Bratisl Lek Listy 2008; 109 (9)
383 – 386

PERSPECTIVES

Bone Quality. Elasticity and Strength

J. Wendlova

Derer's University Hospital and Policlinic, Osteologic Centre, Bratislava, Slovakia.
jwendlova@mail.t-com.sk

Abstract: The aim of the article is to explain in more detail the biomechanical methods used in determining bone quality as well as to describe basic characteristic bone qualities resulting from the application of these methods. Mechanical properties of biomaterials are characterised by stress-strain curves, produced on the basis of testing the biomaterials by progressive tensile and compressive load. According to these curves, the bone counts among brittle materials. Stress-strain curves under tensile and compressive load for brittle materials comprise proportional limit, elastic limit, and breaking strength. Recognition of biomechanical characteristics of bone quality (proportional limit, elastic limit, breaking strength) helps physicians to understand the importance of measuring the new parameters in bone densitometry by DXA (dual energy X-ray absorptiometry) such as femoral strength index (FSI), and safety factor (SF) *(Fig. 2, Ref. 10).* Full text (Free, PDF) *www.bmj.sk.*
Key words: bone quality, biomechanics, proportional limit, elastic limit, breaking strength, compressive load, tensile load.

The quality of osteoporotic bone, elasticity and strength of bone – these are the terms often used in professional osteological literature and at scientific congresses, however, to many physicians the substance of these terms remains unclear. The aim of this article is to explain in more detail the biomechanical methods used in determining bone quality as well as to describe basic characteristic bone qualities resulting from the application of these methods.

Biomaterials may be divided into brittle and tenacious ones according to their mechanical reaction to simple tensile and compression stress. Brittle materials deteriorate by very slight and permanent deformations. Tenacious materials deteriorate after a major and permanent deformation. Mechanical properties of biomaterials are characterised by stress-strain curves, produced on the basis of testing the biomaterials by progressive tensile and compressive load. According to these curves, the bone counts among brittle materials. Stress-strain curves under tensile and compressive load for brittle materials comprise proportional limit, elastic limit, and breaking strength. Regarding the definitions of elasticity and strength, we can state that if the total strain, produced by external load, exceeds the elastic limit of the strained bone, the bone suffers plastic deformation, and exceeding the strength limit leads to bone fracture.

To understand completely the mechanical properties of biomaterials during tensile and compressive load, we have to put them to tests.

Derer's University Hospital and Policlinic, Osteologic centre, Bratislava, Slovakia

Address for correspondence: J. Wendlová MD, PhD, Krizna 30, SK-811 07 Bratislava, Slovakia.

The quality of healthy or osteoporotic bone can be *objectively determined* in biomechanics by destructive methods.

Test bone or its sample is inserted into a special device so that two opposite ends are firmly fixed in the direction of linear axis. Afterwards, the tested sample is gradually loaded by growing tensile or compressive forces until these forces reach the values by which the bone breaks. Measurement results are illustrated by diagrams.

Determination of mechanical properties of bones

Diagrams are constructed in two variants according to the character of variables put onto coordinate axes *x* and *y*:

1. Diagram of tension (compression) test
2. Stress – strain curve under tensile (compressive) loading

Diagram of compression test for bone (Fig. 1a) (1, 2, 3)

We put the gradually increasing values of **compressive force** F_c on the bone in Newtons (*N*) on the *y* axis, and the values of the **absolute shortening of bone** Δl (*mm*) on the *x* axis.

Absolute shortening:

$$\Delta l = \frac{F \times l}{E \times P}$$

Up to the point of yielding (A), shortening of the bone is directly proportional to the compressive force magnitude, and whenever the application of compressive force stops, the bone regains its original length, as its deformation has been only tem-

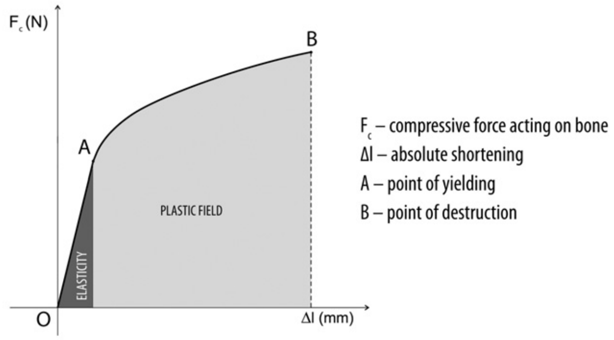

Fig. 1a. Diagram of compression test for bone.

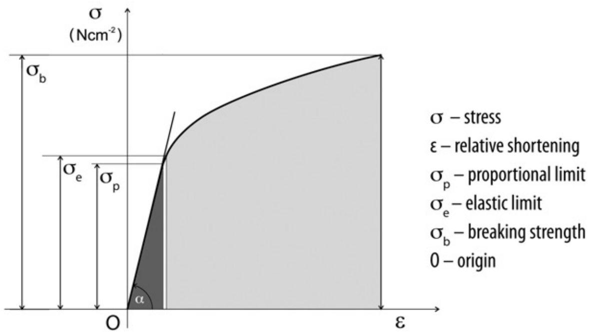

Fig. 1b. Stress-strain curve under compressive loading for bone.

porary (reversible). This part of the diagram is called: bone elasticity. Beyond the point of yielding there is a plastic region, corresponding to bone toughness. Increasing the compressive force results in further shortening of the bone, however, permanent deformations caused by the compressive force persist even after the removal of the compressive force. It is a case of plastic deformation of the bone. The bone begins to crack in the breaking point (B), and increasing the magnitude of applied compressive force completely disrupts its integrity.

Stress-strain curve under compressive loading for bone (Fig. 1b) (5, 6, 7)

The stress values $\boldsymbol{\sigma}$ (Ncm^{-2}) developed during loading the bone by compressive force are put on the ***y*** axis, and the values of relative shortening $\boldsymbol{\varepsilon}$ (non-dimensional number) on the *x* axis.

Stress: $\sigma = \frac{F}{P}$

Relative shortening: $\varepsilon = \frac{\Delta l}{l}$

Hooke's law (law of elasticity): $\Delta l = \frac{F \times l}{E \times P}$

Elasticity modulus under compression:

$$E = \frac{F \times l}{\Delta l \times P} \qquad E = \frac{\sigma}{\varepsilon}$$

F – compression force applied to the bone
P – the section area of the bone, to which the force is applied
l – the length of the test bone sample
E – proportionality coefficient (elasticity modulus under compression)

The diagram includes all magnitudes of tension, characterising mechanical properties of the bone: proportional limit, elastic limit, breaking strength.

The highest value of stress in the bone conditioned by its compressive load, when the Hooke's law still applies, is called a proportional limit. The highest value of stress, when still elastic reversible deformations occur, is called an elastic limit. Points for proportional limit and elastic limit are so close that they are usually considered to be identical.

The stress generated by compressive force, which causes the development of first cracks in the bone, is called a strength limit.

Elasticity modulus (E) under compression for bone

The ratio of the stress under compression for bone (σ) and the relative shortening of bone (ε) is defined as a modulus of elasticity under compression for bone and is a constant of the Hooke's law.

Elasticity modulus is proportional to the gradient (inclination angle tangent α) of the linear part of the diagram curve from zero stress (σ_0) up to proportional limit (σ_p).

Elasticity modulus under compression for bone is a number characterising the bone behaviour under compressive load. The higher the elasticity modulus, the higher stress is needed to achieve bone deformation.

Diagram of tension test for bone (Fig. 2a) (1, 2, 3, 4)

Gradually increasing values of **tensile force F_t** on the bone in Newtons (*N*) are put on the ***y*** axis, and the values of the **absolute extension of bone Δl** (*mm*) on the ***x*** axis.

Absolute extension (Δl):

$$\Delta l = \frac{F \times l}{E \times P}$$

Up to the point of yielding (A), the extension of the bone is directly proportional to the tensile force magnitude, and whenever the application of tensile force stops, the bone regains its original length, as its deformation has been only temporary. This part of the diagram is called: bone elasticity. Beyond the point of yielding there is a plastic region, corresponding to bone toughness. Increasing the tensile force results in further extension of the bone, however, permanent deformations caused by the ten-

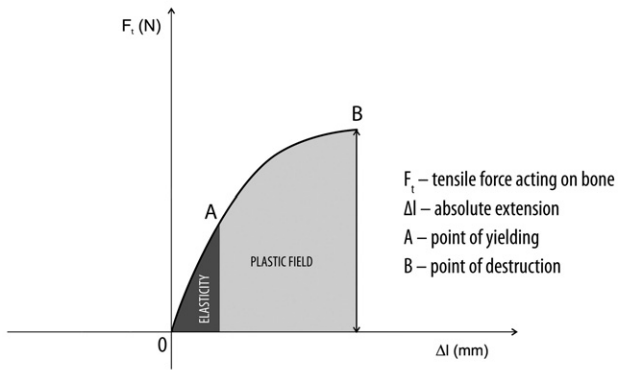

Fig. 2a. Diagram of tension test for bone.

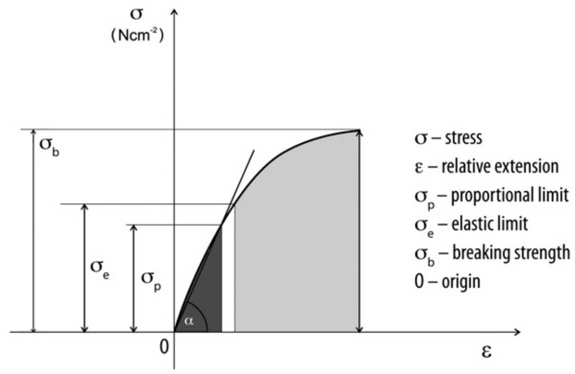

Fig. 2b. Stress-strain curve under tensile loading for bone.

sile force persist even after the removal of the tensile force. It is a case of plastic deformation of the bone. The bone begins to crack in the breaking point (B), and increasing the magnitude of applied tensile force completely disrupts its integrity.

Stress – strain curve under tensile loading for bone (Fig. 2b) (7, 8, 9)

The stress values $\boldsymbol{\sigma}$ (Ncm^{-2}) developed during loading the bone by tensile force are put on the axis ***y***, and the values of relative extension $\boldsymbol{\varepsilon}$ (non-dimensional number) $\boldsymbol{\varepsilon}$ on the axis ***x***.

Tension: $\sigma = \frac{F}{P}$

Relative extension: $\varepsilon = \frac{\Delta l}{l}$

Hooke's law (law of elasticity): $\Delta l = \frac{F \times l}{E \times P}$

Elasticity modulus under tension:

$$E = \frac{F \times l}{\Delta l \times P} \qquad E = \frac{\sigma}{\varepsilon}$$

F – tensile force applied to the bone
P – the section area of the bone, to which the force is applied
l – the length of the test bone sample
E – proportionality coefficient (elasticity modulus under tension)

The diagram includes all magnitudes of stress, characterising mechanical properties of the bone: proportional limit, elastic limit, breaking strength.

The highest value of stress in the bone conditioned by its tensile load, when the Hooke's law still applies, is called a proportional limit. The highest value of stress, when elastic reversible deformations still occur, is called an elastic limit. Points for proportional limit and elastic limit are so close that they are usually considered to be identical.

The stress generated by tensile force, which causes the development of first cracks in the bone, is called a strength limit.

Elasticity modulus (E) under tension for bone

The ratio of the stress under tensile force for bone (σ) and the relative extension of bone (ε) is defined as a modulus of elasticity under tension for bone and is a constant of the Hooke's law.

Elasticity modulus is proportional to the gradient (inclination angle tangent α) of the linear part of the diagram curve from zero stress (σ_0) up to proportional limit (σ_p).

Elasticity modulus under tension for bone is a number characterising the bone behaviour under tensile load. The higher the elasticity modulus, the higher stress is needed to achieve bone deformation.

When comparing the diagram of stress and strain under compression and tension for bone (the diagram of compression and tension tests for bone), we find out that the bone has higher resistance to compressive than to tensile load.

Conclusion

The characteristics of osteoporotic bone quality, which determines risk of fractures, is based on biomechanical principles.

Recognition of biomechanical characteristics of bone quality (proportional limit, elastic limit, breaking strength) helps physicians to understand the importance of measuring the new parameters in bone densitometry by DXA (dual energy X-ray absorptiometry) such as: femoral strength index (FSI), and safety factor (SF). Formulas of these parameters use the characteristics from stress-strain curves for loading the bone by tension and compression (10). More accurate estimate of the risk of osteporotic fractures development is provided by FSI and SI, as compared to currently used BMD (bone mineral density) values, and these parameters are applied in osteological practice with success.

On the contrary, misinterpretation of basic biomechanical relations by medical professional community leads often to the lack of interest in the new methods based on biomechanical principles and delays their implementation in clinical praxis. Even clinical physicians have to understand that biomechanics is becoming an indivisible part of medicine and is contributing to the improvement of diagnostic and therapeutic methods.

References

1. Obetková V, Mamrillová A, Košinárová A. Teoretická mechanika. Bratislava, ALFA 1990, p. 30–94.

2. Adamča LF, Marton P, Pavlík M, Trávníček F. Teoretická mechanika. Bratislava, ALFA 1992, p. 27–37.

3. Bono CM, Einhorn TA. Overview of osteoporosis: pathophysiology and determinants of bone strength. Europ Spine J 2003; 12: 90–96.

4. Chao EY, Inoue N, Koo TK, Kim YH. Biomechanical considerations of fracture treatment and bone quality maintenance in elderly patients and patients with osteoporosis. Clin Orthop Rel Res 2004; 25: 12–25.

5. Lohfeld S, Barron V, Mc Hugh PE. Biomodels of bone: A review. An of Biomed Engineering 2005;10: 145–150.

6. Burr DB. Biomechanics. Clin Rev Bone Miner Metab 2006; 3: 112–117.

7. Einhorn TA, Azria M, Goldstein SA. Stress-strain curve for bone. 13–14. In: Einhorn TA, Azria M, Goldstein S (Eds). Bone fragility. The biomechanics of normal and pathological bone, Sandoz 1992.

8. Özkaya N, Nordin M. Fundamentals of biomechanics: Equilibrium, motion and deformation. New York, Springer Verlag 1999, 45–51.

9. Routh RH, Rumancik S, Pathal RD, Burshell LA, Nauman AE. The relationship between bone mineral density and biomechanics in patients with osteoporosis and scoliosis. Osteoporosis International 2005; 16 (12): 116-122.

10. Faulkner KG, Wacker WK, Barden HS, Simonelli C, Burke PK, Ragi S, Del Rio L. Lemur strength index predicts hip fracture independent of bone density and hip axis length. Osteoporos Int 2006; 17 (4): 593–599.

Received April 22, 2008.
Accepted June 20, 2008.