Improved Motion Correction by Joint Mapping of Slices to an Anantomical Volume Demonstrated by Simulated fMRI Time Series

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Introduction: Subject motion is a major source of localization error in fMRI studies. Generally used fMRI analysis methods employ volume alignment of EPI with the assumption that there is no motion between slice acquisitions [1]. In practice, neighboring slices have significantly different motion trajectories in the reference frame of the magnetic field. A motion correction scheme that accounts for interslice motion, in-plane or out-of-plane, by retrospectively mapping each EPI slice into a 3D reference anatomical volume, map-slice-to-volume (MSV), has been in use for fMRI data analyses [2]. This study investigates a more efficient, joint estimation technique for motion parameters in MSV motion correction. As MSV is driven by mutual information (MI) of an image pair, the joint MSV (JMSV) exploits reliable motion parameters from the information rich, mid-brain slices to improve the registration accuracy in slices with poor information contents, i.e., end cap slices or distorted slices [3]. In JMSV, multiple slices are registered simultaneously with constraints for smoothness in motion. A simulated fMRI time series with a known motion have been processed with JMSV to assess the improvement in accuracy.

Methods: The registration of an EPI slice with an anatomical volume uses a rigid body transformation and MI as a cost function [4]. The motion parameters from MSV can be noisy; typically, at the top or the bottom slices of the EPI scan, whereas accurate registration is obtained for slices with sufficient information, i.e., enough detail and no severe geometric distortion. Here we implement a joint estimation of the registration of slices while penalizing a certain roughness constraint.

$$\hat{\theta} = \arg\max_{\theta}\{\sum_{i=0}^{M-1} MI(S_i(\theta_i), V_{ref}) - \beta R(\theta)\} = \arg\max_{\theta}\{\sum_{i=0}^{M-1}(MI(S_i(\theta_i), V_{ref}) - \beta((\theta_i - \theta_{i-1}) - (\theta_{i+1} - \theta_i))^2)\}$$

$\hat{\theta}$; estimaed motion param. for M slices, θ_i; motion param. for i-th EPI slice, $\theta = (\theta_0, .., \theta_{M-1})$; collection of motion param. over M slices,

S_i; i-th EPI slice, V_{ref}; anatomical volume, $R(\theta)$; roughness penalty, β; weight for roughness penalty.

Motion parameters for M slices are jointly estimated by maximizing the objective function. Smoothness of the motion parameters is implemented through a roughness penalty term R(θ) in the objective function. Second order penalty minimizes forces between slices and third order penalty minimizes changes in forces between slices. We chose 3rd order penalty so that smoothly varying forces can act on slices. We have applied JMSV with β=0 and 0.01 to a set of simulate fMRI time series with known motion parameters, i.e. rotation angles.

A mathematical phantom data series was created to represent a simulated fMRI time series. Simulated T_1 and T_2 –weighted MRI volumes were obtained from International Consortium of Brain Mapping (ICBM) [5]. Time series data were created by rotating T_2 –weighted MRI volume at randomly chosen angles in three directions, x, y and z in the range of –9 to 9 degrees. Smoothness in motion was achieved by a cubic spline fit. Each slice was subject to a set of rotation angles and a simulated fMRI volume consisted of slices stacked in an interleaved acquisition fashion. The final image resolution was 1.56x1.56x6 mm in a matrix 128x128x14.

Results: Errors in estimated motion parameters using JMSV with β=0 and 0.01was calculated against the ground truth are listed in Table 1. In case of beta zero, there is no roughness penalty on motion parameters, however, the joint optimization is still valid. The result shows that the overall error in registration is smaller with JMSV compared to the case with no penalty, which would be comparable to MSV. Within the same method, in plane rotation (i.e., rotation about z-axis) has smaller error than out of plane rotations (i.e., rotation about x and y – axis) since out of plane resolution (i.e., slice thickness, 6 mm) is larger than the in plane resolution (i.e., 1.56 mm). Motion parameters of first four volumes (i.e., 56 slices) are plotted in Figure 1.

Table 1. Error of estimated motion parameters for JMSV. Errors are calculated over 130 volumes. Values in parentheses are standard deviations.

Error [°]	Rotation about x-axis	Rotation about y-axis	Rotation about z-axis
JMSV (β=0)	-0.0425 (0.6945)	-0.0967 (0.7571)	0.0206 (0.2255)
JMSV (β=0.01)	-0.0525 (0.5963)	-0.0796 (0.6540)	0.0153 (0.1292)

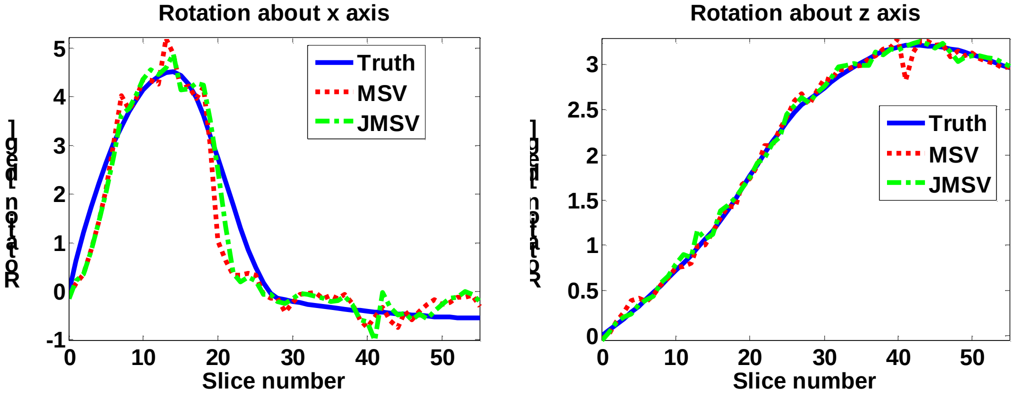

Figure. 1. Plot of motion parameters for the first 4 volumes. The left figure is plot of rotation about x-axis (out of plane rotation) and the right figure is the plot of rotation about z-axis (in plane rotation). Blue solid line is the true motion parameters, red dotted line is the estimate motion parameters by MSV, and green dashed line is the estimated motion parameters by JMSV.

Discussions: We have validated our JMSV method on simulated fMRI data with the ground truth. Improvement of the JMSV method over our previous MSV method is implicated. The improvement is due to the constrained registration where motion parameters of adjacent slices are behaving in a physically meaningful way not independently. The weight for the roughness penalty (i.e., beta) needs to be tuned for specific cases. Larger beta leads to smoother motion parameters and smaller beta allows more independent motion parameters.

Acknowledgements: This work was funded by the NIH grant 1P01CA87634.

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