Bone remodelling : comparing local adaptation and global optimisation

BONE REMODELLING: COMPARING LOCAL ADAPTATION AND GLOBAL OPTIMISATION

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INTRODUCTION

Carter et al. (1) suggested that adaptive bone remodelling and maintenance is governed by the objective of normalising the local strain energy density (SED) per unit of bone mass. This objective can be used in mathematical descriptions of the strain-adaptive remodelling process. Integrated with finite element models, these so-called remodelling rules can be applied to predict the morphology of bone, in terms of apparent density distributions (1,2,3). This process, and its mathematical simulation, is thus considered as a structural optimisation scheme, whereby local cells regulate bone mass in such a way that the objective is met in their environment. It has been shown, that the density distributions so obtained for the proximal femur in the simulation module, closely resemble the real structure. The question addressed in the present paper is whether this localised optimisation procedure is equivalent to a global optimisation scheme. Or, in other words, whether such a local process produces an optimal structure.

METHODOLOGY

A 2-D FEM-model with uniform thickness of a proximal human femur was constructed. A cycle of three loading cases, representing a typical loading history (1), was taken into account.

The remodelling program is an implementation of the remodelling rule $\frac{d\rho}{dt} = c(\frac{U_a}{\rho} - k)$, where ρ(x,y,z) is the apparent density, U_a(x,y,z) is the apparent strain energy density SED, averaged over the loading cycle, and c and k are constants (2,3). This rule describes a process whereby the apparent density adapts its value until the averaged SED per unit bone mass (U_a/ρ) in the same point has reached a uniform value k (in our case 0.0125 J/gr), or until it reaches an upper bound of 1.73 gr/cm^3 or a lower bound of 0.01 gr/cm^3.

The global optimisation program that we developed is a general design-optimisation program. It combines a FEM-code (4) and a non-linear optimisation routine (the sequential quadratic programming routine NCONG (5)), and it employs analytic gradient calculation using the adjoint load method (6), which greatly enhances its efficiency and convergence properties. The program was used to minimise the squared distance between the actual value of U_a/ρ and the uniform target value k, averaged over the bone volume V, that is $f(\rho) = \frac{1}{V} \int\int\int_V (\frac{U_a}{\rho} - k)^2 dV$, by adapting the apparent density of each finite element. In this way the global optimisation program searches the global bone density distribution which the local remodelling process is assumed to reach.

RESULTS

The results of the simulation of the local remodelling process and those of the global optimisation scheme differ, but not to a large extend. The remodelling analysis (Fig. 1a) produces a density distribution very similar to a real bone, featuring cortices, an intramedullary canal, Ward's triangle, metaphyseal cortical shells, and the characteristic density patterns of the femoral head and the greater trochanter. The global optimisation scheme produces a similar structure (Fig. 1b), also with cortices and the suggestion of an intramedullary canal, but the trabecular density distribution is fuzzier and more chaotic, relative to a real bone. The distribution produced by the remodelling process more closely resembles real bone, compared to the one produced by the optimisation scheme but, conversely, the latter one produces more uniform values of the SED per unit of mass; hence, approximates the objective more closely.

DISCUSSION

Two questions are of importance when considering the results obtained. One, to which extent do the density distributions predicted resemble the real bone and, second, to which extend do these patterns produce a uniform SED per unit of mass. The results obtained suggest that the normal density distribution of bone is consistent with the hypothesis that bone locally strives to normalise its SED per unit of bone mass. Conversely, the hypothesis that bone is an optimal structure relative to uniform SED per unit of mass must be rejected. This is equivalent to suggesting that the morphology of bone is the result of a biological optimisation process, rather than the result of a predestined or evolutionary optimisation goal. However, it must be noted that, on the one hand, the differences in the outcome of the two analyses are not extensive and that, on the other hand, the model used and the loads assumed, are relatively simple. Hence, the conclusions can only be considered preliminary.

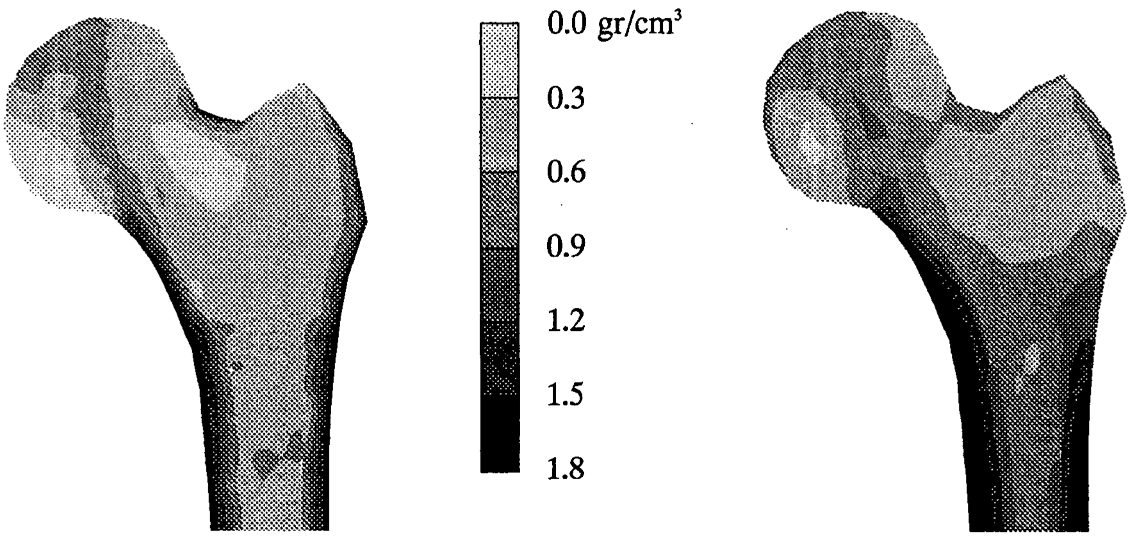

Figure 1a: Apparent density distribution from remodelling simulation.

Figure 1b: Apparent density distribution pro- by optimisation scheme.

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IMPACT TEST FOR EXAMINING JOINT CHARACTERISTICS

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INTRODUCTION

The effect of loading on a joint depends on many factors: amplitude, frequency, duration and rate of application. The joint's biomechanical characteristics can be revealed by mechanical tests among which an impact test is one. This paper outlines a simple experimental procedure to examine the transmissibility of longitudinal impulsive stress in a segment of bovine coccygeal