A note on optimization of skeletal structures

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It is a pleasure to take up Dr Lekszycki's invitation to write a mini-paper for International Society for Structural and Multidisciplinary Optimization Working Group on Optimization in Biomechanics. What follows is a continuation of what I presented at the 15th meeting of the Italian Association of Theoretical and Applied Mechanics [1]. In that paper I suggested that optimization is not a useful hypothesis in biomechanics, unless it is reformulated in some way.

Regarding optimization, research to date has shown that we can find examples where structural optimization procedures return structures that are similar to those observed; this has been done most often for the proximal femur. I suggest that there are two areas of difficulty with this kind of bio-optimization research (I include our own research in this criticism):

(a) The external shape of the femur, and the pattern of material distribution within the bone, is the result of two processes which cannot be easily separated: the first is the ontogenetic process occurring over the lifetime of the individual and the second is a phylogenetic process occurring over evolutionary time (i.e. natural selection). Natural selection has created a program for the growth and adaptation of a bone from an initial rudiment to some baseline bone shape. It has also created the mechano-regulation rules for adaptation; however collaboration of these two processes on making a structure "optimised" is not explicitly recognised.

(b) There are no clear differences between the solutions for various different local remodelling rules: all seem to predict the solution equally well (e.g. strain, strain energy, damage, optimal response [1,2]). This is partly because anatomical variation precludes accurate confirmation of the algorithms against reality and, in all cases where this bone has been analysed, the loading conditions are rather arbitrary and the domain of solution has been fixed. Therefore, even if it were true that the bone was optimized, we would not be able to prove it from the computational simulations because of the unknown nature of the boundary and initial conditions.

Consider Darwinian evolution as the process which has created the present shape of a bone – say the femur. We could recast the optimization problem slightly. According to the biomechanical theory, there exists some form of mechano-regulation rule (by definition a local remodelling or adaptation equation) which describes how the tissues become adapted to their mechanical function. These rules explicitly include biological constraints, such as limits on the rate of tissue formation, etc.

I suggest we should consider is that these mechano-regulation rules are also subject to pressures of natural selection, and the form of them will vary between and within species. (If evolution tries to optimize these rules then animals with relatively more optimal mechano-regulation than others will have a survival advantage.) Animals will evolve these rules over evolutionary time – let's think about what an optimal mechano-regulation algorithm might be rather than whether or not the actual structure is optimal. What kind of analyses do we need to perform to get to that objective? Maybe we can use optimization theory (not being much familiar with it I cannot say). It would be interesting to know id bio-optimists have any way of addressing this problem.

[1] P.J. Prendergast "Mechanics applied to skeletal ontogeny and phylogeny", *Meccanica* (Special Issue on *Mechanics of Tissues and Implants*, Edited by Prendergast, P.J., Contro, R.) Vol. 37, pp. 317-334, Nr. 4-5, 2002.

[2] Pedersen, P., Bendsoe, M.P. (Editors), "IUTAM Symposium on Synthesis in Bio-Solid Mechanics", Kluwer, Dordrecht, 1999.