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Modelling the force-dependent morphogenesis of fish vertebra with topology optimization

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Wolff's law states that bone morphology evolves according to their external mechanical loading. Following this law, researchers have tried to simulate bone shape formation, especially for trabecular bone, using topology optimization [1]. Less attention has been given to the bone outer shape, composed of cortical bone. However, trabecular bone and cortical bone are both mainly formed by osteoblasts and osteoclasts. Therefore, we hypothesize that the bone outer shape also adapts to the external forces. The aim of this research is to understand the mechanism that generates the bone outer shape by reproducing the latter using topology optimization.

The fish vertebra can be divided into two parts: an inner hourglass-like structure and an outer lateral structure. Based on our observations, it turns out that numerous species present a similar hourglass-like structure but that the lateral structure strongly depends on the fish species. Lateral structures can be classified into two types. The first type exhibits a ridge structure with one or more thick plate-like bones and the second type exhibits a netlike structure in which thin plate-like bones are randomly oriented. These differences seem related to the fish motion, i.e. the swimming type of the fish, and therefore, it is assumed that lateral structures also evolve based on external loading conditions.

In standard topology optimization, the density at each material point is only constrained by the total volume of material. However, the activity of osteoblast and osteoclast is more a local phenomenon. Hence, the standard topology optimization problem is supplemented with a local density penalization to mimic this local phenomenon. To solve the optimization problem, a method based on a time dependent reaction-diffusion equation is employed [2]. The equation is driven by the sensitivity S, in which the Lagrangian multiplier λ is introduced. Solving this optimization problem gives an optimized structure with respect to the imposed boundary and loading conditions. The penalization term enables to control locally the feature size.

Using this equation, we developed a 3-D mathematical model to generate fish vertebra. Without local density penalization, thick beams appear similarly to the ridge structure. Penalizing locally the density, thinner beams are promoted and they tend to form a netlike structure. Numerical results show that the proposed model can produce both types of lateral structures, i.e. ridge structure and netlike structure, which are similar to the actual fish bone. In the future, it would be interesting to be able to produce various forms of fish vertebra by only adjusting a few parameters of the penalization law.

[1] Jang *et al.*, 2009
[2] Kawamoto *et al.*, 2013

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