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To cite this version:
hal-02956889

HAL Id: hal-02956889
https://hal.science/hal-02956889
Submitted on 3 Oct 2020

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A FRAMEWORK TO STUDY THE IMPACT OF INITIAL GEOMETRY ON CORTICAL MORPHOGENESIS

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Poster Number: Th483

Introduction

Cortical folding pattern is a main characteristic of geometry of the human brain which is composed of gyri (ridges) and sulci (valleys). Several hypotheses have suggested different mechanisms that attempt to explain the development of cortical folding (van Essen et al., 1997 and Richman et al., 1975). In this work, we compare biomechanical simulations for several initial conditions by using an adaptive spherical parameterization approach (Lefèvre et al., 2015). Our approach allows to study and explore one of the most potential sources of reproducible cortical folding pattern: the specification of initial geometry of the brain.

Methods

Goal \rightarrow Study the impact of the initial geometry of the human fetal brain on surface morphology during the cortical development process.

How \rightarrow Using an adaptive spherical parameterization to compare several cortical surfaces of fetal brains generated by the biomechanical model based on the finite element model of differential cortical and subcortical growth introduced in (Tallinen et al., 2016).

Step 1: \( \begin{bmatrix} \mathbf{B}_{\text{ref}} \end{bmatrix} \) \( \begin{bmatrix} \mathbf{M}_{\text{ab}} \end{bmatrix} \) \( \begin{bmatrix} \mathbf{B}_{\text{a,b}} \end{bmatrix} \)
\( (\mathbf{B}_{\text{ref}}, \mathbf{B}_{\text{a,b}}) \) \( \mathbf{Biomechanical Model} \) \( (\mathbf{S}_{\text{ref}}(t), \mathbf{S}_{\text{a,b}}(t)) \)

Step 2 \& 3: Compute and smooth curvatures of \( \mathbf{S}_{\text{ref}}(t) \) and \( \mathbf{S}_{\text{a,b}}(t) \)

Step 4: The spherical mapping is, then, defined by selecting the three best non-trivial eigenfunctions with only two nodal domains, from a set of six first eigenfunctions of the Laplace-Beltrami operator of \( \mathbf{S}_{\text{ref}}(t) \) and \( \mathbf{S}_{\text{a,b}}(t) \).

\( \mathbf{S}_{\text{ref}}(t).\mathbf{S}_{\text{a,b}}(t) \rightarrow \mathbb{R}^2 \rightarrow \mathbb{S}^2 \)
\( p \rightarrow (\mathbf{\Phi}_1(p), \mathbf{\Phi}_2(p), \mathbf{\Phi}_3(p)) \rightarrow \sqrt{\mathbf{\Phi}_1^2(p) + \mathbf{\Phi}_2^2(p) + \mathbf{\Phi}_3^2(p)} \)

Step 5: Resample the curvature of the spherical map of \( \mathbf{S}_{\text{ref}}(t) \) on that of \( \mathbf{S}_{\text{a,b}}(t) \).

Step 6: Measure the similarity between the curvature of the surface \( \mathbf{S}_{\text{ref}}(t) \) and the resampled one of the surface \( \mathbf{S}_{\text{a,b}}(t) \).

Results

✓ \( \mathbf{M}_{\text{ab}} \) is applied to \( \mathbf{B}_{\text{ref}} \) with \( (a, b) \in [0.9 : 0.02 : 1.1] \).
✓ Correlation coefficients are computed between \( \mathbf{S}_{\text{ref}} \) and \( \mathbf{S}_{\text{a,b}} \) at simulation steps 500, 9000 and 22000.

Variations in the initial geometry of the brain strongly influences cortical folding patterns, either in terms of shape, size, placement and orientation of cortical folds

✓ At step 500: strong correlations for almost all scale factors \((a, b)\).
\rightarrow At the beginning of the biomechanical simulation, cortical surfaces are still smooth, which did not influence the similarity between \( \mathbf{S}_{\text{ref}} \) and \( \mathbf{S}_{\text{a,b}} \).

✓ At step 9000: correlation values vary between 0.45 and 1.
\rightarrow Folds begin to appear and are different from a simulation to another.

✓ Finally, at step 22000: correlation values fall except for values of \((a, b)\) between 0.98 and 1.02.
\rightarrow Folds become more apparent.

Discussion

✓ Our framework enables to exploit both, realistic mechanical properties of the human brain and the global characteristics of the cortical surface via shape descriptors based on a spherical mapping.
✓ Compare simulated cortical surfaces with real ones, and consequently to measuring efficiency of a biomechanical model in terms of generating folds at the right positions and having forms consistent with that of real ones.
✓ Analyze the folds orientations changes using an estimation of the principal curvatures directions.

References