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Probing Mechanical Mechanism of Three-Hinge Formation on a Growing Brain: A Numerical and Experimental Study

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Abstract : Cortical folding, characterized by convex gyri and concave sulci, has an intrinsic relationship to the brain's functional organization. Understanding the mechanism of the brain's convoluted patterns can provide useful clues into normal and pathological brain function. During the development, the cerebral cortex experiences a noticeable expansion in volume and surface area accompanied by tremendous tissue folding which may be attributed to many possible factors. Despite decades of endeavors, the fundamental mechanism and key regulators of this crucial process remain incompletely understood. Therefore, to taking even a small role in unraveling of brain folding mystery, we present a mechanical model to find mechanism of 3-hinges formation in a growing brain that it has not been addressed before. A 3-hinge is defined as a gyral region where three gyral crests (hinge-lines) join. The reasons that how and why brain prefers to develop 3-hinges have not been answered very well. Therefore, we offer a theoretical and computational explanation to mechanism of 3-hinges formation in a growing brain and validate it by experimental observations. In theoretical approach, the dynamic behavior of brain tissue is examined and described with the aid of a large strain and nonlinear constitutive model. Derived constitute model is used in the computational model to define material behavior. Since the theoretical approach cannot predict the evolution of cortical complex convolution after instability, non-linear finite element models are employed to study the 3-hinges formation and secondary morphological folds of the developing brain. Three-dimensional (3D) finite element analyses on a multi-layer soft tissue model which mimics a small piece of the brain are performed to investigate the fundamental mechanism of consistent hinge formation in the cortical folding. Results show that after certain amount growth of cortex, mechanical model starts to be unstable and then by formation of creases enters to a new configuration with lower strain energy. By further growth of the model, formed shallow creases start to form convoluted patterns and then develop 3-hinge patterns. Simulation results related to 3-hinges in models show good agreement with experimental observations from macaque, chimpanzee and human brain images. These results have great potential to reveal fundamental principles of brain architecture and to produce a unified theoretical framework that convincingly explains the intrinsic relationship between cortical folding and 3-hinges formation. This achieved fundamental understanding of the intrinsic relationship between cortical folding and 3-hinges formation would potentially shed new insights into the diagnosis of many brain disorders such as schizophrenia, autism, lissencephaly and polymicrogyria.

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