Chapter 2
Literature Review Fatigue Analysis in Trabecular Bone

Abstract Normal walking is the most action impose on the skeleton structure. The microarchitecture of trabecular bone plays an important role respect to mechanical properties. Analyse the fatigue behaviour of the trabecular bone respect to physiological activity (Normal Walking), subjected to combination of axial compression and torsional (multi-axial) load counted as the main aim of this study. The osteoclast is responsible for modelling and remodelling of bone and is defined as a large multinucleate bone cell that absorbs bone tissue during growth and healing. Irregularities and disorders in trabecular bone cause to reduction of bone mass and its architecture. The standard method applied to extract bone structures properties is 2D section of bone biopsies. Tetrahedrons technique is applied to calculate bone volume (BV), total volume (TV) is the volume of whole bone structures. Trabecular bone has a significant portion in respect of resisting compression and shear. Data extracted from experimental test is depends on many parameters such as geometry of bone and measurement of strain. Trabecular architecture has a specific properties respect to tension loading. Almost all load due to physiological activates are counted as cyclic loading. Lifetimes were found to be highly dependent on the axis of loading and are drastically reduced for off-axis loading.

2.1 Introduction

Since skeleton play an important role on supports weight of body, analysis of mechanical properties is highly recommended to identify weaken parts due to physiological activities, however, among daily activities normal walking is the most action impose on the skeleton structure. Human bone is categorized in two various types, the first is called Cortical bone which has high porosity and density, the second one that is inner part of bone structure is called trabecular bone or Cancellous as commercial name.

M. Mostakhdemin et al., *Multi-axial Fatigue of Trabecular Bone with Respect to Normal Walking*, Forensic and Medical Bioinformatics,
DOI 10.1007/978-981-287-621-8_2

Since daily activities, bone structures face with various types of loading with which trabecular bone tolerates approximately 70 % of total load [1]. The micro-architecture of trabecular bone plays an important role respect to mechanical properties. To analyse samples constructed by micro-CT scan images, finite element model was applied for failure mechanism and local strain field.

Damage accumulation is a major factor of weakens vertebrae due to cyclic loading and is also cause of failure in implants [2]. Among many researches that covers fatigue analysis, fatigue parameters such as fatigue strength in cortical parts is extensively reported [3–6] however, fewer data are reported for trabecular part [7]. Analyse the fatigue behaviour of the trabecular bone respect to physiological activity (Normal Walking), subjected to combination of axial compression and torsional (multi-axial) load counted as the main aim of this study.

2.2 Bone Rehabilitation Mechanism

Since skeleton has duties as framework of body to tolerate load and stresses due to daily activities, remodel and reshape itself by some cells in a cyclic period of time. Bone consists of organic matrix, inorganic minerals, cells and water that resist mechanical forces.

2.2.1 Bone Modelling and Remodelling

Bone remodelling (bone metabolism) is a process which is done by cell called the osteoclast that diminish mature bone and another cell called osteoblast which has a duty of rehabilitation of those spaces that faced with osteoclast and this process is called ossification. This process is completely varied among different ages, such a process is done 100 % for first year of life, however, for adult it will decreases to 10 % totally. Remodelling process and its effect on bone can be counted as a mechanical function, and this condition of bone structures can be analysed based on human activities or any fracture, thus, micro damage occurred in bone.

2.2.1.1 Osteoblast Cells in Bone

The osteoblast supports bone in the sense of producing more cells matrix, termed osteoid. In adulthood, osteoid exists on the surface of trabecular bone, however, on the inner lining of cortical bone.

2.2.1.2 Osteoclast Cells in Bone

The osteoclast is responsible for modelling and remodelling of bone and is defined as a large multinucleate bone cell that absorbs bone tissue during growth and healing.

2.3 Bone Architecture and Materials

Bone is divided into two types, the one is immature and the second is mature. Mature bone is formed by immature one, and following its remodelling. Mature bone is divided into two types: Trabecular bone or cancellous bone and compact or cortical bone. Trabecular bone has a space with marrow cavities, which is a space for vessels and mineral nutrition pass; on the other hand, compact bone is more rigid respect to cancellous bone and include of the marrow channel. Cortical bone has enough strength for withstand of weight and forces imposed by physiological activities, however, trabecular bone is more flexible and reservoir for calcium homeostasis. By become older and older, portion of trabecular bone diminish. Trabecular form a network of rod and plate-like elements that suitable for blood vessels pass and more lighten than cortical bone with marrow cavities. Detail is illustrated in Fig. 2.1 [8].

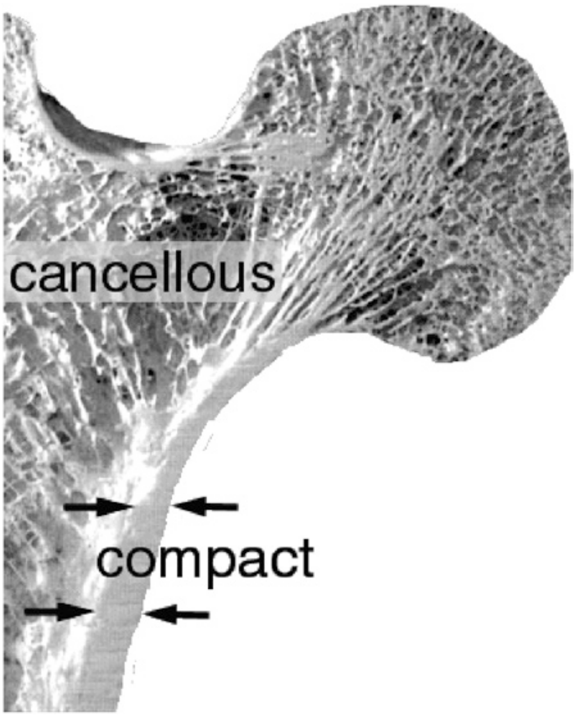

Fig. 2.1 Trabecular bone

The trabecular bone is made up of trabecular plates and rods (struts and plates). Whilst cortical bone can be regarded as homogeneous and isotropic, in comparison of trabecular bone that is anisotropic and inhomogeneous [9] has variations in its structures depends on different anatomical sites [10].

2.4 Morphological Indices of Bone

Irregularities and disorders in trabecular bone cause to reduction of bone mass and its architecture, 94 % is counted as trabecular strength if bone density and architectural are measured, furthermore, use of bone density, 64 % is counted as its portion alone. The standard method applied to extract bone structures properties is 2D section of bone biopsies. In addition, three dimensional morphology indices will be extracted form 2D images that this technique is called stereological methods. Some morphological indices such as bone volume (BV/TV) and surface density (BS/BV) are extracted from samples, and other crucial data such as trabecular thickness (Tb. TH), trabecular separation (Tb. SP), and trabecular number (Tb. N) are extracted indirectly if structure is assumed fixed part, but trabecular bone is faced with changes in its shape and architecture within different times, so this assumption will lead to have error on extracted indices [11].

Marching Cubes method (MCM) is used to calculate bone surface area (BS) in this methods surface being triangulated of mineralized bone phase. Tetrahedrons technique is applied to calculate bone volume (BV), total volume (TV) is the volume of whole bone structures. BV/TV and BS/TS are used to compare samples with different architecture.

2.5 Bone Mechanical Properties

Since many reasons, studies of mechanical properties of bone make it useful for orthopaedic science. First, knowledge of this properties will clearance what behave is expected from bone in life and to what extend bone has abilities for absorbing energy and so on. Bone is known as composite materials, include of minerals, waters and cells.

According to the different sites, ages and diet, this composition is differed. In this composition, 90 % of bone matrix is collagen. Collagen has a low modulus, poor compressive strength and excellent strength in tensile. Hydroxyapatite is mineral phase of bone that is stiff and with good tensile strength regards of mechanical aspects. Combinations of these two materials make bone as anisotropy material that is strong in compression but weak in shear, however, in respect of tension is intermediate compare to another [12].

Trabecular bone has a significant portion in respect of resisting compression and shear, also trabecular bone get 25 % as dense, 500 % as ductile and 10 % as stiff as cortical bone. Based on different position and ages, trabecular has different mechanical properties, it is open-celled porous foam and combination of rod and plate–like that depends on architecture and orientation of those rod and plate-like, mechanical properties varies functionality [12].

2.5.1 Static Properties of Bone

2.5.1.1 Compression Properties of Trabecular and Cortical Bone

Many studies report mechanical compressive characterization of the human trabecular bone. Compressive properties and their relations with the trabecular bone density and morphological parameters are well known. Most of these studies aim to predict the trabecular bone strength in normal in vivo loading; however, trabecular bone transmits essentially compressive and tensile loads and due to this transition trabecular is faced with multi axial stresses [13]. Since trabecular bone mechanical testing is not as convenient as cortical bone, and based on some experimental research, mechanical properties of trabecular bone is close to cortical bone, for example, Young's modulus for trabecular bone is 20 % lower than cortical bone [14]. Data extracted from experimental test is depends on many parameters such as geometry of bone and measurement of strain [15, 16]. Failure properties of trabecular bone in compression test cannot be exactly explained with established material properties of cortical one [17].

Some research carried out on uniaxial and confined compression proof that hydrostatic yield stress with uniaxial yield stress for trabecular bone is equal, further pressure dependent plasticity is more accurate for simulation [18]. In addition, elastic modulus and yield strain of trabecular bone is reported lower than cortical bone and this cause to cumulative effect between cortical and trabecular tissue with which tissue strength for cortical bone is 25 % greater than trabecular tissue [19]. Compression loading to reach yield strain in on-axis loading and off-axis has been performed, yield strain increased in off-axis loading and reduction in strength that is related to the off-axis loading is greater than modulus [9].

According to the compression and torsion loading, powers of density in compression is larger than in torsion, however strain rate has larger value in torsion than compression. In addition, for different trabecular shear properties, effect of density is weaker compared with effect of strain rate which is stronger [20]. In this study they performed that in compression loading the changes in bone volume cause compress marrow and this phenomenon is counted as reason of bone stiffening increase within compression loading, the power of density has significant contribution in compression than those in torsion. On the other hand, ultimate strength, yield strength and bone stiffness have a close relation in compression loading for trabecular bone, finite element analysis is applied to measure the bone strength by estimation stiffness [21].

2.5.1.2 Torsion Properties of Trabecular Bone

Torsion and shear properties are significantly correlated respectively with apparent densities of torsion and shear specimens [22]. Some parameters such as damage shear modulus, shear yield stress and ultimate shear stress has are related to induce damage to analysis of bone strength in especial disease such as osteoporosis. Changes in ultimate shear strength and toughness are proportional to decrease shear modulus, these two factors are more susceptible in diminishing volume fraction [23].

First of all measuring elastic properties of high degree porosity structure such as trabecular bone is difficult with traditional methods, the best technique of measuring Young's modulus and shear modulus is using ultrasonic technique [24]. Some researches carried out on the torsional properties, effect of trabecular bone in two various group such as bone with marrow and without were investigated, [20] reported applied these groups in low strain rate ($0.002\,\mathrm{s}^{-1}$) and high strain rate ($0.05\,\mathrm{s}^{-1}$), power relation to determine shear strength and shear modulus has been applied as shown in Eqs. 2.1 and 2.2 [25].

$$\sigma_u = 40.2 \times \rho^{1.65} \times \dot{\varepsilon}^{0.0\dot{7}3} \tag{2.1}$$

$$\mathrm{E} = 2232 \times \rho^{1.56} \times \dot{\varepsilon}^{0.0\dot{4}7} \tag{2.2}$$

In this report, shear strength was proportional to the density raised to the 1.02 power and strain rate was raised to the 0.13 powers. In addition the shear modulus is proportional to apparent density raised to 1.08 and strain rate raised to 0.07 powers. However, [23] performed decreasing in shear modulus cause to changes toughness and shear strength.

2.5.1.3 Calculation of Shear Stress and Shear Strain for Trabecular Bone

After preparation of bone sample for torsional test in the sense of using water jet to remove all marrow and filled samples up by PMMA for its fixation part and put it in the brass shaft to hold sample, torque (N m) versus deformation θ (°) curve will be obtained. The linear region of such a curve is torsional stiffness which is defined by $\mathrm{K} = \frac{\Delta \mathrm{T}}{\Delta \theta}$ [20]. Then shear modulus calculated as

$$G = \frac{K \times L}{J} \tag{2.3}$$

where T is the applied torque, L is the gage length and J is the polar moment of inertia. It is possible to consider trabecular bone as a continuum structure if more than five intra trabecular spaces exist within its dimensions [26, 27]. Our sample has more than 5 intra trabecular so it is possible to consider it as a continuum structure.

Shear stress is calculated by using torque-angle diagram and following equation reported [28]. Shear stress equation is as shown below:

$$\tau = \frac{1}{2\pi R^3}(\emptyset\frac{dT}{d\emptyset} + 3T) \tag{2.4}$$

where Ø is the angular deformation per unit length ($\emptyset = \left(\frac{\theta}{L}\right)$) and R is the specimen radius. This equation is appropriate for approximately transversely isotopic trabecular bone samples.

To find maximum shear strength, consideration of the maximum point (peak) of torque-deformation diagram where $\frac{dT}{d\emptyset} = \frac{dT}{d\theta} = 0$ gives maximum shear stress as formulated below [20].

$$\tau max = \frac{3T max}{2\pi R^3} \tag{2.5}$$

Shear strain rate also is calculated as

$$\dot{\gamma} = \frac{R \times \dot{\theta}}{L} \tag{2.6}$$

which $\dot{\theta}$ is the deformation rate; with these two equations maximum shear stress and strain on the surface of bone would be calculated.

Correlation between strain rate increasing and significant increase in samples shear modulus and shear strength reported in [20]. They performed that presence of bone marrow did not effect on the shear modulus and shear strength. The power of density has significant contribution in compression than those in torsion; however, the power of strain rate is larger in torsion in respect to the compression.

2.5.1.4 Tensile Properties of Trabecular Bone

Trabecular architecture has a specific properties respect to tension loading. Apparent yield strain versus bone properties such as volume fraction is counted as function of each other in tension and compression loading, which yield strain remains constant within an anatomic site. In the axial loading, variation of yield strain in tissue level and apparent level has connectivity with each other, however, for bending loading is not [29]. Apparent yield strain variation within an anatomic site is too small and this result has been investigated [30].

Trabecular bone subjected to a bending load will face with high tensile stresses that would effect on strain localization within the bone. Tensile loading condition is assumed to be following Woff's law. When load direction is normal to the principal trabecular orientation, neither the compressively nor the tensile strain regions were clearly elongated, but they were generally within the transverse plane perpendicular to the vertical trabecular. Moreover, the regions were less than one half of the mean thickness of the trabecular struts, and the number and mean volume of the yielded regions both increased uniformly with increasing apparent strain. Together these findings are consistent with bending of the trabecular and the formation of plastic or damage hinge [31]

2.6 Fatigue Behaviour of Trabecular Bone

Almost all load due to physiological activates are counted as cyclic loading. These days, damage of trabecular tissue due to repeated loading is highly demand area in aspect of biological analysis. Cyclic loading cause damage and initiate crack, even though the load and stress amplitude is far below yield strength. Cyclic failures of bone due to accumulation of plastic strain is known clinically as overuse injuries or stress fractures. Cyclic loading and damage is reported to weaken vertebrae [32].

Lifetimes were found to be highly dependent on the axis of loading and are drastically reduced for off-axis loading. Also strains at failure showed to be a function of the deviation from the physiological axis which may reject the assumption of isotropic failure strains [1] The significant increase in life when material degradation is included may be understood by examining the various parameters (stress, modulus degradation and plastic strain) at a local level. Within the structure, material degradation was limited to highly localized regions around the areas of peak stresses. Due to the intrinsic weakness of bone in tension, material degradation was initiated in the regions of high tensile stresses.

Once a trabecular had completely fractured, stresses were redistributed to nearby trabecular, which experienced greater damage rates, and rapid failure of the sample then occurred. At a localized level, within the early load cycle's material degradation caused a reduction in the peak tissue stresses. During the fatigue life, significant modulus degradation and permanent strains were observed in these high stress regions. However, the volume of material undergoing material degradation only accounted for a small percentage of the total bone volume. On a global level, significant modulus degradation only occurred once a trabecular had fractured. Also, the accumulated permanent strain at failure was typically 10 % of the initial applied apparent strain. As the initial apparent strain level was increased, there was a trend of increasing the degree of modulus degradation and accumulated permanent strain just prior to failure [33].

Modulus reduction and specimen residual strain increased when maximum compressive strain increase. The post-test mechanical properties were most depends on maximum compressive strain and suggested that trabecular bone failure is largely strain based [34].

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Multi-axial Fatigue of Trabecular Bone with Respect to Normal Walking
Mostakhdemin, M.; Sadegh Amiri, I.; Syahrom, A.
2016, VIII, 55 p. 29 illus., 12 illus. in color., Softcover
ISBN: 978-981-287-620-1