Reliability of Using Elastic Modulus for Non- Homogeneous Materials

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Abstract. This paper investigates the literature available for derivation of the elastic modulus (E) as employed specifically in non-homogenous materials. There is a big pool of E-values in the literature which user can pick and use. However their reliability is still a question. This study will therefore focus on the values of elastic modulus acquired from the secondary databases and their reliability in numerical methods like Finite Elements (FE). This study uses E-values obtained from bones, muscles and tissues. Bone is a composite material with a very intricate internal geometry. Acquiring the elastic modulus values for irregular geometries like bones is not a straight forward process. This study therefore compares the different studies provided in literature for derivation of elastic properties of bones from different vertebrates and investigates the reason of variations. The study infers that populating all the values of elastic modulus without a standard procedure, creates a level of ambiguity that bars the understanding of the use of modulus of elasticity where insightful procedures are in question for example finite element analysis of sensitive materials . Therefore there is a need to take great care in deriving the values of E.

1 Introduction

The Elastic Modulus (E) is a mechanical property of solids in which the force is exerted on a body to cause the deformation [1]. Elastic modulus (E) defines the relationship between stress in which force acts per unit area whereas strain signify deformation in a material [2]. While dealing with mechanics of biological materials the structural properties and mechanical properties are in major focus. Structural properties show a relationship between the force and deformation while the mechanical properties express the behavior of material in terms of stress-strain relationship in the materials [3].

The strength of a material will always be different compared to the corresponding modulus of elasticity or stiffness except bending mode of loading. It is known that stiffness is the property of a material that represents the ability of a material to resist the deformation while it has been observed that a stiffer material has a higher elasticity to deform [4]. The need to understand why elastic modulus value could be misleading is due to the large variation of its values. There is a big factor of ambiguity in literature as to what method of testing holds true for a specific value of elastic modulus.

In a linearly elastic material, the Young's Modulus describes how a material responds to stress. However, if we consider a microscopically refined level, it is similar to a spring constant. Conceptually, atoms in a solid are bonded to other atoms. If you force two atoms apart, there will be a force that attempts to restore them to their equilibrium distance. This is similar to having two wooden blocks connected to a spring and then pulling

them apart. As a result, the blocks will jump back together if you let go. The restoring force depends on what the spring is made of, so the Young's modulus describes how "stiff" the bonds of a solid are relative to the material itself.

Thus, in archiving values for the modulus of elasticity for non-homogenous materials, materials should be sensibly characterized. Materials are of two types' ideal materials and non-ideal materials. Ideal materials are isotropic and homogenous which shows that their properties are same in all directions while anisotropic and non-homogenous material varies in all directions [5]. This study will include all the non-homogenous material data for bone, muscles and tissue to investigate the cause of variation in the values of elastic modulus.

2 Background

A Bone is one of the major composite materials which consist of both fluid and solid phases [6]. Bone is made up of two main solid phases; organic and inorganic phase which provides hardness to the bone. The organic phase provides flexibility to the bone while the inorganic material of the bone gives its resilience [7]. In any long bone ,the cortical bone is roughly four times the mass of cancellous bone [8]. The porosity of cortical bone ranges from 5 to 30% while cancellous bone's porosity ranges from 30-90%. The bone porosity is not fixed and it can be changed in response to the altered load, or any disease and also other factors like aging [9]. The mechanical properties of biomaterial are difficult to predict.

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This study will therefore focus on the values of elastic modulus acquired from the secondary databases and their reliability. Various studies are conducted to acquire value of elastic modulus using different types of testing methods. Studies including [1], [3] where deformations based acquisition of bone's properties employing theoretical models are predicted; the accuracy is a function of material properties itself. To-date these values in the literature is a matter of question.

Recent studies have shown new ways of predicting the accuracy of the biomaterials as in case of bones. Some of which considered the entire surface of the bone for deformation [10] and others entirely different procedures. In the next section, mechanics of bone including various types of test to derive elastic modulus is explained briefly.

3 Mechanics of bone

This section will cover the mechanics of biomaterials (especially bones) in correspondence to the elastic modulus values. A bone is a term used for hard and rigid structure of the vertebral skeleton system, that gives shape and support to the body and it also protect the body [11]. Composition, structure and mechanical properties of bone may continuously vary or in discrete steps from one part to another part [10]. The arrangement of constituents of bones and its classified structure give rise to a very complex material type structure that cannot define the single significance for particular mechanical property. Next sections explain some basic types of testing methods to find values of elastic modulus.

Stress and Strain are the properties of the materials such that, that when an external force is applied the structure deforms. Stress is defined as internal force per unit area [12], on the contrary strain is the change in shape or size of an object due to the outwardly applied forces to the object [13]. Stress is much more complex entity in more rigorous situations and the units of stress is Pascal (Pa) which is equal to the one Newton per meter square ($1N/m^2$)[14].

Among the various forms of stresses, tensile stress is the type of stress in which the length of material extends and it act as normal to the stressed area (Fig. 1). Compressive stress is the type of stress that have tendency to compress or shorten the length of the material, it also acts normal to the stressed area and shear Stress is the type of stress that has tendency to act in the planes of stressed area at the right angles [15, 16].
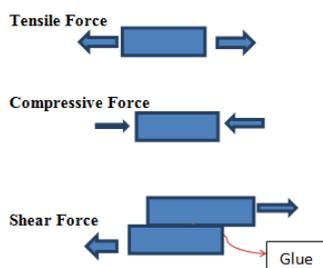

Figure 1. Illustration of tension, compression and shear forces.

In all these types of testing methods, it is easy to develop a stress-strain curve, which can be eventually used to derive the values of elastic modulus.

4 Derivation of elastic modulus using different loading tests

Most studies of the mechanical testing of bones depend upon `the in vivo and in vitro experiments. Torsional and impact loading are less frequently used. Our investigation in this study will only focus on the most commonly used mechanical tests in literature. Among the traditional testing methods like bending, compression and tension tests, finite element method recently, is extensively being used to determine the modulus of elasticity in biomaterials [17].

Bending test is mainly used to illustrate the mechanical behavior of the biomaterials [18-21]. This test however measures the coarse value of Young's modulus or Elastic modulus (E) from the geometry of the loading device in some cases [22] and at the same time restrains toughness of the material [23]. One of the studies show the value of elastic modulus of the compact bone after applying the mechanical test of bending is 115 GPa [24] for apatite which is over-estimated in our knowledge while on the other hand, for the muscles that are attached to this consumes a value of 40.3GPa from bending [9].

Torsion is another form of basic loading mode, where forces tend to twist the object along the longitudinal axis [25]. The intricate torsion forces can be used to acquire the values of elastic modulus by generating stress-strain curve. In tension, the two forces act on an object and try to pull the object in opposite direction. As a result the object is stretched and become thinner and longer than the original one [19].

Bones respond intermediately to the tension forces. This is the most basic method to obtain value Young's modulus (again) by creating a load-force curves. It is possible to do tension test on muscles as well in order to obtain stiffness. Muscles respond to the tension forces called tension load. They either contract that pulls the tendons at both ends. This cause little stretch in the muscles and length of the tissues also change [26].

Various studies show several values of elastic modulus in muscles, bones and tissues [27]. Zajac [28] proposed the value of elastic modulus as 80 GPa for a muscle and for the compact human bone the value of elastic modulus was reported as 0.053 GPa by [29]. Continuing Doblare's work [29] regarding modeling of bone tissue fracture and healing, some contradictory values of elastic modulus (E) were also reported for compact human bone [9].

This difference primarily is due to the different loading tests in both data sets. Compression however, involves forces that push the object along the axis and makes it thicker and bulge out as a result the material length is shortened [30]. Tension and compression forces both act as axial stresses because they both act on structure longitudinal axis. The value of elastic modulus

acquired by Reilly and Burstein using compression is reported as 0.131GPa on a human compact bone [31].

Other compression tests including tests on cortical femoral bone reports E-value of 2.065GPa [27] while the human trabecular bone with an E-value of 1.904GPa [32] in the same axial direction using different bone-types. Another study investigates the compressive strength of the cancellous bone as 20GPa [5]. Similarly, numerical methods such as Finite Element Method (FEM), which is one of the most widely used methods to assess the strength and quality of bone in terms of stiffness; has been in practice to identify the behavior of bone, for the past 40 years [3]. Various studies have been conducted for the derivation of E-values and to manipulate the mechanical behavior of bones, muscles and tissues [33-35]. It is not possible to cite all the relevant references using FEM, in this short investigation paper however one of the studies reports E-value as 18.4GPa [36] which is considered to be the most widely used E-value for cancellous bone.

5 Results and conclusions

Many studies show that behavior of bone is affected by different mechanical properties [5]. After careful investigation, we have identified different studies which are using various kinds of bones employing different scheme of methods; in order to derive values for elastic modulus. In total, the data was roughly pulled out from studies reported in literature. It should also be noted that the investigation carried out in this paper is based on twenty study subjects (Fig. 2) only, which is not a very big number and that's probably one of the limitations of this study.
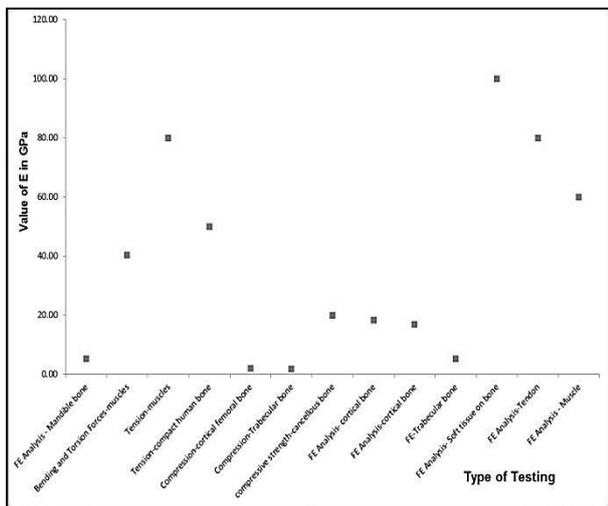

Figure 2. Scatter of Young's modulus values for different types of loading tests.

Each study focused on the derivation of elastic modulus. It is observed, that there is no consistency in the values of elastic modulus, throughout the literature. Perhaps one reason might be the use of different loading and testing methods to acquire values of elastic modulus. Additionally, different authors use bones from different species and different parts. For example an elastic modulus for human compact bone from the femur will yield different value compared to the elastic modulus of the human compact bone from the humerus.

There is a significant need to pay attention to this area where values of elastic modulus is of great importance (especially) for the applications which requires sensitive procedures. In the field of civil engineering where elastic modulus of concrete holds much importance because this mechanical parameter reflects the ability of the concrete to deform elastically. For example, in pre-stressed concrete structures, elastic shortening of pre-stressed concrete is one of the main factors contributing to pre-stress loss.

Experiments shows that Young's modulus value also increases if the bone starts to mineralize more due to high mineral content and collagen fibers [7]. The collagen fibers tend to increase the value of elastic/Young's modulus due to high value of stiffness [37].Usually in the literature the bone's elasticity is ranged between 15-25 GPa [38] which is one third of a metallic aluminum [39]. The bone's elasticity is important because, it gives the bone ability to dissipate energy during deformation phenomena's. Methods like Finite Elements, which requires the value of elastic modulus as one of the major inputs predicts results of simulation on the basis of E-value that is used as an input. If one value goes wrong the whole simulation will result into an inaccurate and ambiguous situation. Apparently, the criticality of this basic factor is under estimated and it might result into the situations which do not relate to any real physical phenomena's at all.

Therefore, there is a need to look into the importance of methods used to derive elastic modulus of various materials and the steps followed, so that a consistency can be maintained in the literature housing the values of Young's modulus over a wide range.

References

1. D. Burr, C. Milgrom, D. Fyhrie, M. Forwood, M. Nyska, A. Finestone, et al., In vivo measurement of human tibial strains during vigorous activity, Bone, **18**, 405-410 (1996)
2. C. Milgrom, A. Finestone, A. Hamel, V. Mandes, D. Burr, N. Sharkey, A comparison of bone strain measurements at anatomically relevant sites using surface gauges versus strain gauged bone staples, Journal of biomechanics, **37**, 947-952 (2004)
3. M. J. Silva, M. D. Brodt, W. J. Hucker, Finite element analysis of the mouse tibia: Estimating endocortical strain during three‐point bending in SAMP6 osteoporotic mice, The Anatomical Record Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology, **283**, 380-390 (2005)
4. H. Gao, Application of fracture mechanics concepts to hierarchical biomechanics of bone and bone-like materials, International Journal of Fracture, **138**, 101-137 (2006)

5. L. J. Gibson, The mechanical behaviour of cancellous bone, Journal of biomechanics, **18**, 317-328 (1985)

6. S. C. Cowin, Bone mechanics handbook, (2001)

7. P. D. Delmas, R. P. Tracy, B. L. Riggs, K. G. Mann, Identification of the noncollagenous proteins of bovine bone by two-dimensional gel electrophoresis, Calcified tissue international, **36**, 308-316 (1984)

8. A. Sharir, M. M. Barak, R. Shahar, Whole bone mechanics and mechanical testing, The Veterinary Journal, **177**, 8-17 (2008)

9. J. D. Currey, The effect of porosity and mineral content on the Young's modulus of elasticity of compact bone, Journal of biomechanics, **21**, 131-139 (1988)

10. S. Suresh, Graded materials for resistance to contact deformation and damage, Science, **292**, 2447-2451 (2001)

11. D. G. Steele, C. A. Bramblett, The anatomy and biology of the human skeleton: Texas A&M University Press, (1988)

12. Y.-c. Fung, P. Tong, Classical and computational solid mechanics vol. 1: World scientific, (2001)

13. H. Davies, The timing and distribution of strains around the surface of the midshaft of the third metacarpal bone during treadmill exercise in one Thoroughbred racehorse, Australian veterinary journal, **83**, 157-162 (2005)

14. C. Bitsakos, J. Kerner, I. Fisher, A. A. Amis, The effect of muscle loading on the simulation of bone remodelling in the proximal femur, Journal of biomechanics, **38**, 133-139 (2005)

15. A. Palevski, I. Glaich, S. Portnoy, E. Linder-Ganz, A. Gefen, Stress relaxation of porcine gluteus muscle subjected to sudden transverse deformation as related to pressure sore modeling, Journal of biomechanical engineering, **128**, 782-787 (2006)

16. Y. Zheng, A. F. Mak, Effective elastic properties for lower limb soft tissues from manual indentation experiment, Rehabilitation Engineering, IEEE Transactions on, **7**, 257-267 (1999)

17. A. G. Robling, D. B. Burr, C. H. Turner, Recovery periods restore mechanosensitivity to dynamically loaded bone, Journal of Experimental Biology, **204**, 3389-3399 (2001)

18. C. T. Rubin, L. E. Lanyon, Regulation of bone mass by mechanical strain magnitude, Calcified tissue international, **37**, 411-417 (1985)

19. P. Ammann, R. Rizzoli, Bone strength and its determinants, Osteoporosis International, **14**, 13-18, (2003)

20. S. J. Warden, J. A. Hurst, M. S. Sanders, C. H. Turner, D. B. Burr, J. Li, Bone adaptation to a mechanical loading program significantly increases skeletal fatigue resistance, Journal of bone and mineral research, **20**, 809-816 (2005)

21. N. E. Lane, W. Yao, M. Balooch, R. K. Nalla, G. Balooch, S. Habelitz, et al., Glucocorticoid‐Treated mice have localized changes in trabecular bone material properties and osteocyte lacunar size that are not observed in placebo‐Treated or estrogen‐

deficient mice, Journal of bone and mineral research, **21**, 466-476 (2006)

22. S. Judex, X. Lei, D. Han, C. Rubin, Low-magnitude mechanical signals that stimulate bone formation in the ovariectomized rat are dependent on the applied frequency but not on the strain magnitude, Journal of biomechanics, **40**, 1333-1339 (2007)

23. E. Linder-Ganz, N. Shabshin, Y. Itzchak, and A. Gefen, Assessment of mechanical conditions in sub-dermal tissues during sitting: A combined experimental-MRI and finite element approach," Journal of biomechanics, **40**, 1443-1454 (2007)

24. J. Katz, The biophysical and biomechanical properties of bone, bone-mineral and some synthetic bone biomaterials, bulletin de la Société chimique de France, 514-518 (1985)

25. J. Nowinski, C. Davis, The flexure and torsion of bones viewed as anisotropic poroelastic bodies, International Journal of Engineering Science, **10**, 1063-1079 (1972)

26. R. B. Bach, D. Burr, N. A. Sharkey, Skeletal tissue mechanics: Springer Science & Business Media, (2013)

27. J. C. Lotz, T. N. Gerhart, W. C. Hayes, Mechanical properties of metaphyseal bone in the proximal femur, Journal of biomechanics, **24**, 317-329 (1991)

28. F. E. Zajac, Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control, Critical reviews in biomedical engineering, **17**, 359-411 (1988)

29. M. Doblaré, J. Garcıa, M. Gómez, Modelling bone tissue fracture and healing: a review, Engineering Fracture Mechanics, **71**, 1809-1840 (2004)

30. D. M. Cullinane, T. A. Einhorn, Biomechanics of bone, Principles of bone biology, **1**, 17-32 (2002)

31. D. T. Reilly, A. H. Burstein, The elastic and ultimate properties of compact bone tissue, Journal of biomechanics, **8**, 393-405 (1975)

32. S. Pietruszczak, D. Inglis, G. Pande, A fabric-dependent fracture criterion for bone, Journal of biomechanics, **32**, 1071-1079 (1999)

33. M. Zhang, Y. Zheng, A. F. Mak, Estimating the effective Young's modulus of soft tissues from indentation tests—nonlinear finite element analysis of effects of friction and large deformation, Medical engineering & physics, **19**, 512-517 (1997)

34. T. J. Hughes, The finite element method: linear static and dynamic finite element analysis: Courier Corporation, (2012)

35. J.-Y. Rho, L. Kuhn-Spearing, P. Zioupos, Mechanical properties and the hierarchical structure of bone, Medical engineering & physics, **20**, 92-102 (1998)

36. T. Gardnera, T. Stoll, L. Marks, S. Mishra, M. K. Tate, The influence of mechanical stimulus on the pattern of tissue differentiation in a long bone fracture—an FEM study, Journal of biomechanics, **33**, 415-425 (2000)

37. V. K. Goel, S. A. Ramirez, W. Kong, L. G. Gilbertson, Cancellous bone Young's modulus variation within the vertebral body of a ligamentous lumbar spine—application of bone adaptive

remodeling concepts, Journal of biomechanical engineering, **117**, 266-271 (1995)

38. B. Van Rietbergen, R. Huiskes, F. Eckstein, and P. Rüegsegger, Trabecular bone tissue strains in the healthy and osteoporotic human femur, Journal of Bone and Mineral Research, **18**, 1781-1788 (2003)

39. B. Van Rietbergen, A. Odgaard, J. Kabel, R. Huiskes, Direct mechanics assessment of elastic symmetries and properties of trabecular bone architecture, Journal of biomechanics, **29**, 1653-1657 (1996)