AGE EFFECT ON THE MECHANICAL PROPERTIES OF HIP JOINT BONE: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT

Bone is one of the important body components of all vertebrates. It is a natural composite, composed of bone-salt plates as matrix binder and soft collagen as reinforcing fibers. As bone supports all the organs of a body so its mechanical behavior is of prime importance. The mechanical properties of bone varies with age. In this paper, the effect of age on various mechanical properties of hip joint bone was investigated experimentally. For this purpose hip joint bone specimens of male bovine of different age groups were tested for fracture toughness, young modulus and tensile strength in the longitudinal and transverse directions of the collagen's fibers. Compact tension specimen was used for the fracture toughness, while for young modulus and tensile strength, rectangular flat specimens were used. The test procedures were similar to ASTM (American standard for testing and measurements) techniques. The test result revealed reduction in mechanical properties of hip joint bone with the age.

KEY WORDS: *Bone, fracture toughness, Hip joint, Age effect*

1. INTRODUCTION

Bone is an example of naturally occurring composite material and is an important body part which constitutes the skeleton of all vertebrates. The function of bone is to structurally support, protect body organs against internal and external loads as well as transmit loads within the body. Bone houses marrow (a flexible tissue in the interior of bones) and act as a reservoir for the calcium homeostasis. Bone is composed of organic and inorganic materials. The organic component of bone is collagen fibers while the inorganic component is hydroxyapatite. The strength and flexibility of bone is due to collagen fibers. Load among the collegen fibers is transfered by a matrix structure known as hydroxyapitite. Bone differs from other engineering materials in that it repairs itself against wear and tear during service life[1,2].

As bone is a mean of structural support to a body, its mechanical properties e.g. strength, stiffness, fracture toughness etc are of prime importance. Due to this reason, the mechanical behavior of bone has been extensively studied[1-4]. The properties of bones constantly change with age and it gets and loose mass (the organic mineral content) in a balanced manner through a process of absorption and formation. With increasing age the balance between bone absorption and bone formation changes, which leads to decrease in bone mass density and results in the loss/degradation of mechanical properties. The process is known as bone remodeling.

Wang et al[5] investigated the ageeffect on toughness of human cadaveric femurs bone and found that the strength, elastic modulus, fracture toughness and energy to fracture were decreased with age. Zimmermann et al.[6] studied the effect of age on bone plasticity and the corresponding change in toughness of the cortical bone of human body by using X-ray scattering and diffraction. The fracture toughness was measured in SEM. It was observed that due to structural changes caused by aging, the fracture toughness of the cortical bone decreases. The loss of toughness was attributed to the higher collagen cross linking due to aging. The quantitative assessment of age effect on fracture toughness of human cortical bone in the transverse orienetation was analyzed by Koster et. al[3]. It was observed that the crack initiation as well as crack-growth toughness decrease with aging. The decrease in toughness was reported to be smaller than the longitudinal direction fracture toughness. Rhoa et al.[7] investigated the age related effect on the mechanical behavior of human femora bone. A model relating the micro structural properties at the matrix level with the bending modulus of the bone was proposed. Nalla et al.[8] reported a decrease in the crack initiation toughness up to 40% on human cortical bones. The crack growth toughness becomes extremely small in the age of 100 years. The reduction in crack-growth toughness was attributed to the decrease in the extrinsic toughening

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mechanism e.g. fiber bridging.

The literature discussed above and other studies reported in references revealed that in the past. The mechanical behavior of various bone types have been studied for the assessment of age effect by many researchers[4,9-12], but no work has been performed for the effects on the hip joint bone. It is a fact that the composition and the structure of bones varies with its location in the skeleton site, so the behavior of one bone type can't be described with another type.

The objective of this study was to experimental investigating the age effect on the mechanical properties, namely tensile strength, young modulus and fracture toughness of the hip joint bone. The bovine hip joint bone samples were tensile tested for the investigation of the age effect on longitudinal and transverse tensile strengths and young module. The effect on fracture toughness was assesed using compact tension (CT) specimens. The next section describes the experimental program that is followed by results and discussion.

2. EXPERIMENTAL TESTING

Two types of tests were performed to investigate variation in mechanical properties of hip joint bone with age. In first type, CT specimens were used to observe variation of fracture toughness with age while the variation of tensile strength and young modulus of the hip bone in longitudinal and transverse directions was investigated in second type. The two test programs are described in the following sections.

2.2. FRACTURE TOUGHNESS TESTING

2.2.1. MATERIAL AND SPECIMEN PREPARATION

Fresh, hipbones were obtained from male bovine within 24 hours of slaughter. There were seven different ages of bone, which was used for experimentation. The bones were frozen at 0°C.The specimens were machined within 48 hours after obtaining the bone. The samples were cut using a hacksaw. The final shape of the specimens were obtained using file. Twelve CT specimens were prepared according to ASTM-E399[13]. Table 1 is the test matrix of the specimens. Figure 1 shows the location where the specimens were cut out from the hip bone. Two types of CT specimens were prepared, longitudinal and transverse. In longitudinal specimens the collagen fibers are parallel to the specimen's axis Whereas, in the transverse specimens, the collagen fibers are perpendicular to the specimen's axis. Figure 2 shows the geometry of a typical CT specimen.

2.2.2. TEST PROCEDURE

The test was conducted in UTM-E-100 at HITECH University Taxila. The specimen was bolted to the steel blocks and held in the machine grips. Figure 3 illustrates the experimental setup. The test was performed ambient conditions andthe load was applied by machine at a cross head speed of 0.5mm/minute. During tests, the applied load and the corresponding deformation were recorded by the computer connected to the machine.

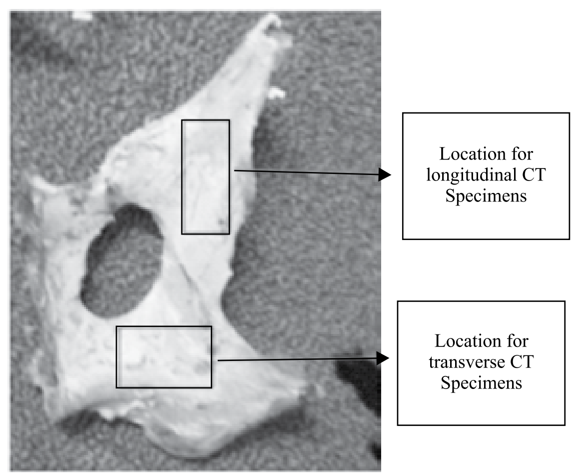

Figure 1. Location of the specimen extraction from hip joint bone

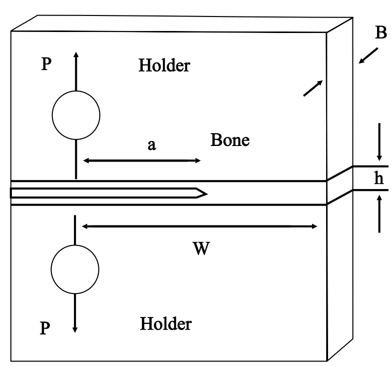

Figure 2. Geometry of a typical CT Specimen

Table 1: Test Matrix of CT Specimens

S. No	Specimen Name	Age (Year)	LCT	TCT	Width (mm)	Crack Length (mm)	Thickness (mm)
1	S1	1	✓		31.11	12.4	2.15
2	S2	1		✓	29.00	11.60	2.3
3	S3	2	✓		30.70	11.61	3.19
4	S4	2		✓	29.72	11.19	3.7
5	S5	2.5	✓		31	12.9	2.00
6	S6	2.5		✓	30.82	12.13	2.4
7	S7	3	✓		30.26	10.61	2.7
8	S8	3		✓	30.57	12	2.6
9	S9	4	✓		31	12.40	3
10	S10	4		✓	29.92	11.26	3.3
11	S11	5	✓		20.06	6.33	1.8
12	S12	5		✓	15.77	4.21	2

The specimen was loaded till the crack started to grow and at this point the test was stopped.

2.3. TENSILE TESTING

2.3.1. MATERIAL AND SPECIMEN PREPARATION

The test material was collected in similar manner as described in section 2.2. The tensile test specimens were prepared according to ASTM D3039[14]. Figure 4 shows the typical tensile specimens, while table 2 depicts the test matrix of prepared hip bone specimens for tensile testing.

2.3.2. TEST PROCEDURE

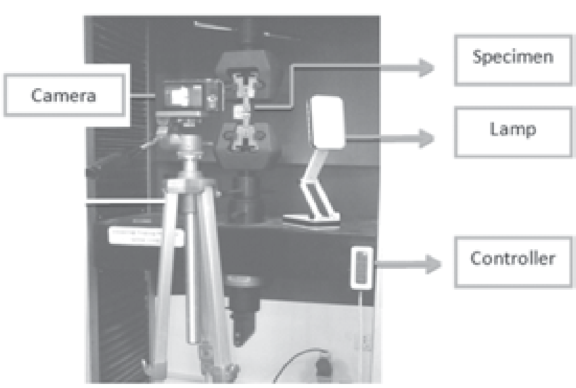

Figure 3. Fracture toughness test setup

The specimens were gripped in the same UTM machine described in section 2 as shown in figure 5. During test, the specimen was loaded at a cross head of 1 mm per minute. The load and displacements were recorded by the machine computer ergularly. The test was stopped as the specimen failed.

3. EXPERIMENTAL DATA ANALYSIS

3.1 FRACTURE TOUGHNESS TEST DATA ANALYSIS:

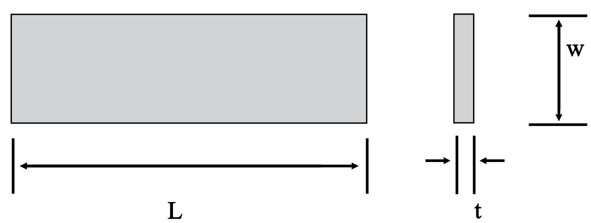

Figure 4. Geometry of tensile test specimen

The fracture toughness K was determined by using the equation: 1[13]

$$K = \frac{F_C Y}{tw^{1/5}} \tag{1}$$

Where Fc is the critical load at fracture, t is the specimen thickness and W is the specimen width as shown in figure 4. The value of Y is given by following equation:

Table 2. Test matrix of prepared hip bone specimens for tensile testing.

Sr No	Specimen Name	Age	Longitudinal Tensile Test Specimen	Transverse Tensile Test Specimen	Width (mm)	Length (mm)	Thickness (mm)
1	S1	1	✓		16.54	7.4	2.10
2	S1	1		✓	16.22	5.91	2.18
3	S2	2	✓		16.46	6.21	2.7
4	S2	2		✓	16.28	5.7	3.00
5	S3	2.5	✓		13.26	4.07	1.91
6	S3	2.5		✓	17.68	6.35	2.00
7	S4	3	✓		15.88	3.91	2.30
8	S4	3		✓	12.32	3.3	2.03
9	S5	4	✓		16.22	5.7	2.36
10	S5	4		✓	16.22	5.08	2.50
11	S6	5	✓		13.30	5.08	1.91
12	S6	5		✓	16.26	5.15	2.00

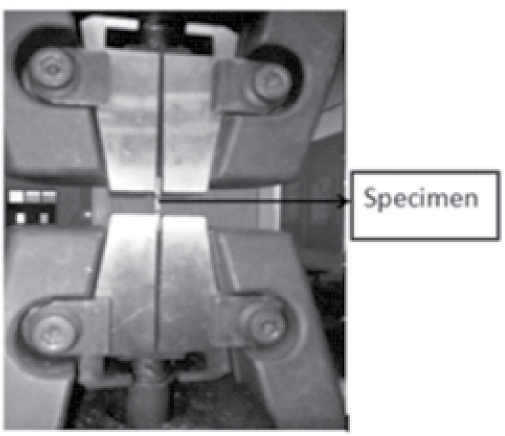

Figure 5. Experimental setup for tensile test

$$Y = 29.6\left(\frac{a}{w}\right)^{0.5} - 185.5\left(\frac{a}{w}\right)^{1.5} + 655.7\left(\frac{a}{w}\right)^{2.5} - 1017\left(\frac{a}{w}\right)^{3.5} + 638.9\left(\frac{a}{w}\right)^{4.5} \quad (2)$$

In above equation a is crack length of CT specimen.

3.2. TENSILE TEST DATA ANALYSIS

The stress σ and strain ε was calculated using equation: 3 and 4 respectively

$$\sigma = F/A \quad (3)$$

$$\varepsilon = \delta/l \quad (4)$$

Where F is the load applied

A is the cross sectional area of the specimen.

δ is the deformation of the specimen

l is initial length of the specimen.

From stress-starin data, young modulus 'E" was calculated using equation: 5

$$E = \frac{\sigma max}{\varepsilon max} \quad (5)$$

Where σmax and εmax are the maximum stress and maximum strain at failure.

4. RESULTS AND DISCUSSION

The effect of age on fracture toughness is described in figure 6. It is observed that the fracture toughness slightly increases in the initial period from one to two year of age span in both longitudinal and transverse directions. However mixed trend was observed in the age span between 2-2.5 year. The toughness decreases in both directions with the age after 2.5 years. In the initial 1-2 year period, the fracture toughness in transverse direction is almost twice the longitudinal direction. The higher toughness value in this case may be attributed to the higher resistance to crack growth in transverse direction. The crack path after the fracture is nearly parallel to the initial notch plane in case of longitudinal specimen. In longitudinal direction the crack takes its path between collagen layers facing least resistance. Figure 7 shows the images of the longitudinal CT specimen before and after failure. The fracture plane of the specimen is parallel to the initial crack as shown. In case of transverse CT specimen the crack has to cross the collagen layer network due to which it faces higher resistance promoting higher fracture toughness. The crack path after in this case is diverted from the initial artificial crack plain as shown in figure 8.

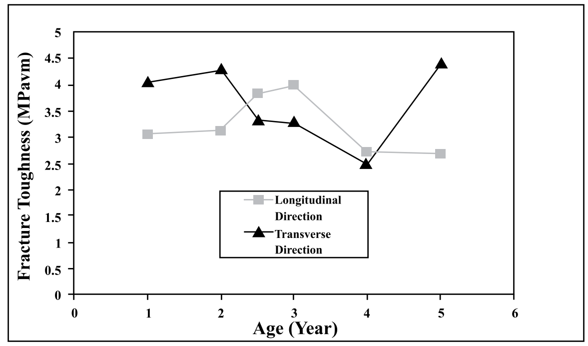

Figure 6. Hip bone fracture toughness versus age

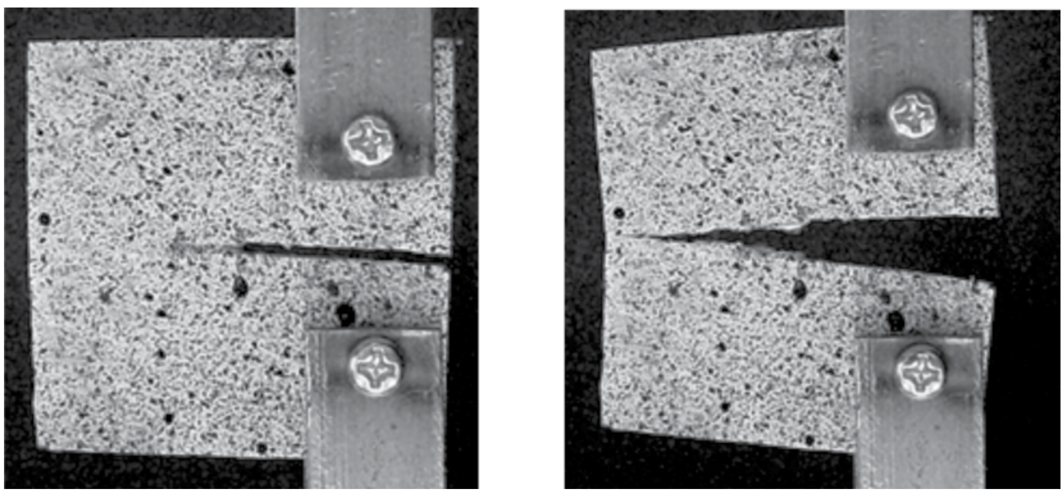

Figure 7. Longitudinal CT specimen before failure (left) and after failure (right)

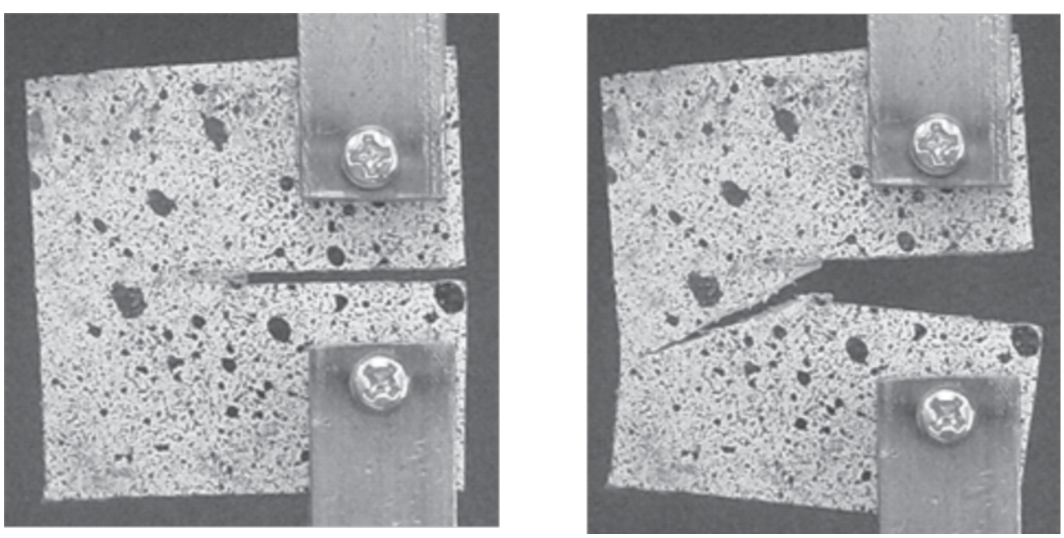

Figure 8. Transverse CT specimen before failure (left) and after failure (right)

The value of the fracture toughness does not remain high for the transverse direction for the entire age span. The two values of fracture toughness (longitudinal and transverse) become nearly equal at the age of 2 years as shown in figure 6. This implies that the bone mass density variation with age is not uniform in both directions.

The young modulus of the bone is plotted against the age in figure 9. The overall trend of young modulus in the longitudinal direction and transverse direction show a decrease. In the initial age of 1-2.5 years, the young modulus in transverse direction is slightly higher than the longitudinal direction.

The behavior of the hip bone's ultimate strength with the age is shown in figure 10. The figure shows that the strength is decreased in both directions in initial two years; however there is no clear trend of the strength after two years. The strength is nearly equal in the mod span of the age of bone from 2-3 years. In the early age <2 years, the strength in longitudinal direction is higher. After 3 years of age the strength in the transverse direction is higher as shown in figure 10.

The variation in the mechanical properties of bone is attributed to the variation in the bone mass density with age. The bone mineral density increases with age up to middle age and then declines[15]. High BMD results in enhanced mechanical properties.

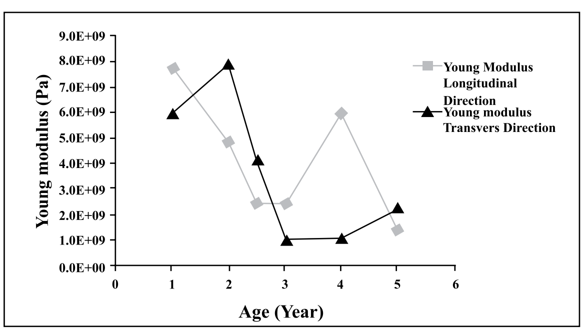

Figure 9. Young modulus of hip bone versus age of the bone

The research carried in this paper on the bovine hip bone has direct implication on the treatment of human hip bone. The bone grafting has been increased in past few decades and bone is the second most transplanted tissue after skin. Currently three techniques namely autografting, allografting and synthetics biomaterial grafting are practiced for bone transplantation. These techniques have limitations and problems for example autografting have bulk limitations, graft donor site

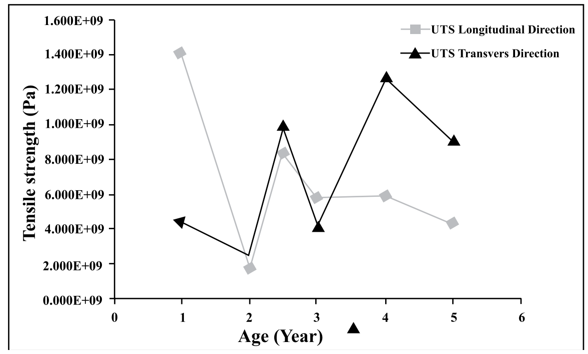

Figure 10. Ultimate Strength of the hip bone versus age

morbidity and long procedure time. Allografting is expensive, have limited availability, infection risk and reproducibility problem[16]. Recently the bovine bone has been investigated as a potential substitute for human because it is biocompatible for human osteoblasts. The bovine bone grafts are called Xenografts. Hubble et al[17] showed that bovine bone exhibited similar stability to human bone when used as a graft in impaction grafting of the femur bone.

5. CONCLUSIONS

The effect of age on the fracture toughness, young modulus and tensile strength of hip bovine bone in the longitudinal and transverse directions was experimentally investigated in this study; CT specimens were used for the measurement of fracture toughness. The tensile properties were tested using flat rectangular specimens. The value of fracture toughness and young modulus decreases with the age. The tensile strength decreases in the initial age span. The decrease in the properties is attributed to the bone density loss. It is also concluded that the fracture toughness is higher in the transverse direction in the early age span, and becomes similar to the longitudinal fracture toughness in the mid age span. Due to the presence of collagen fibers in the crack path, the resistance to crack growth increases which results in higher fracture toughness in transverse direction.

Nomenclature

BMD Bone Mass Density

CT Compact Tension

UTM Universal Testing Machine

ASTM American Standard for Testing And Materials

REFERENCES

1. *Fratzl, P., Gupta, H. S., Paschalis, E. P., Roschger, P., 2004. "Structure and mechanical quality of the collagen–mineral nano-composite in bone". Journal of materials chemistry 14(14): 2115-2123.*

2. *Currey, John, D., 1999. "The design of mineralised hard tissues for their mechanical functions." Journal of Experimental Biology 202(23):3285-3294.*

3. *Koester, K. J., Barth, H. D., Ritchie, R. O., 2011. "Effect of aging on the transverse toughness of human cortical bone: evaluation by R-curves". Journal of the mechanical behavior of biomedical materials 4 (7) :1504-1513.*

4. *Mayhew, P. M., Thomas, C. D., Clement, J. G., Loveridge, N., Beck, T. J., Bonfield, W., Reeve, J., 2005. "Relation between age, femoral neck cortical stability, and hip fracture risk". The Lancet, 366(9480): 129-135.*

5. *Wang, X., Shen, X., Li, X., & Agrawal, C. M. 2002. "Age-related changes in the collagen network and toughness of bone". Bone, 31(1):1-7.*

6. *Zimmermann, Elizabeth A., Eric Schaible, Hrishikesh Bale, Holly D. Barth, Simon Y. Tang, Peter Reichert, BjoernBusse, Tamara Alliston, Joel W. Ager, and Robert O. Ritchie., 2011. "Age-related changes in the plasticity and toughness of human cortical bone at multiple length scales". Proceedings of the National Academy of Sciences 108 (35):14416-14421.*

7. *Rho, J. Y., Zioupos, P., Currey, J. D., & Pharr, G. M. 2002. "Microstructural elasticity and regional heterogeneity in human femoral bone of various ages examined by nano-indentation". Journal of biomechanics, 35(2):189-198.*

8. *Nalla, R. K., Kruzic, J. J., Kinney, J. H., Balooch, M., Ager, J. W., & Ritchie, R. O. 2006. "Role of microstructure in the aging-related deterioration of the toughness of human cortical bone". Materials Science and Engineering: C, 26(8):1251-1260.*

9. *Nicks, K. M., Amin, S., Atkinson, E. J., Riggs, B. L., Melton, L. J., & Khosla, S. 2012. "Relationship of age to bone microstructure independent of areal bone mineral density". Journal of Bone and Mineral Research, 27(3):637-644.*

10. *Currey, John D., Kevin Brear, and Peter Zioupos., 1996. "The effects of ageing and changes in mineral content in degrading the toughness of human femora". Journal of biomechanics 29(2):257-260.*

11. *Siris, E. S., Brenneman, S. K., Barrett-Connor, E., Miller, P. D., Sajjan, S., Berger, M. L., & Chen, Y. T., 2006. "The effect of age and bone mineral density on the absolute, excess, and relative risk of fracture in postmenopausal women aged 50–99: results from the National Osteoporosis Risk Assessment (NORA)". Osteoporosis international, 17(4):565-574.*

12. *Tang, S. Y., and D. Vashishth., 2011. "The relative contributions of non-enzymatic glycation and cortical porosity on the fracture toughness of aging bone". Journal of biomechanics 44(2): 330-336.*

13. *ASTM E399, Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K Ic of Metallic Materials.*

14. *ASTM D 3039, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, D3039/D3039M − 14.*

15. *Steiger, P., Cummings, S. R., Black, D. M., Spencer, N. E., Genant, H. K., 1992. "Age-related decrements in bone mineral density in women over 65".Journal of Bone and Mineral research, 7(6):625-632.*

16. *Blom, Ashley., 2007. "Which scaffold for which application?". Current Orthopaedics 21(4): 280-287.*

17. *Hubble, M. J., Goodship, A. E., Learmonth, I. D., 1997 " Xenograft bone for impaction in revision total hip arthroplasty. An in vivo pilot study". Journal of Bone and Joint Surgery (British volume), Orthopaedic Proceedings, 79: 468-468.*