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TRABECULAR BONE MECHANICAL PROPERTIES FROM NORMALS AND PATIENTS WITH HIP FRACTURES DIFFER ON THE APPARENT LEVEL, NOT ON THE TISSUE LEVEL

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Introduction:

Osteoporosis is currently defined in terms of low bone mass. However, the source of fragility leading to fracture has not been adequately described. In particular, the contributions of bone tissue properties and architecture to the risk of fracture are poorly understood. In an earlier experimental study, it was found that the *architectural* anisotropy of trabecular bone from fracture patients was significantly increased compared to age and density matched controls[1]. An alternative explanation for the increased fracture risk may be a decrease in stiffness and strength of the bone tissue material itself. A number of studies concerning tissue properties of individuals with and without fractures suggest that in a fracture group the average tissue density is either unchanged or slightly decreased, and that the number of microcracks in the tissue is unchanged[2,3,4,5,6]. Reductions of these could reduce the strength and stiffness of the tissue material, to find out whether these really were reduced, we extended this earlier work. To estimate the tissue mechanical properties we used micro finite element analysis combined with compression testing. We also calculated other variables which could potentially explain the reduced strength in the fracture group, but which could not be evaluated experimentally, such as *mechanical* anisotropy, tissue strain distribution, and the relationship between apparent yield stress and apparent modulus.

Materials and Methods:

We used specimens, matched for age (80 ± 12 years) and volume fraction (0.17 ± 0.03), that came either from women who had undergone arthroplasty for neck fractures of the proximal femur (n=19, fracture group), or from female cadavers (n=11, control group). Trabecular bone cubes were cut from the middle of the femoral heads immediately inferior to the epiphysial scar, and were grossly aligned to the primary orientation of the trabeculae (IS-direction) as visualized by radiographs. The apparent elastic modulus and the apparent yield stress and strain in the IS-direction were evaluated using a uniaxial compression test. Before mechanical testing, all specimens were scanned with micro computed-tomography and finite element models with 50 µm-cubic elements were constructed. All elements received an isotropic, linear elastic tissue modulus of 1 GPa and a Poisson's ratio of 0.3. Using micro finite element analyses (µFEA) we simulated the compression tests, we loaded the models to their apparent yield strain and assembled frequency plots to determine the amount of tissue at risk of failure (i.e. loaded beyond 10 000 µstrain[7]), and we determined the Young's and shear moduli in the directions of maximal elastic moduli[8]. In order to compare the variation in stiffness with direction, each apparent modulus was normalized relative to the average elastic modulus for that specimen.The ratio between the experimentally measured apparent stiffness and the calculated apparent stiffness is the value of the true tissue modulus[9].

Results:

The tissue modulus was 10.0 GPa (SD: 2.2) for the control group and 10.8 GPa (SD: 3.3) for the fracture group (not significant, table 1). There were no significant differences either in the apparent yield strains, in the percentages of highly strained tissue, and in the relationship between apparent yield stress and apparent elastic modulus (table 1). At the apparent level, the fracture group showed a significantly decreased third principal Young's modulus, E_3, and a significantly increased shear modulus, G_{12}, relative to the normal group. As a result, the mechanical anisotropy was significantly higher in the fracture group (table 2).

Discussion:

From the µFEA in combination with the compression tests, we estimated the tissue elastic modulus to be a little over 10 GPa for both groups. This value falls well within the range of values reported in literature for healthy bone. Also, we do not expect a difference in the tissue yield properties. If the tissue yield properties had been different, this would have resulted in a different relationship between apparent yield stress and apparent elastic modulus[7]. Also, when the samples were loaded to the apparent yield strain, there were no differences in the percentage of tissue with high compressive strains. Earlier studies suggested that in a fracture group the average tissue density is either unchanged or slightly decreased, and that the number of microcracks in the tissue is unchanged[2,3,4,5,6]. We found no differences in the average mechanical properties of the tissue material between the normal group and the fracture group.

Since a strong relationship is known to exist between stiffness and strength, the elastic moduli give us an estimate about strength as well. Fracture cases showed significantly lower third principal Young's modulus, E_3, and higher shear modulus, G_{12}. This indicates that the mechanical anisotropy was significantly increased in the fracture group, demonstrating either a predisposition or an 'over adaptation' to the primary load axis in the fracture group. This is probably caused by a thinning or even resorption of the transverse trabeculae. During normal physiological activities the trabecular bone is generally loaded in the primary loading direction. The stiffness (and strength) in this direction was found to be similar in the control and fracture groups. However, during abnormal loading, such as during a fall, the trabecular bone may be over-loaded in the transverse direction. In this direction the stiffness (and strength) of the trabecular bone was reduced in fracture cases, leading to an increased risk of fracture in case of a fall. This reduced stiffness (and strength) in the ML-direction could explain why 90% of all hip-fractures are the result of a fall, and in particular why fractures often occur from a fall to the side (ML-direction)[10,11].

In summary, we found no significant differences in the average tissue modulus between patients with and without fractures. A difference in the average tissue yield properties is also highly unlikely. Trabecular bone from fracture cases had a significantly higher mechanical anisotropy, likely related to an increased fracture risk when the bone is loaded in a direction different from its normal load-bearing direction.

	control	fracture	p
Volume fraction [µm/µm]	0.17 ± 0.02	0.18 ± 0.03	0.316
Apparent modulus [MPa]	635 ± 253	742 ± 234	0.283
Apparent yield stress [MPa]	6.7 ± 2.6	8.2 ± 2.6	0.150
Apparent yield strain [µstrain]	11112 ± 2037	11949 ± 2677	0.362
Tissue modulus [GPa]	10.0 ± 2.2	10.8 ± 3.3	0.451
Average tissue strain [µstrain]	4203 ± 1139	4521 ± 1354	0.515
Tissue at risk of fracture [%]	6.1 ± 3.9	6.5 ± 4.8	0.849

Table 1: Summary of results (mean ± SD).

	control	fracture	p
$E_{average}$ [MPa]	485 ± 76	523 ± 149	0.569
E_1 [Mpa/MPa]	1.66 ± 0.07	1.71 ± 0.17	0.225
E_2 [Mpa/Mpa]	0.83 ± 0.06	0.85 ± 0.15	0.580
E_3 [Mpa/Mpa]	0.52 ± 0.05	0.44 ± 0.09	**0.006**
G_{12} [Mpa/Mpa]	1.40 ± 0.05	1.48 ± 0.12	**0.019**
G_{23} [Mpa/Mpa]	0.72 ± 0.05	0.69 ± 0.09	0.301
G_{31} [Mpa/Mpa]	0.88 ± 0.08	0.83 ± 0.08	0.106
Anisotropy [Mpa/MPa]	3.2 ± 0.5	4.1 ± 0.9	**0.003**

Table 2: Normalized principal Young's and shear moduli (mean ± SD).

References:

[1] Ciarelli et al. JBMR 15:32-40, 2000. [2] Faccini et al. Lancet 1:1089-1092, 1976. [3] Katz et al. Trans. ORS 263, 1987. [4] Li and Aspden JBMR 12:641-651, 1997. [5] McCreadie PhD-Dissertation, 2000. [6] Mori et al. Bone 21:521-526, 1997. [9] van-Rietbergen et al. J.Biomech. 28:69-81, 1995. [8] van-Rietbergen et al. J.Biomech. 29:1653-1657, 1996. [7] Niebur et al. J.Biomech. 33:1575-1583, 2000. [10] Greenspan et al. JAMA 271:128-133, 1994. [11] Pinilla et al. Calif.Tiss.Int. 58:231-235, 1996.

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