On a Fundamental Principle for Morphomechanics

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Embryogenesis involves a carefully coordinated series of morphogenetic events, which are carried out by a relatively limited number of basic cellular processes, including migration, multiplication, and the stretching and folding of epithelia (cell sheets). These events are regulated by a dynamic interaction between genetic and environmental factors (chemical and mechanical), with adjustments being made continually through feedback mechanisms. The nature of this interaction remains a central question of developmental biology. Today, most researchers agree that mechanics plays a significant role in regulating morphogenesis (e.g., through mechanotransduction).

Here, computational models are used to explore the possibility that morphogenesis is regulated, in part, by feedback from mechanical stress. Comparing theoretical and experimental results, we consider the following questions: Is the behavior of developing tissues governed by a fundamental principle for morphogenesis? Can such a principle be expressed mathematically? While it is clear that developing tissues must obey the quantitative laws of physics, it is not clear that they also obey quantitative laws of biology. To date, these issues have been discussed primarily in philosophical terms, with many investigators arguing that mathematical laws in biology simply cannot exist.

The results from this study suggest that cellular responses depend on the rate of loading caused by external or internally generated forces. Morphomechanical laws are proposed for slow, medium, and fast stress rates, and the feasibility of these laws are illustrated by models for stretching of epithelia and axons, invagination of sea urchin embryos, growth of arteries, wound healing, and early heart development. This study represents an initial attempt to formulate a general principle for the mechanics of soft tissue growth and development.