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## **BONE SINTERING FOR STRENGTH ASSESSMENT: FIRST RESULTS IN BOSSA PROJECT**

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### **Summary**

Bone fracture risk is strongly related not only to the mass content, but also to the bone micro-architecture. While the compressive strength of cancellous bone is proportional to its Young modulus, it is unfortunately impossible to perform mechanical tests *in vivo*. Three-dimensional numerical analysis of bone volumes has proved an important tool in this field, but when comparing simulation results with experimental ones there are some unavoidable uncertainties. Experimental tests are also affected by intrinsic difficulties that are amplified, as the test is unique and unrepeatable.

The aim of this work is to show that sintered replicas of the examined bone portion - built by rapid prototyping in a relatively homogeneous and well characterized material - can be used in mechanical tests to assess the bone architecture load bearing capabilities and provide a validation tool for numerical simulations.

*Key words: bone mechanics, rapid prototyping, mechanical testing, computed tomography*

## 1. Introduction

The onset of osteoporosis and the consequent fracture risk are known to depend on two factors: bone mass content and trabecular micro-architecture [1]. Conventional diagnosis techniques focus on the first aspect, but, in order to achieve a deeper understanding of bone strength modifications, a lot of research activities have been carried on in the effort of quantifying also the influence of bone micro-structural arrangement changes.

While *in vitro* medical imaging techniques allow the definition of trabecular architecture, the problem of its influence quantification has not been solved yet, although several methods have been proposed.

Studies on osteoporosis, osteoarthritis and orthopedic implants would greatly benefit from a better, quantitative understanding of the factors that influence the mechanical properties of trabecular bone.

*In vitro* mechanical tests on bone samples are affected by intrinsic difficulties, whose effect is amplified by the uniqueness of the sample and the impossibility to repeat the test.

A characterization of elastic properties of cancellous bone with traditional mechanical tests could appear simple, but is affected by two major problems:

1. trabecular bone anisotropy, that makes elastic behavior description a prohibitive task, involving up to 21 elastic constants [2];
2. errors and difficulties that affect mechanical tests, such as specimen geometry, friction at endplates, structural end phenomena, storage, continuum assumption, viscoelasticity and temperature effects[3].

The consequences are errors in stiffness and strength determination. Moreover, inaccuracy might vary with the trabecular architecture, making it impossible to detect those effects of microstructure changes that are the aim of the research itself.

Three-dimensional numerical analysis of bone volumes has proved an important tool in this field [4–9], but when comparing simulation results with experimental ones again new uncertainties add up, for example in the definition of the elastic properties for the bone phase to be used in the simulations.

Rapid prototyping is known to be a technology that can be used to manufacture complex 3D structures with open cavities in a relatively homogeneous and well-characterized material.

The BOSSA project aims to overcome some of the problems encountered when addressing the quantification of bone micro-architecture by applying selective laser sintering for bone samples reconstruction.

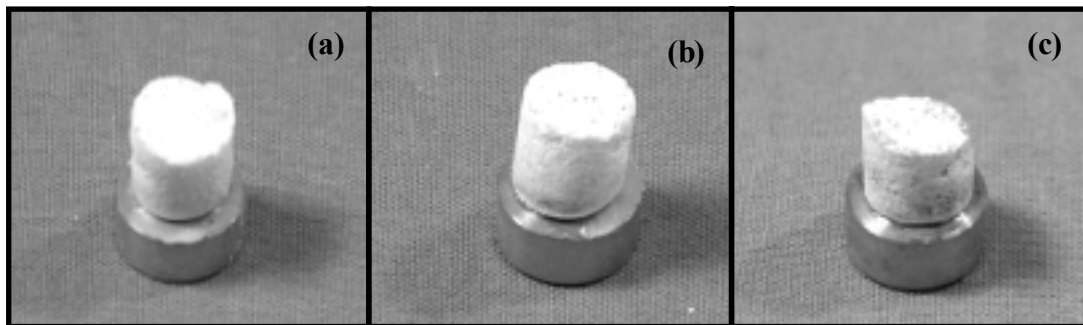
From 3D reconstructed images obtained by  $\mu$ CT with synchrotron radiation, replicas of trabecular bone have been manufactured by rapid prototyping. Such replicas provide an important tool for enhanced visualization [10–12] and have now been used in mechanical tests to assess the bone architecture load bearing capabilities. Moreover, they can be employed as a validation tool for the numerical simulations.

## 2. Materials and Methods

Three cylindrical samples of trabecular bone (Fig.1) were taken from different pig shoulder sites:

- (a) and (b) from an *in vivo* loaded regions,
- (c) from an *in vivo* weakly loaded region.

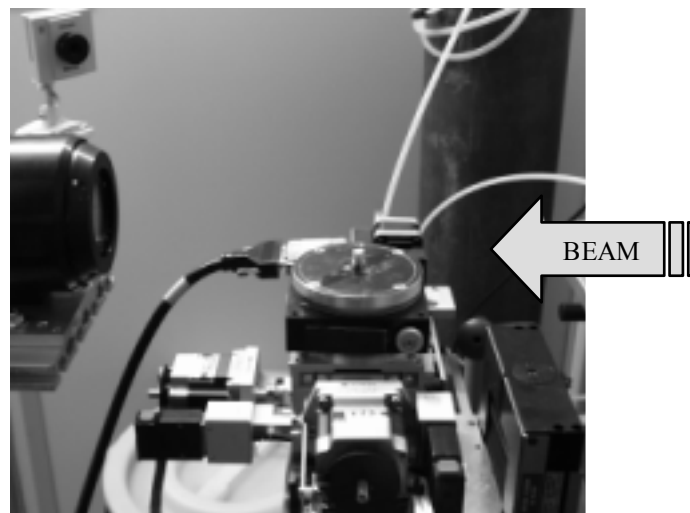
The samples, approximately 8 mm in diameter and from 5 mm to 8 mm high, were stabilized by chemical treatment and were glued to a brass holder.



**Fig. 1** The samples: (a) and (b) from an *in vivo* loaded regions, (c) from a weakly loaded region

At Elettra SYRMEP beamline, in Trieste, the samples were subjected to  $\mu$ CT. Synchrotron radiation consists in a monochromatic X-ray beam and is characterized by energy tuneability and high photon flux.

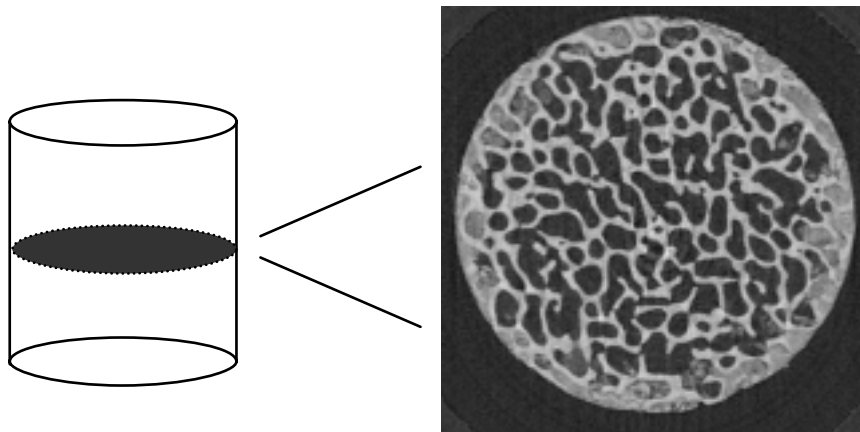
The sample, visible at the center of Fig.2, is placed on a rotary table, aligned by a system of orthogonal cradles. The CCD, a 16 bit 2048x2048 matrix with 14 micron pixel size camera, is equipped with a Gadolinium Oxy sulfide screen 20 micron thick.



**Fig. 2** The set-up at Elettra - SYRMEP beamline

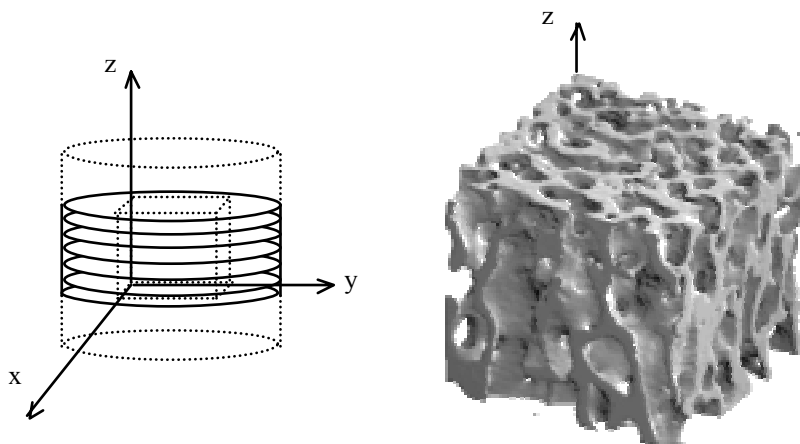
The radiographic images obtained were elaborated and filtered. The  $\mu$ CT yields a series of X-ray based cross-sectional images – tomographies – of the examined sample, in which the trabecular structure is clearly visible. One of the tomographies obtained in one of the samples is shown in Fig. 3. For each sample, the complete set of tomographies showing the internal micro-architecture was obtained.

These 2D images were further elaborated, stacked using a modified marching-cube algorithm. A reconstructed 3D image of a cubical portion of the examined trabecular bone phase was thus obtained. An example of the final result of the image elaboration is shown in Fig.4.



**Fig. 3** The trabecular structure in a cross-sectional image of the sample.

As already mentioned, the samples come from sites that *in vivo* are subject to a different stress distribution, and are consequently arranged in different microstructures depending on load intensity and direction.



**Fig. 4** The 3D image reconstruction of a cubical portion of trabecular bone.

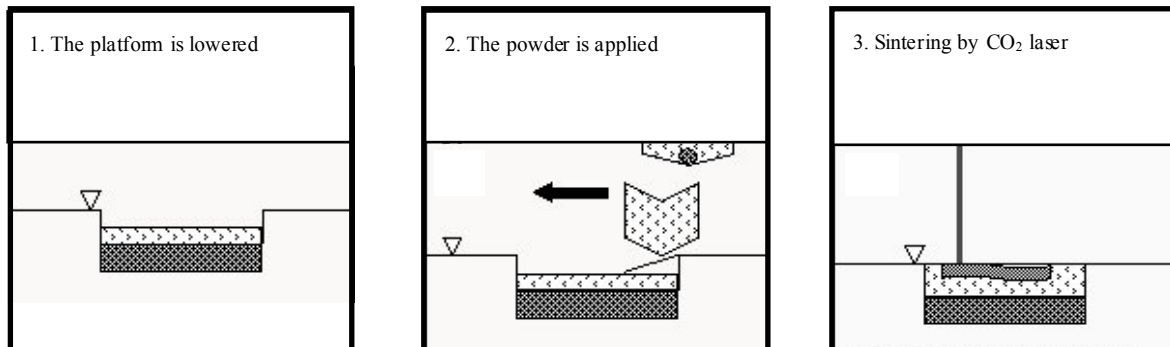
The experimental testing of *in vitro* bone specimen is a task affected by major intrinsic difficulties. Unavoidable uncertainties in the tests results are due to specimen geometry, friction at endplates, structural end phenomena, storage, viscoelasticity and temperature.

All of these difficulties and error sources are amplified by the fact that the sample is unique and the test cannot be repeated. The error magnitude will in turn depend on the particular arrangement of the trabecular structure. The detection of the influence on the bone strength of trabecular micro-structural differences can hence become impossible.

The image 3D reconstruction was thus used to obtain replicas of the examined bone portions built by rapid prototyping.

The availability of a 3D physical reconstruction consented to perform the mechanical tests not on the original samples, but on the sintered replicas, built in a relatively homogeneous and well-characterized material. Thus, the experimental test is more reliable as it can be repeated along the same axis. Moreover, it is possible to perform tests along different axes on the replicas of the same bone portion, providing a measure for the local structural anisotropy.

The selective laser sintering (SLS) process has been employed. This sintering process is a Layer Manufacturing Technology (LMT), where parts are manufactured layer by layer from polyamide powder with the help of a CO<sub>2</sub> laser. The process is illustrated in Fig.5.



**Fig. 5** The selective laser sintering process.

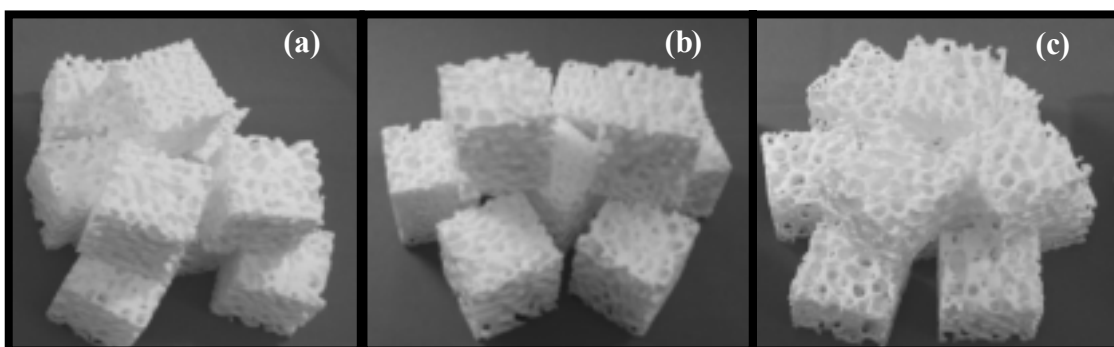
Complex structures with internal open cavities, such as the trabecular architecture, can be built with this recent technology.

In input, a CAD definition of the object had to be created from the reconstructed 3D image [13, 14]. This task is critical, as this conversion can easily produce geometrically incompatible models.

A procedure involving the following three steps was developed to achieve this task:

1. An intermediate representation, by means of triangles, of the surface of the object to be manufactured is obtained (iso-surface generation);
2. The triangles vertexes are used to create a DXF file representing the aforementioned surface;
3. A commercial program is employed for the DXF file conversion in a rapid prototyping STL file format.

A set of 9 prototyped replicas was obtained for each sample, as shown in Fig.6. The replica side was 50 mm, corresponding to 2.8 mm in the original bone.



**Fig. 6** The replicas obtained by rapid prototyping.

### 3. Results

Within each set, 3 prototypes were tested in compression along each axis of a reference frame parallel to the replicas sides and with z-axis along the extraction direction of the sample (approximately along *in vivo* load flux).

The elastic modulus obtained from the experimental stress was chosen as a measure of the architectural arrangement contribution to the bone trabecular strength. In fact, the compressive strength of cancellous bone widely recognized to be proportional to its elastic modulus [15, 16].

The elastic modulus of sintered polyamide samples is 1050 MPa and can be considered independent of direction.

The Young modulus values obtained by the test performed with a Shimadzu machine on the sintered replicas are summarized in Table 1, where the average weight  $w$  of the replicas is also shown.

The replicas were manufactured simultaneously and therefore were not expected to differ in powder composition, but differences appeared in the measured value of the elastic modulus along a direction also for samples belonging to the same set.

*A posteriori* it was recognized that these discrepancies were mainly caused by differences in the temperature achieved in particular positions within the creation chamber during the sintering process. Values in brackets refer to the samples.

**Table 1** Elastic modulus  $E_x$ ,  $E_y$ ,  $E_z$  and average weight  $w$  of the sintered replicas

	$E_x$ (MPa)	$E_y$ (MPa)	$E_z$ (MPa)
(a) - load bearing $w = 61$ g	<b>402, 413</b> (575)	<b>426, 444</b> (615)	<b>339, 401</b> (522)
(b) - load bearing $w = 59$ g	<b>472, 475, 476</b>	<b>462, 498</b> (619)	<b>386, 400</b> (727)
(c) - weakly loaded $w = 36$ g	<b>291, 328</b> (398)	<b>377, 398</b> (558)	<b>283, 318</b> (190)

Besides these considerations, some interesting aspects emerge.

First of all, it can be noted that both load-bearing structures exhibit higher values of elastic modulus than the weakly loaded region. This behavior confirms their higher ability to carry the load at a micro-architectural level.

Load bearing samples come from regions that in vivo are subjected to different load distributions, and are consequently expected to exhibit different trabecular structures. The measured Young modulus values confirm this hypothesis. For example, the different structural arrangement explains why the elastic modulus of sample (a) along  $z$ -direction is very close to the elastic modulus of sample (c) along  $y$ -direction, although the weight of sample (a) is almost double of that of sample (b).

The structure extracted from the weakly loaded site is not only characterized by lower average values of the elastic modulus as expected, but it also exhibits a distinct anisotropy.

The use of prototyped replicas for experimental testing has therefore been able to detect the changes due to the micro-structural arrangement in the mechanical behaviour of trabecular bone.

An important aspect that must be underlined is that if sintered replicas are used instead of the original bone sample, then the tests can be repeated to ensure reproducibility. Moreover, replicas of the same bone portion can be tested along different direction, providing a measure for the local structural anisotropy.

#### 4. Conclusions and discussion

A novel application of rapid prototyping has been investigated. It has been shown that sintered replicas of the examined bone portion can be used in mechanical tests to overcome the numerous difficulties encountered in the attempt to quantify the bone architecture load bearing capabilities.

Preliminary results have shown that sintered replicas of trabecular bone portions may help not only visualization but also quantification of bone structure load bearing capabilities.

Several replicas of the same bone portion can be simultaneously built. The tests can be therefore repeated, thus increasing reliability. Moreover, replicas of the same bone portion can be tested along different direction, providing a measure for the local structural anisotropy.

The process of obtaining such replicas involves several crucial steps that have been discussed.

First, a high-resolution 3D reconstruction of the examined bone portion is used to generate a CAD file that must be converted in the proper STL format.

Particular care is also needed during the manufacturing phase because of the parameters influence on reproducibility, with special regard to the position of the samples in the chamber.

More extensive testing is being planned at the moment. The application as a validation tool for numerical simulations is currently being developed.

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