Mechanical stability of trabecular bone morphology as a measure for osteoporosis

MECHANICAL STABILITY OF TRABECULAR BONE MORPHOLOGY AS A MEASURE FOR OSTEOPOROSIS

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Abstract: A new technique for assessing the mechanical stability of trabecular bone was introduced. This technique uses a full three dimensional reconstruction of a trabecular bone specimen and a finite element model to calculate the local stress distribution within the trabeculae. A little bone was artificially removed in the model at highly loaded locations and the changed stress distributions were determined. The changes in these distributions are indicative for the mechanical stability (change in fracture risk) of the trabecular architecture with respect to small changes in mass. We propose that this method can be used to measure the mechanical efficacy of a trabecular architecture in terms of fracture risk, thereby defining osteoporosis in a quantitative way.

Introduction: The assessment of osteoporosis usually refers to poor bone mass, although it is known that detrimental architectural changes without net bone loss can have a substantial effect on the load bearing capacity of the structure. More refined techniques to directly measure morphometric parameters are developed, but it is not precisely clear to which extent these parameters address the strength of the structure, since the relationships between bone architecture and strength are not well determined, yet. Another potential problem of morphometric parameters is that they refer to a static situation and do not address the sensitivity of the trabecular architecture to small changes. There are indications that in particular for osteoporotic patients very small amounts of bone loss can result in a large increase of the fracture risk, since critical trabecular connectivity can be lost[1]. In other words, a structure being strong enough at one moment, may become very weak after minor loss of bone mineral. The architecture is in such a case unstable with respect to small changes in mass. This study proposes a method to investigate the inherent mechanical stability of a trabecular architecture. For this purpose we used finite element models of trabecular bone specimens loaded in a physiological range, to calculate the changes in stress distributions after a small percentage bone loss.

Methods: A cubic specimen of trabecular bone from the human tibia (appr. 6*6*6 mm) was serially sectioned in slices of 20 micron. Each section was digitized and the three dimensional architecture was numerically reconstructed[2]. This procedure provided ± 137,000 bone voxels for the specimen, which were converted to brick elements in a finite element model to calculate the stress distribution in the architecture[3] (Fig.1).

Figure 1 Finite element model of the proximal tibia specimen.

The finite element model of the specimen was loaded in the longitudinal direction with a force of 18 N. This resulted in an apparent stress of 0.5 MPa which is in the range of physiological loading.

The maximal principal stress (absolute value) in every element was calculated in the model and a distribution diagram of the local stresses in the trabeculae of the structure was constructed. To study effects of small amounts of bone loss in the specimen, bone was removed at locations of the highest stress. It was assumed that these locations were the most unfavorable for loosing bone mineral, thus this procedure provided a worst case stress increase. The consequence of fracture risk was calculated and represented as a failure index defined by the amount of bone loaded above a threshold principal stress level of 40 MPa. With the present elastic modulus of the tissue this equaled 0.4 percent strain, which is roughly known to be a yield limit for trabecular bone.

Results: The distribution of the maximal principal stresses in the trabecular structure in the initial configuration showed a peak around 2 MPa. Since the distribution was skewed the average value was higher; 5.7 MPa. Less than 0.1 percent of the voxels had a principal stress above the chosen yield level of 40 MPa, indicating a considerable safety factor against failure. Bone was removed in steps of 1 percent and the stress distribution was again calculated (see Figure 2).

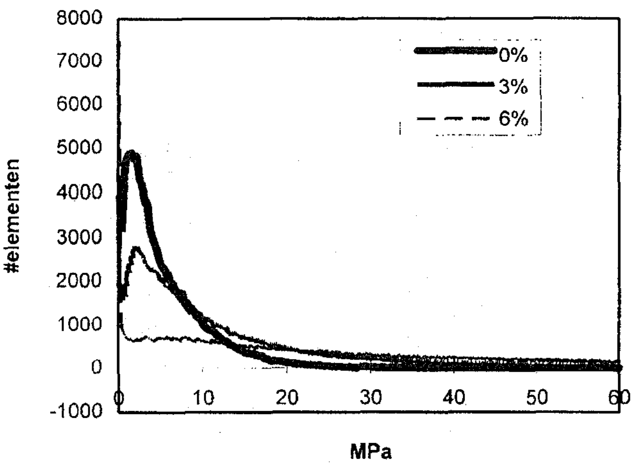

Figure 2 Distribution of the maximal principal stress for the initial configuration (0%), after 3% bone removal and after 6% bone removal. Bone was removed at locations of the highest principal stress. With ongoing bone loss the distribution smoothens out, indicating less efficiency (higher failure risk).

With 3 percent bone loss the peak in the stress distribution occurred at the same location (± 2 MPa), but the average value increased 2 fold to 11.5 MPa. The distribution became less uniform as is indicated in Fig. 2. At this stage 3.2 percent of the elements were found above the threshold level of 40 MPa. With 7 percent bone loss the stress distribution became very flat (nonuniform) and a 10 fold increase for the average stress was found (Fig. 3). Up to 34 percent of the elements were loaded above the 40 MPa threshold level. In fact the structure became completely mechanically unstable.

Discussion: The results of bone removal at locations where the highest stress occurred showed two effects. First, the stress distribution became less uniform. More voxels were driven to regions of overload (stress peaks) and underload (disuse). Second, the failure index, defined here as the percentage of bone above the 40 MPa threshold level, increased nonlinearly with bone removal (see Figure 3).

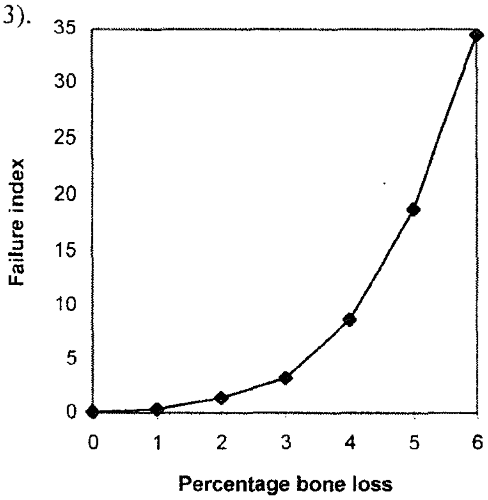

Figure 3 Percentage bone loss versus the percentage of elements above the threshold level of 40 MPa (Failure Index). A nonlinear increase in Failure Index resulted with ongoing bone loss.

This study showed that trabecular bone can be very sensitive for relative small amounts of bone loss and in a worst case only a few percent reduction in bone mineral can potentially degenerate the structure in a mechanical sense. This sensitivity or inherent stability is of course dependent on the precise architecture of the structure. The proposed method can therefore differentiate between a stable and an unstable architecture. In potential the method can define osteoporosis in a quantitative way, directly referring to the fracture risk or mechanical stability (increase in fracture risk after little bone loss).

References

1. Kleerekoper et al., Calcif Tissue Int 37:594, 1985.
2. Odgaard et al., J Micros 159:691
3. Van Rietbergen et al., J Biomech 28:69-81.

Acknowledgement

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