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

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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 -> Study the impact of the initial geometry of the human fetal brain on surface morphology during the cortical development process.

How -> 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: $B_{ref} \xrightarrow{M_{a,b}} B_{a,b}$, with $M_{a,b} = \begin{pmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{pmatrix}$
 $(B_{ref}, B_{a,b}) \xrightarrow{\text{Biomechanical Model}} (S_{ref}(t), S_{a,b}(t))$

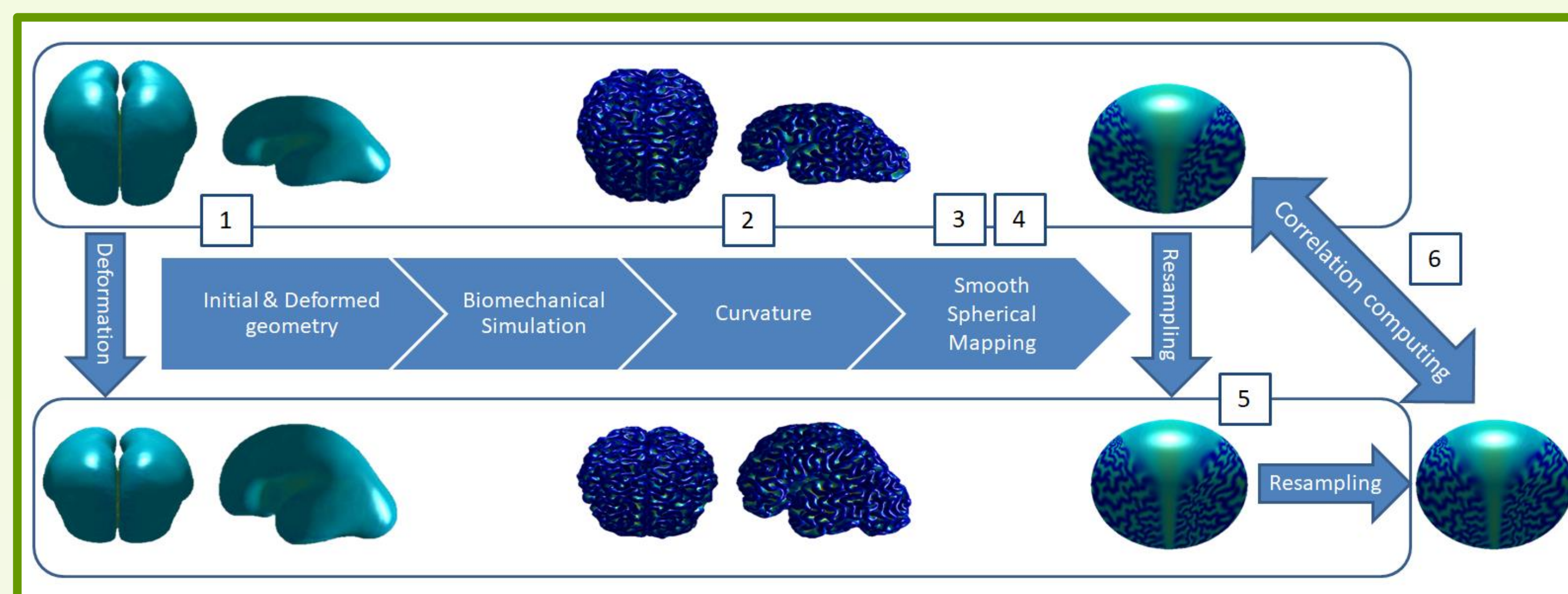
Step 2 & 3: Compute and smooth curvatures of $S_{ref}(t)$ and $S_{a,b}(t)$

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 $S_{ref}(t)$ and $S_{a,b}(t)$.

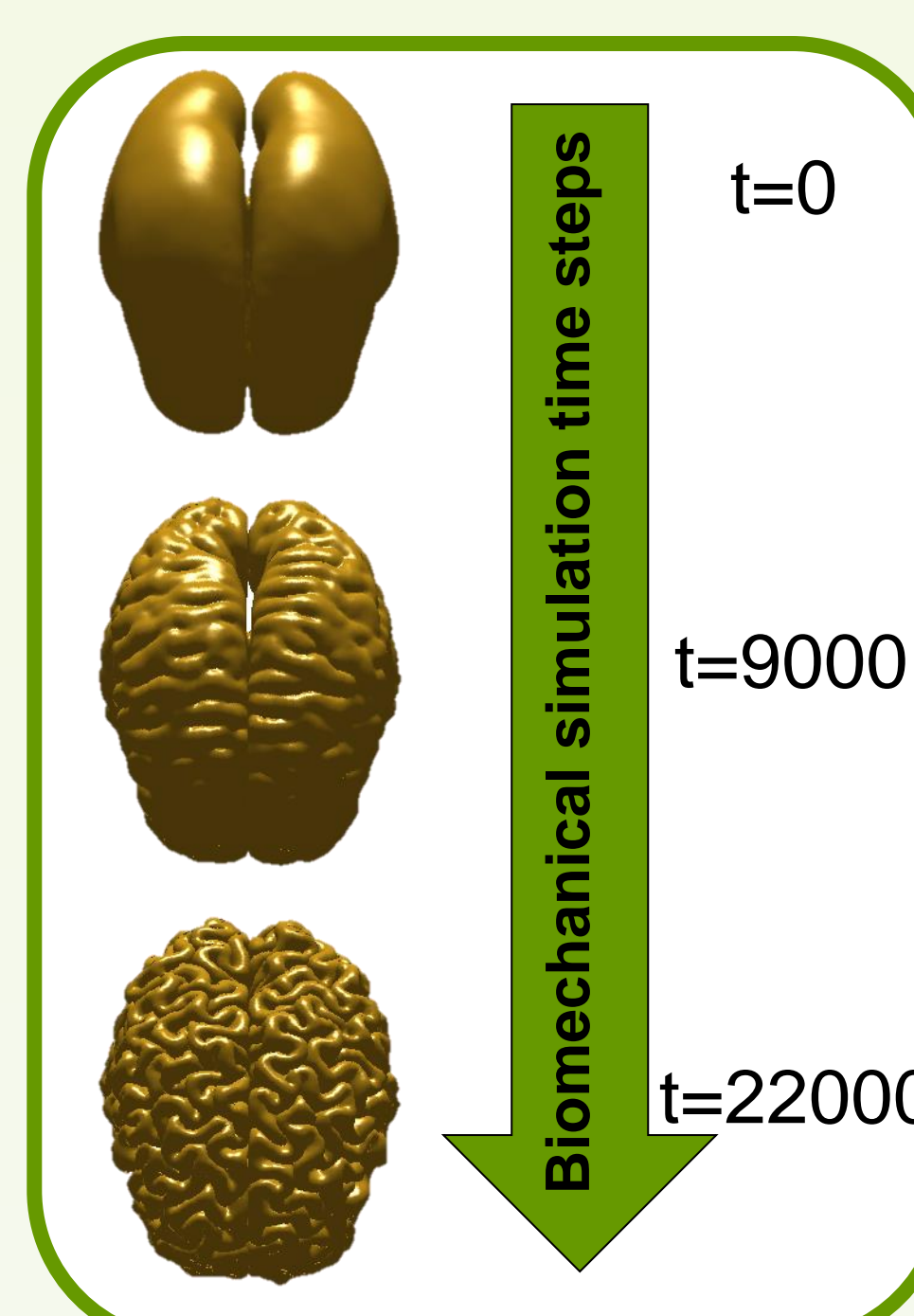
$$\begin{aligned} S_{ref}(t), S_{a,b}(t) &\rightarrow \mathbb{R}^3 && \rightarrow \mathbb{S}^2 \\ p &\rightarrow (\Phi_1(p), \Phi_2(p), \Phi_3(p)) && \rightarrow \frac{(\Phi_1(p), \Phi_2(p), \Phi_3(p))}{\sqrt{\Phi_1(p)^2 + \Phi_2(p)^2 + \Phi_3(p)^2}} \end{aligned}$$

Step 5: Resample the curvature of the spherical map of $S_{ref}(t)$ on that of $S_{a,b}(t)$.

Step 6: Measure the similarity between the curvature of the surface $S_{ref}(t)$ and the resampled one of the surface $S_{a,b}(t)$.



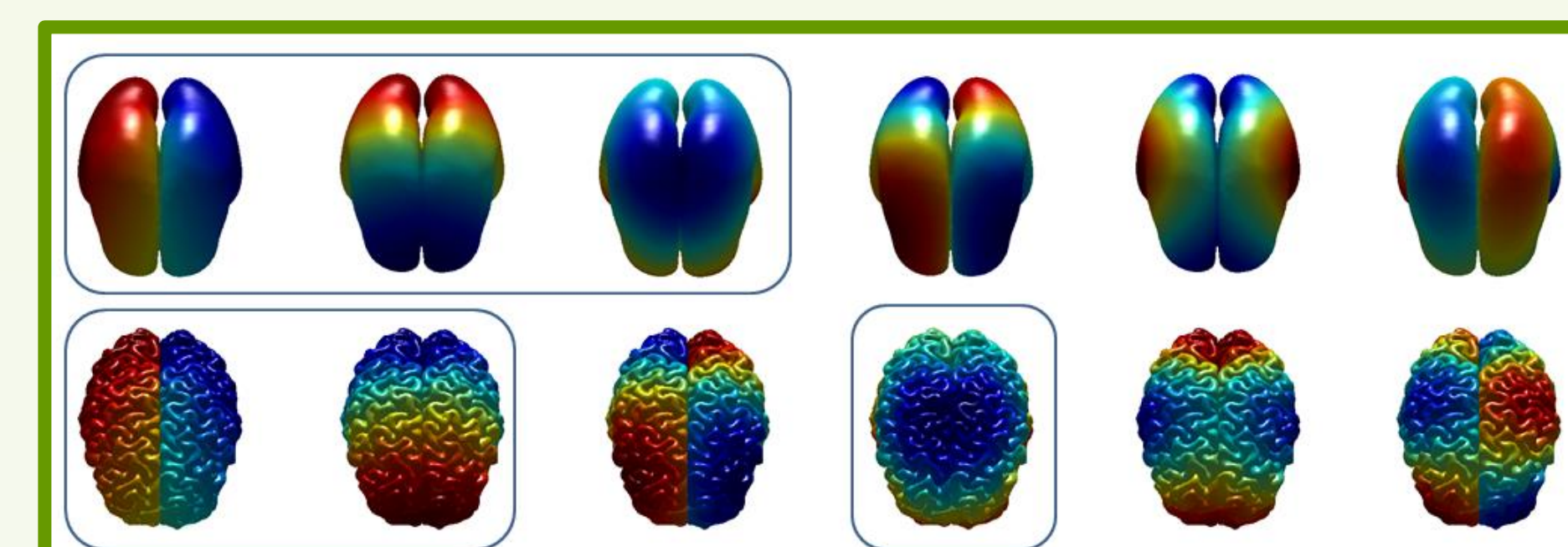
Pipeline of the proposed framework of comparing to brains surfaces. Colormap goes from blue (-) to red (+)



Simulated cortical surfaces $S_{ref}(t)$ for simulation timesteps $t=0, 9000$ and 22000



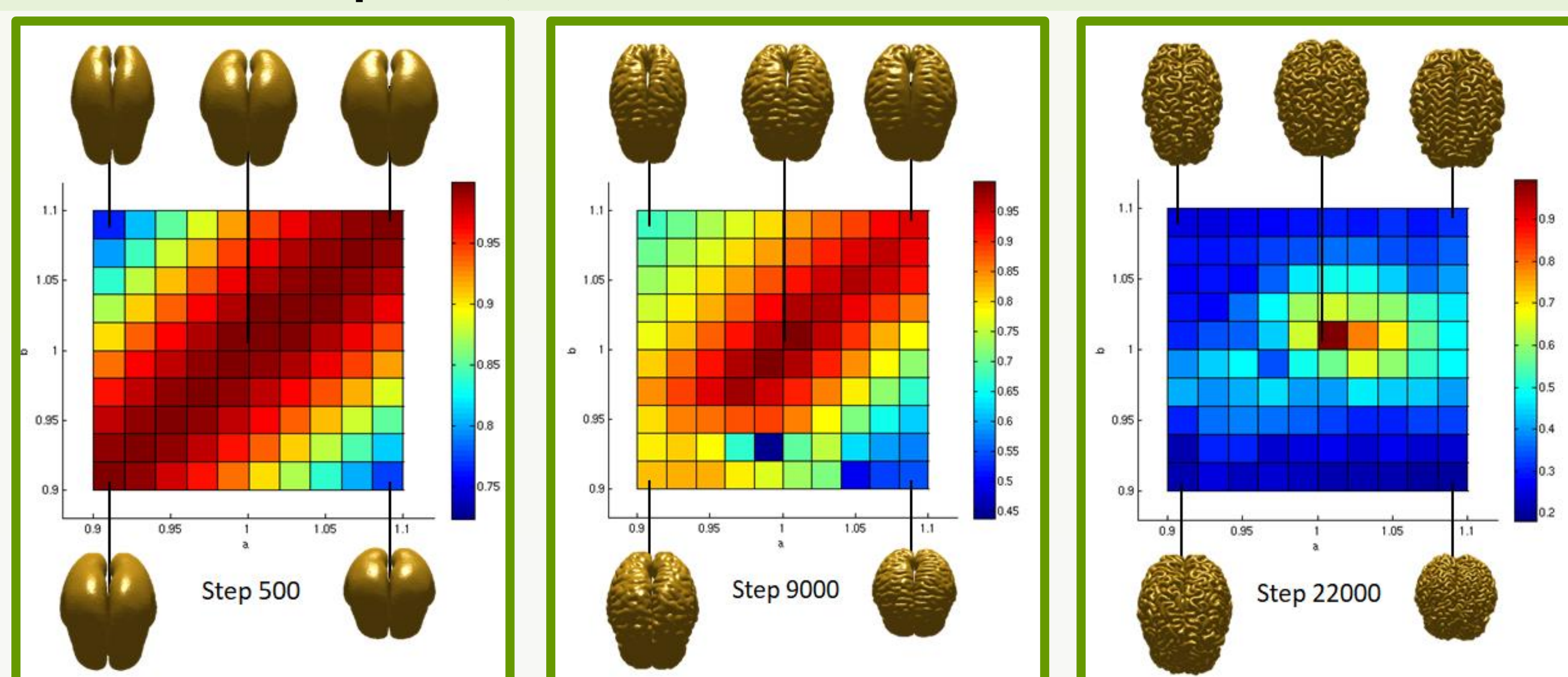
From left to right: three first non-trivial eigenfunctions. Each nodal sets are in green. (Lefèvre et al., 2015)



Six first eigenfunctions for a smooth fetal brain (first row) and a simulated cortex (second row).

Results

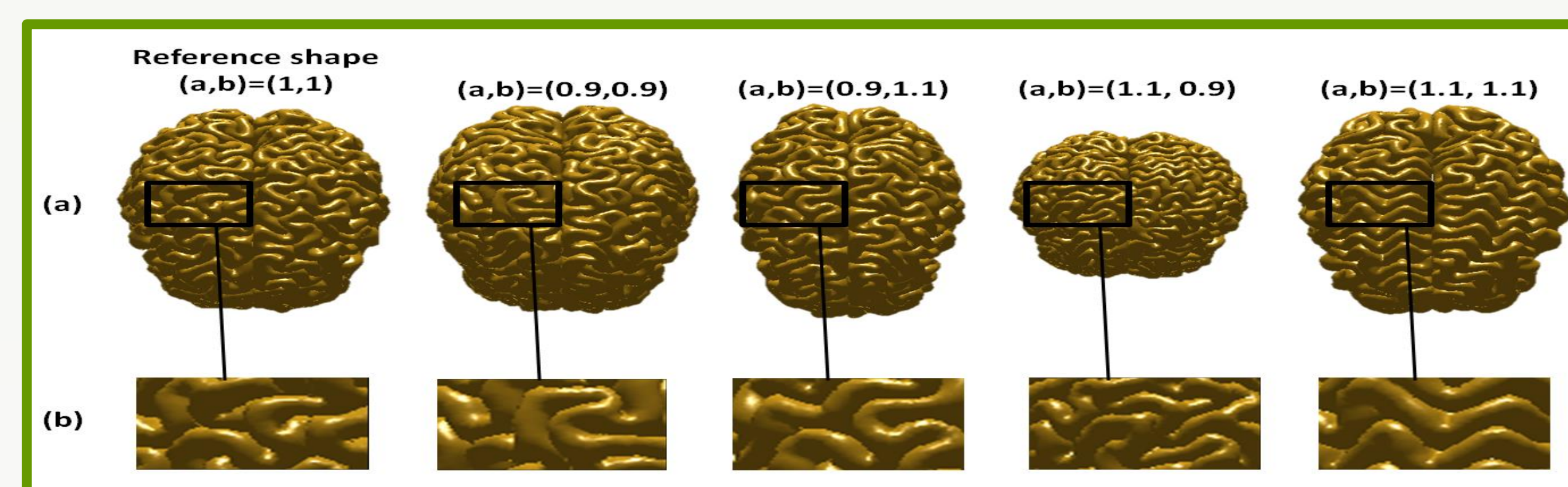
- ✓ $M_{a,b}$ is applied to B_{ref} with $(a, b) \in [0.9 : 0.02 : 1.1]$.
- ✓ Correlation coefficients are computed between S_{ref} and $S_{a,b}$ at simulation steps 500, 9000 and 22000.



Correlation values for different scale factors at step 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) .
-> At the beginning of the biomechanical simulation, cortical surfaces are still smooth, which did not influence the similarity between S_{ref} and $S_{a,b}$.
- ✓ At step 9000: correlation values vary between 0.45 and 1.
-> 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.
-> Folds become more apparent.



Variations in shape, size, placement and orientation of cortical folds across simulations

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.

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