Evaluation of a New Index of Bone Structure Load Bearing Capability

Francesca Cosmi[1], Diego Dreossi[2]
[1] Energetics Department, University of Trieste, Italy
[2]Physics Department, University of Trieste, Italy
Corresponding author: F. Cosmi, Energetics Dept.,University of Trieste,via A. Valerio 10, 34127 Trieste, cosmi@units.it

This paper introduces a new system that aims at giving an indication on bone structure load bearing capability and its pathological modifications, and may be regarded as a complement to the diagnosis methodologies that are now in use.
Starting from digital radiographic images, a numerical model is used to estimate the elastic properties of the examined trabecular bone architecture, which are related to the bone load bearing capabilities. The system is currently being subjected to a first clinical validation.

INTRODUCTION

Osteoporosis is defined as a disease characterized by low bone mass and micro-architectural deterioration of bone tissue, leading to an enhanced bone fragility and a consequent increase in fracture risk (1). This definition underlines how fracture risk doesn't depend on bone mineral content alone: bone strength is also strongly influenced by the trabecular arrangement in space.
At present there are no accurate ways to measure bone strength in clinical practice. Bone mineral density (BMD) measures the demineralization of the bones and is used to determine if a patient has osteoporosis and/or is at risk for bone fracture. This test also helps to monitor the effectiveness of treatment.
In particular, DEXA is the current gold standard for measuring bone density. This specialized x-ray technique can detect changes in bone mass using a comparison of normal, healthy individuals of the same gender. Two or more DEXA studies on the same person over time (usually one or two years apart) allow changes in bone mass to be determined. Bone density in the hip, spine, or wrist can be measured. The World Health Organization (WHO) operationally defines osteoporosis as bone density 2.5 standard deviations below the mean (T-score ≤ –2.5) for young white adult women. (This does not apply to men or children).
For advanced osteoporosis, simple X-ray measurements e.g. loss of vertebral height, can be used to confirm the diagnosis.
Recently, quantitative ultrasound techniques (QUS) have been introduced. They measure the changes in amplitude and speed of the ultrasound beam as it passes bone (usually heel or finger). These factors depend on bone structure, elasticity, and strength and may help the physician in assessing the fracture risk
While measuring the amount of calcium in urine is of limited value, a number of newer tests to evaluate bone turnover are becoming available and in the future they may become of help in the diagnosis of early osteoporosis.
Other research approaches have been focusing on the second mentioned aspect of osteoporosis, that is the micro-architectural deterioration of bone tissue. In fact, the 3D architecture of bone biopsies is accessible by technique such as μCT (2) and μMRI (3) and a lot of effort has been aimed at estimating bone strength through the assessment of bone elastic properties, as obtained from morphological parameters and μFEA analysis (4), (5), (6), (7), (8), (9), (10).
Although μFEA is a very powerful tool, its clinical use does not seem likely in the near future. In fact, *in-vivo* 3D scans leading to a definition of the trabecular architecture that is sufficiently accurate for μFEA are not largely diffused yet. Moreover, it is very difficult to obtain an accurate estimate of human trabecular bone mechanical properties because the characteristic length of intertrabecular spacing is of the same order of magnitude as the characteristic length of architectural heterogeneities and specimen size (5). Besides, μFEA implies the use of millions of elements to describe the complex 3D trabecular structure. This drawback essentially derives from limits imposed by the mathematical differential formulation on which the Finite Element Method is based. Therefore, modeling of structures with this degree of complexity becomes a prohibitive task or leads to unacceptable simplifications.
This paper introduces a new method that aims at giving an indication on bone structure load bearing capability and its pathological modifications. This exam can be easily introduced in clinical use, is not expensive and may be regarded as a complement to BMD and to the diagnosis methodologies that are now in use.
The system is currently being subjected to a first clinical validation at the Azienda Sanitaria n.2- Gorizia.

MATERIAL AND METHODS

The proposed method is based on numerical simulations on a structure obtained from high definition digital radiographic images of the examined bone tissue, in this specific application the base of the proximal phalanxes of the non-dominant hand.
The before mentioned drawbacks have been overcome. A recently developed numerical method, the Cell Method (CM), has been employed. The Cell Method

(11) is based on a direct discrete formulation of equilibrium equations, thus avoiding the need for a differential formulation of balance. Numerical results obtained in structural problems (in 2D and 3D) with the Cell Method are comparable with, and in some cases even better than, the ones achieved with Finite Elements (12). One of the consequences of the Cell Method approach is that the characteristic length of the elementary cell of the discretization may be of the same order as the heterogeneities of the structure. For example, the results obtained simulating the mechanical behaviour of porous materials such as sintered alloys are in very good agreement with experimental data (13).
It is true that an accurate representation of the trabecular bone architecture can be only achieved with a complete 3D reconstruction; nevertheless, a considerable amount of information (although at the price of a loss in accuracy) can be extracted also from 2D representation of the structure, as achievable from high-resolution digital radiographies. The first tests confirm that the amount of information retained in the 2D representation may be sufficient to give an indication of the structure load bearing capabilities and complement the conventional information for the osteoporosis diagnosis and the determination of the fracture risk.
The main purpose of the paper is to illustrate the proposed methodology, while an exhaustive discussion of the clinical tests performed on 98 subjects will be the object of a successive work.
A digital radiographic image of a human hand, obtained by means of a digital radiography with a flat panel produced by General Electric, is processed. The investigation is performed in a trabecular zone identified inside the radiographic image. In this specific case, in the proximal zone of the first phalange of the index finger was selected, although, obviously, also the other fingers and many other parts of the body can be used. An example is shown in Fig.1.

Figure 1. The radiographic hand image (left), a zoom of the region of interest (upper right) and the trabecular zone at the base of the phalanx selected for the structural analysis (bottom right).

The image of the zone identified is oriented so as to have the horizontal direction, axis x, orthogonal to the direction of the finger and the vertical direction, axis y, along the phalange (fig.3).

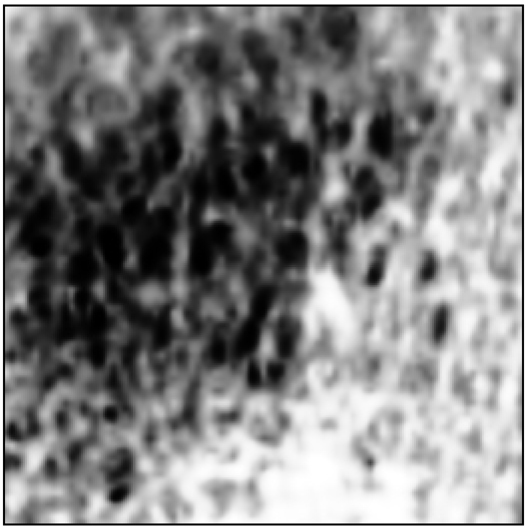

Figure 2. The region of analysis.

The bone matrix is extracted by means of applying particular non-linear filters (in this specific case a sub-threshold erosion filter). After processing, each pixel of the image in the selected zone has a value of the shade between 0 and 255. The result can be represented graphically with an image of the type shown in fig. 3.

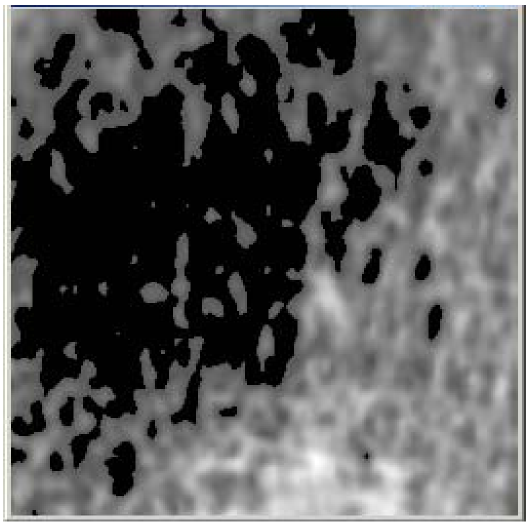

Figure 3. The region of analysis after filtering.

On the resultant image a grid of nodes was deposited. The nodes are automatically connected together to form the mesh, a complex of triangular cells, as shown in fig.4.
An index is then attributed to each cell. It is obtained by adding together the values of the shade in the vertexes, barycentre and middle points of the sides of the cell, and by normalizing the result to 1. The physical significance

of this index characterizing the cell is that it represents an indication of the matter content in the cell. Fig. 5 shows the result of this operation.

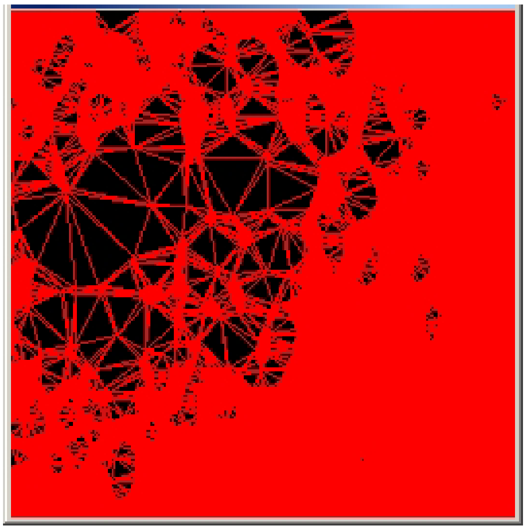

Figure 4. The mesh obtained from fig.3, 19487 nodes.

In order to characterize the structure ability to bear the load, an elastic-linear isotropic constitutive law was assumed. The Poisson ratio is assumed equal to 0.3. The cells with an index of 0 do not possess any mechanical characteristics. In the cells with an index of 1, the Young (elastic) module was assumed equal to 1 GPa. In the cells that have intermediate index values, the Young module was related to the value of the cell index. For example, if in a cell the index is 0.5, the elastic module of the cell is set to 0.5 GPa, and so on. Fig. 4 is therefore also representative of the values assumed by the Young module of each cell.
A content factor *CF* can be defined for the whole structure as the sum of all the indexes of the cells, divided by the number of cells.

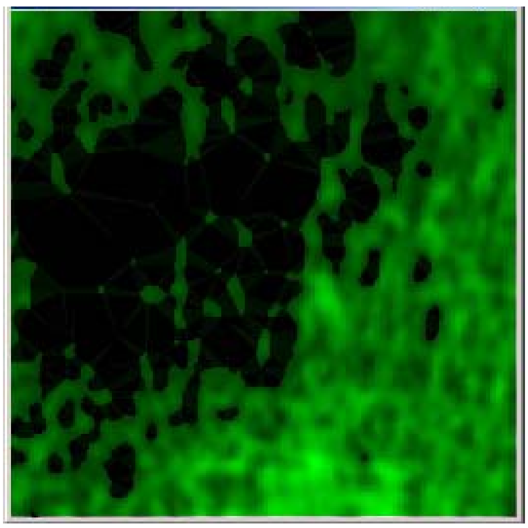

Figure 5. Representation of the cells index (and elastic modulus values) for the mesh in fig.3.

The model so obtained was then subjected to two simulated compression tests with the Cell Method, one along each side of the image (x and y axes). The result of the simulations was the compression value of the apparent Young modulus E_x, E_y in the two directions for the structure modelled starting from the digital radiography examined.
The content factor *CF* and the compression elastic modulus E_x, E_y of the structure were further elaborated to define a structure parameter, *SP*:
$SP = (E_x + E_y - 1000^* CF)/100$,
which is indicative of the structure load bearing capabilities and consequent fracture risk.

RESULTS AND DISCUSSION

A first clinical validation of the test is currently being conducted and its results will be the object of further work. In this paper, to give an example of the method, two cases are presented.
The first is a clinically positive (DEXA T-score = –3.33 in the hip) female aged 59 with recognized osteoporosis. A digital radiography of her non-dominant left hand has been taken with a flat panel produced by General Electric in a hospital department. Figures from 1 to 4 refer to this analysis.
The second is a clinically negative female, aged 42, with no sign of osteoporosis. A digital radiography of her non-dominant left hand has been taken in the same conditions. The region of analysis is shown in fig.6.

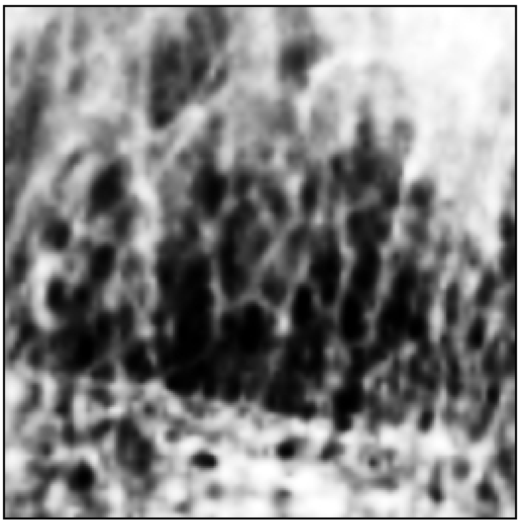

Figure 6. The region of analysis for the second subject.

The trabecular structures visible in the picture in this second case are different from those of the first one. The method presented allows a quantitative analysis of these differences.
The mesh employed for the structural analysis in the second case is shown in fig. 7.
Results of the analysis performed on the two subjects are shown in Table 1. The time required for the entire

image elaboration plus model computation was a few minutes on a common PC.

Table 1. Results.

Subject	*CF*	E_x	E_y	*SP*
1	0.485	310	321	1.46
2	0.594	430	406	2.42

The elastic modulus computed in the *x* direction is different from the one along *y* in both subjects, confirming the method's ability to identify a certain degree of anisotropy in the microstructure examined. Moreover, the structure parameter *SP* (and, to a lower degree, the elastic modulus E_x and E_y) of the first subject exhibited lower values than those found in the second subject. This result is due to the different resistance of the two structures examined, depending on the presence, in the first case, of pathology.
In general, preliminary findings indicate that *SP* values lower than or equal to 1.7 are indicative of high fracture risk, while values larger than 2.0 are related to low fracture risk.

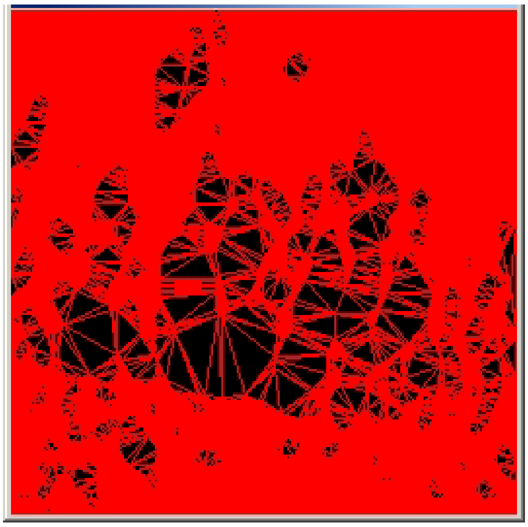

Figure 7. The mesh obtained from fig.5, 20786 nodes.

CONCLUSIONS

The modifications in the trabecular structure due to osteoporosis have been detected and quantified by a new method. The system, based on an application of the Cell Method, estimates a new index related to the elastic properties and load bearing capabilities of the trabecular structure as obtained from digital radiographic images. Examples of the application of the method have been given. The system is currently being subjected to a first clinical validation.

Acknowledgements

The Area Science Park project SISTER, founded by FVG Region, financially supported the work presented in this paper. The image acquisitions and clinical evaluations were performed by proff. Moro and Rizzatto and their staff at CSMMO (University of Trieste and Azienda Sanitaria n.2 Isontina), Gorizia.
Patent: PCT WO03/082118 2002, deposited by University of Trieste.

References

1 Consensus development conference. Diagnosis, prophylaxis and treatment of osteoporosis, AM J Med 94; 1993: 646-650.

2 Feldkamp L.A., Goldstein S.A., Ciarelli M.J., et al. The relationship between the structural and orthogonal compressive properties of trabecular bone. J. Bone and Mineral Research 1989, 4, 3-11.

3 Chung H., Wehrli F.W., Williams J.L. et al. Relationship between NMR transverse relaxation, trabecular bone architecture, and strength. Proc. of the National Academy of Sciences 90, 1993, 10250-4.

4 Homminga J., Mccreadie B.R., Weinans H., Huiskes R. The dependence of the elastic properties of osteoporotic cancellous bone on volume fraction and fabric. J. Biomechanics 2003, 36, 1461-7.

5 Zysset P.K. A review of morphology-elasticity relationhips in human trabecular bone: theories and experiments. J. Biomechanics 2003, 36, 1469-85.

6 Van Rietbergen B., Odgaar A., Kabel J., Huiskes R., Direct Mechanics Assessment of Elastic Symmetries and Properties of Trabecular Bone Architecture, J. Biomechanics1996, 29(12): 1653-7.

7 Kabel J., Odgaard A., Van Rietbergen B., Huiskes R., The relation between connectivity and elastic proprierties of cancellous bone, Bone1999, 24: 115-20.

8 Ulrich, D., van Rietbergen B., Weinans H., Rüegsegger P. Non-invasive bone biopsy: a new method to analyse and display the three-dimensional structure of trabecular bone. J. Biomechanics 1998, 31, 1187-92.

9 Niebur G.L., Feldstein M.J., Yuen J.C., Chen T.J., Keaveny T.M. High resolution finite element models with tissue strength asymmetry accurately predict failure of trabecular bone. J. Biomechanics 2000, 33, 1575-83.

10 Homminga J., Huiskes R., Van Rietbergen B., Rüegsegger P., Weinans H. Introduction and evaluation of a gray-value voxel conversion technique. J. Biomechanics 2001, 34, 513-17.

11 Tonti E. A Direct Discrete Formulation of Field Laws: The Cell Method. CMES 2001, 2, 237-8.

12 Cosmi F. Numerical Solution of Plane Elasticity Problems with the Cell Method. CMES 2001, 2, 365-72

13 Cosmi F. Numerical Modelling of Porous Materials Mechanical Behaviour with the Cell Method. Proc. of the Second M.I.T. Conference on Computational Fluid and Solid Mechanics, Cambridge MA, USA, 17-20 June, 2003