{Bmatrix} d\Omega + \int_{\Omega} \begin{Bmatrix} \omega_1 f_x \\ \omega_2 f_y \end{Bmatrix} d\Omega + \int_{r_n} \begin{Bmatrix} \omega_1 \overline{\Phi}_x \\ \omega_2 \overline{\Phi}_y \end{Bmatrix} dr = 0$$

Where the limits to natural are conditions and can be rewritten into:r_n

$$\int_{\Omega} \begin{Bmatrix} \dfrac{\partial \omega_1}{\partial x} & 0 & \dfrac{\partial \omega_1}{\partial y} \\ 0 & \dfrac{\partial \omega_2}{\partial y} & \dfrac{\partial \omega_2}{\partial x} \end{Bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} d\Omega = \int_{\Omega} \begin{Bmatrix} \omega_1 f_x \\ \omega_2 f_y \end{Bmatrix} d\Omega + \int_{r_n} \begin{Bmatrix} \omega_1 \overline{\Phi}_x \\ \omega_2 \overline{\Phi}_y \end{Bmatrix} dr$$

Subtitute constitutive equations to produce:

$$\int_{\Omega} \begin{Bmatrix} \dfrac{\partial \omega_1}{\partial x} & 0 & \dfrac{\partial \omega_1}{\partial y} \\ 0 & \dfrac{\partial \omega_2}{\partial y} & \dfrac{\partial \omega_2}{\partial x} \end{Bmatrix} [D] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} d\Omega = \int_{\Omega} \begin{Bmatrix} \omega_1 f_x \\ \omega_2 f_y \end{Bmatrix} d\Omega + \int_{r_n} \begin{Bmatrix} \omega_1 \overline{\Phi}_x \\ \omega_2 \overline{\Phi}_y \end{Bmatrix} dr$$

With subtitute kinetic equation is obtained:

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

Discretization domain using linear triangular elements as in the following image

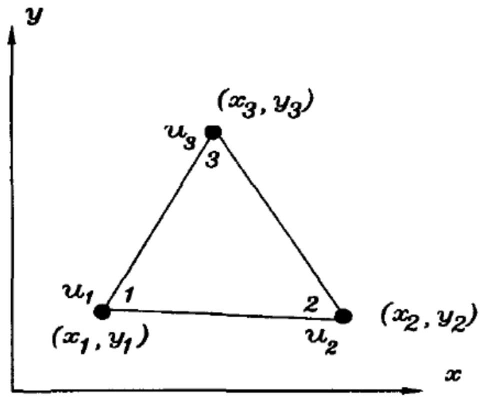

Figure A2. linear triangular elements.

Displacement and interpolated using some form of functionality.uv

$$u(x,y) = \sum_{i=1}^{3} H_i(x,y)u_i$$

$$v(x,y) = \sum_{i=1}^{3} H_i(x,y)v_i$$

Displacement can also be formed into.

$$\begin{Bmatrix} u \\ v \end{Bmatrix} = \begin{bmatrix} H_1 & 0 & H_2 & 0 & H_3 & 0 \\ 0 & H_1 & 0 & H_2 & 0 & H_3 \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ u_3 \\ v_3 \end{Bmatrix} = [N]\{d\}$$

Where is the displacement vector. Using this form for the results of strain.$\{d\} = \{u_1 \quad v_1 \quad u_2 \quad v_2 \quad u_3 \quad v_3\}^T$

$$\begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} = \begin{bmatrix} \frac{\partial H_1}{\partial x} & 0 & \frac{\partial H_2}{\partial x} & 0 & \frac{\partial H_3}{\partial x} & 0 \\ 0 & \frac{\partial H_1}{\partial y} & 0 & \frac{\partial H_2}{\partial y} & 0 & \frac{\partial H_3}{\partial y} \\ \frac{\partial H_1}{\partial y} & \frac{\partial H_1}{\partial x} & \frac{\partial H_2}{\partial y} & \frac{\partial H_2}{\partial x} & \frac{\partial H_3}{\partial y} & \frac{\partial H_3}{\partial x} \end{bmatrix} \{d\}$$

We use the symbol to show the form of matrix in the equation above.$[B]$

$$\{\varepsilon\} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} = [B]\{d\}$$

And Galerkin method. Applying this weighted function provides the finite element domain integral form.$\omega_1 = H_i(i = 1,2,3)\omega_2 = H_i(i = 1,2,3)$

$$\int_{\Omega^*} [B]^T[D][B]d\Omega\{d\}$$

Which shows doamin elements. Thus, kekekuan matrix elements for elasticity can be formed as:Ω^*

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

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

$$[K^e] = [B]^T [D][B] A$$

$$[K^e]\{d\} = [f^e]$$