Emergent mechanical patterns in biological tissues

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The embryogenesis is the process from which a single turns into a living organism. Through several stages of development, the cell population proliferates at the same time the embryo shapes and the organs develop gaining their functionality. This is possible through, biochemical, genetic and epigenetic (e.g. mechanical) factors that are involved in a complex interaction of processes organized in different levels and in different spatio-temporal scales. The embryogenesis, through this complexity, develops in a robust and reproducible way, but allowing variability that makes possible the diversity of living specimens. Through embryogenesis, tissues gain their shape, properties and functionality.

The advances in physics of microscopes and the appearance of fluorescent proteins that can be attached to expression chains, reporting about structural and functional elements of the cell, have enabled for the in-vivo observation of embryogenesis. The imaging procedures result in sequences of high spatio-temporal resolution 3D + time data of the biological processes, obtaining a digital representation of tissues that can be further analyzed, provided image processing and data analysis techniques are developed.

One of the most relevant and challenging lines of research in the field is the quantification of the mechanical factors and processes involved in the embryogenesis and organogenesis and their relations with genetics. Due to the complexity of the processes, studies have focused on specific problems and scales controlled in the experiments, posing and testing hypothesis to gain new biological insight. However, methodologies are necessary to seed light about emergent patterns that define biological properties across specimens and phenotypes. My research is framed within this paradigm, proposing systematic methodology to quantify the emergent deformation patterns from the motion estimated in in-vivo images of biological tissues. With this framework it is possible to quantify not only local mechanisms, but to discover and characterize the scales of mechanical organization in tissues.

The framework focuses on the quantification of the motion kinematics (deformation and strains) from images in a non-invasive way. From this quantification it would be possible to infer stresses if constitutive equations are formulated and mechanical properties are measured in a non-invasive way as well. However, experimental and methodological challenges hamper the quantification of exerted forces and the mechanical properties of tissues. Nevertheless, a descriptive framework of deformation patterns provides valuable insight about the organization and scales of the mechanical interactions of developing tissues and working organs. Such a characterization helps to improve mechanical models and progressively understand the complexity of biological systems and tissues.

Technically, the framework relies on a Lagrangian representation of the cell dynamics system based on spatio-temporal trajectories instead of spatial positions. This approach of analysis enables the reconstruction of the mechanical patterning as experienced by the cells.
and tissues. Thus, we can build temporal profiles of deformation along stages of development, comprising both the instantaneous events and the cumulative deformation history.

The application of this framework to 3D + time data of zebrafish embryogenesis allowed us to discover mechanical profiles that stabilized through time forming structures that organize in a scale comparable to the map of cell differentiation (fate map), and also suggesting correlation with genetic patterns. The framework was also applied to the analysis of the Amnioserosa tissue in the Drosophila’s dorsal closure, revealing that the oscillatory contraction triggered by the acto-myosin network organized as a complex coupling at different scales: local force generation foci, cellular morphology control mechanisms and tissue geometrical constraints. The framework can be also applied to tissues to measure their deformation history during their functioning to profile behaviours or detect anomalies.

In summary, this research proposes a theoretical framework for the analysis of multi-scale cell dynamics that enables to quantify automatically mechanical patterns and also offers a new representation of tissue dynamics as experienced by cells instead of how the microscope captures instantaneously the processes. Therefore, this framework enables for new strategies of quantitative analysis and comparison between embryos and tissues from in-vivo images. Theoretically, we propose a framework for physics to detect emergent patterns in the complexity of biological processes is proposed. We also expect this work to be a reference for tissue engineering and biomedical applications.

References
D. Pastor-Escuredo et al. https://www.biorxiv.org/content/early/2016/10/19/054353 (revision)