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To cite this version:

HAL Id: inserm-01871274
https://www.hal.inserm.fr/inserm-01871274
Submitted on 10 Sep 2018

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Anisotropic similarity, a constrained affine transformation: Application to brain development analysis

Antoine Legouhy¹, Olivier Commowick¹, François Rousseau² and Christian Barillot¹

¹ Univ Rennes, CNRS, INRIA, INSERM, IRISA UMR 6074, VISAGES ERL U-1228, F-35000, Rennes, France
² IMT Atlantique, LaTIM U1101 INSERM, UBL, Brest, France

Objective: quantify regional brain growth in 3 orthogonal directions by linearly registering subjects on a common basis.

Approach: introduce an affine transformation with constrained scaling directions (9 degrees of freedom).

Material and Methods

Affine transformation: $y = Lx + t$
$L = RSU^T$

- $U$ is a rotation matrix that determines scaling directions
- $S$ is an anisotropic scaling (diagonal matrix)
- $R$ is a rotation matrix

Anisotropic similarity: affine transformation with fixed $U$

Block-matching registration [1][2]:
1. Matching: find homologous blocks in both images best satisfying a similarity criterion
2. Aggregation into a global transformation by minimizing the distance between the sets of blocks

For an anisotropic similarity:

Minimize: $\tilde{C}(R, S, t) = \sum ||y_i - (RSU^T x_i + t)||^2$, $U$ fixed

$\tilde{t} = g - RSU^T \bar{x}$

$\tilde{C}(R, S) = \sum ||y_i' - R S \bar{x}_i||^2$

$y_i' = y_i - \bar{g}$, $\bar{x} = UT(x_i - \bar{x})$

$\tilde{C}(q, S) = \sum ||y_i' - q \cdot \xi_i + \bar{q}||^2$

$\xi_i = S \bar{x}_i$ [3]

Matricial quaternions: $y_i' \cdot q = Q_{y_i'} q$ and $-q \cdot \xi_i = -P_{\xi_i} q = P_{\xi_i} q$

$\tilde{C}(q, S) = -q^T \left( -\sum_i (Q_{y_i'} + P_{\xi_i})^2 \right) q$

$A_i = (Q_{y_i'} + P_{\xi_i})^2$ and $A = \sum_i A_i$.

Alternate optimization each having an analytical solution:
- For fixed $S$, $\tilde{q}$ eigenvector with smallest eigenvalue of $A$
- For fixed $q$, $\tilde{S}_{ij} = \frac{1}{\sum_k z_k^2} q^T \left( \sum_i Q_{y_i'} \frac{\partial P_{\xi_i}}{\partial s_{ij}} \right) q$

We registered whole brain and lobes from 308 subjects onto an atlas based on this population using anisotropic similarity with chosen $U$.

Then we extracted the associated scaling factors describing brain growth.

Results

Scaling factors along chosen directions
Black curve represents average model
Fitted using first order rational regression: $y = \frac{ax + b}{x + c}$

Chosen scaling directions fixed on the reference image:
1. Orthogonal to the mid-sagittal plane (blue) [4]
2. and 3. Principal directions of voxel coordinates projected on mid-sagittal plane (red and green)

Scaling factors over age in years
whole brain

Conclusion

We developed a method to quantify regional brain growth in 3 orthogonal directions through anisotropic similarity registration.

An interesting continuation is to compare the results among groups of population.