Prospective Motion Correction of Functional MRI Using Markerless Tracking

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Synopsis

Motivation: Head motion during fMRI causes significant artifacts, disrupting activation patterns, particularly in clinical settings where realistic, challenging motion is common. Existing methods inadequately address within-volume motion, impacting clinical usability.

Goal(s): This study evaluates the effectiveness of prospective motion correction (PMC) in real-time compensation of head motion artifacts in fMRI, enhancing reliability under clinical conditions.

Approach: We assessed PMC-enabled fMRI scans in three volunteers performing controlled head motion, comparing activation and tSNR maps across PMC-on and PMC-off conditions.

Results: PMC improved tSNR and restored motor cortex activation disrupted by motion, recovering some activation in the primary expected areas, suggesting PMC's potential for clinical application.

Impact: While PMC shows potential for improving fMRI reliability in clinical settings, enhancing brain mapping despite patient motion, these findings should be approached cautiously. Further research into real-time motion tracking integration is essential, especially for patients with limited motion control.

Introduction

Functional MRI (fMRI) is crucial for noninvasively mapping brain function but is highly susceptible to artifacts caused by head motion. Even minimal head motion can lead to spatial misalignment and signal dropout. This study aims to explore the effectiveness of prospective motion correction (PMC) as a real-time solution for compensating motion artifacts in functional MRI (fMRI) [1,2], addressing the limitations of retrospective motion correction (RMC) techniques for within-volume motion.

Methods

Three healthy male volunteers (ages 23-42, Sub-1 and Sub-2 right-handed, Sub-3 left-handed) were scanned on a 3T Prisma MRI system (Siemens, Erlangen, Germany) using 64 channel head/neck coil. Each participants performed a block-design finger-tapping task with their non dominant hand during acquisition of a prototype 2D-BOLD-EPI sequence capable of performing PMC [3]. Acquisition parameters included: TE=30ms, FOV=192x192x128mm^3, voxel resolution=2.04x2.04x2.62mm^3, with 100 volumes per scan. For each 2D-EPI, 49 interleaved slices per volume were acquired, with TR of 3s, flip angle of 90, and a pixel bandwidth of 2315Hz.
Rigid-body head motion was recorded using a markerless motion tracking system (Tracoline TCL 3.2, TracInnovations, Ballerup, Denmark) [4,5]. To induce head motion artifacts, participants were instructed to perform exaggerated breathing motion (Fig. 1).
Data preprocessing included Slice Timing Correction, rigid-body volume realignment (aligning all volumes to the first via iterative Gauss-Newton L2 minimization), spatial smoothing (FWHM 5.2 mm) and co-registration of fMRI to T1 weighted structural scans using PyPreprocess [6,7]. Single-subject statistical analyses were conducted using Nilearn [8]. A high pass-temporal filter was used to remove low-frequency drift below 0.025 Hz [9].
To evaluate PMC´s impact, we compared activation maps across four conditions: (1) PMC-off and (2) PMC-on with no intentional motion; (3) PMC-off and (4) PMC-on with intentional head motion. For each condition, the full preprocessing pipeline was applied, including General Linear Model (GLM) analysis using motion parameters estimated from retrospective volume alignment as regressors-of-no-interest. Temporal Signal to Noise Ratio (tSNR) maps from acquisitions corrected by RMC were compared to directly assess the effects of PMC on signal stability.

Results

Figure 1 shows the recorded motion parameters for each of the three subjects (Sub-1, Sub-2, and Sub-3) performing intentional heavy breathing motion in scans with PMC-off and PMC-on. All three subjects were able to produce motion with similar amplitude and breathing frequency in both scans (PMC-off and PMC-on).
Figure 2 shows tSNR maps for acquisitions under intentional motion. Enabling PMC results in an overall increase in tSNR for Sub-1 and Sub-2, with the most notable improvements observed in the frontal brain regions. Similarly, for Sub-3, PMC enhances tSNR in the frontal areas; however, no overall tSNR increase is observed in this subject.
Figure 3 presents activation maps for three subjects across four conditions: PMC-off and PMC-on with and without intentional motion.
In the Still PMC-off condition, all subjects exhibit expected activation in the primary motor cortex and other motor-related regions. In the Still PMC-on, all subjects show more localized activation in the primary motor cortex. However, in the PMC-off condition with motion, activation in the primary motor cortex is absent for Sub-1 and Sub-2. Enabling PMC in the motion condition recovers some activation in the primary motor cortex for these two subjects, though differences remain compared to the still PMC-off condition.

Discussion and Conclusion

Our results suggest that prospective motion correction (PMC) may help preserve reliable fMRI activation maps during head motion, though the benefits vary. Without PMC, motion significantly disrupts activation patterns in motor areas, with some subjects showing no detectable activation, while others show spurious activation due to motion. When PMC is enabled, expected activation in the primary motor cortex partially reappears, and in the still case it seems to localize it better, suggesting an improvement in spatial specificity.
The impact of PMC is also observed in tSNR maps, where substantial improvements are observed when PMC is enabled compared to just RMC, especially in the front of the brain where we expect the highest voxel displacement from the performed motion. Our PMC-implementation allows for FOV-updates of individual slices in real-time enabling correction of effects from in-volume motion not otherwise correctible with conventional image-based alignment,

such as through-plane motion and spin-history effects (Figure 4). Unlike other studies that rely on external markers [2], our approach is entirely markerless and applicable to 2D-EPI sequences, making it suitable for a realistic clinical setting.
Some differences remain between activations maps in still scans and PMC-on scans primarily due to secondary effects of motion not correctible with the applied method, such as motion-induced B0 and B1 field disturbance leading to non-rigid geometric distortions and local signal intensity variations.

Acknowledgements

No acknowledgement found.

References

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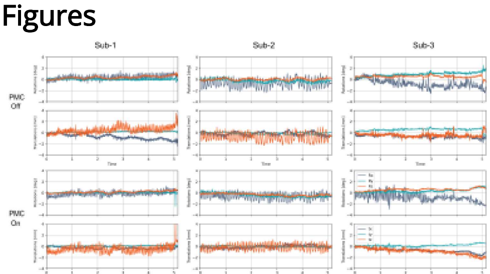
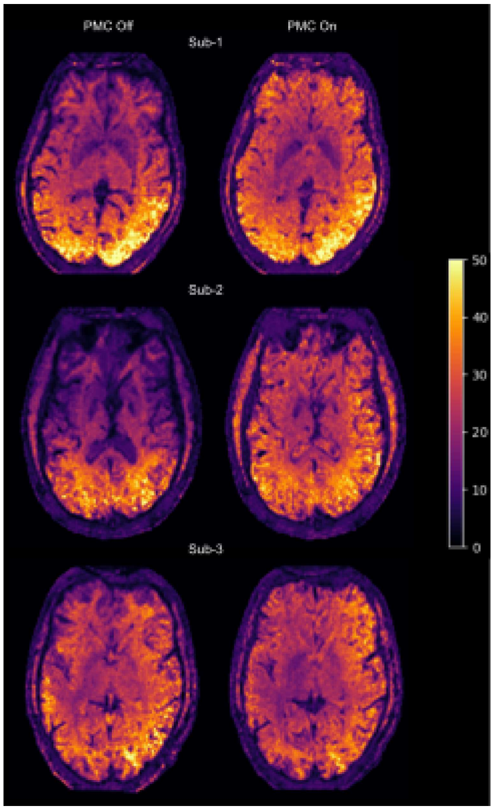
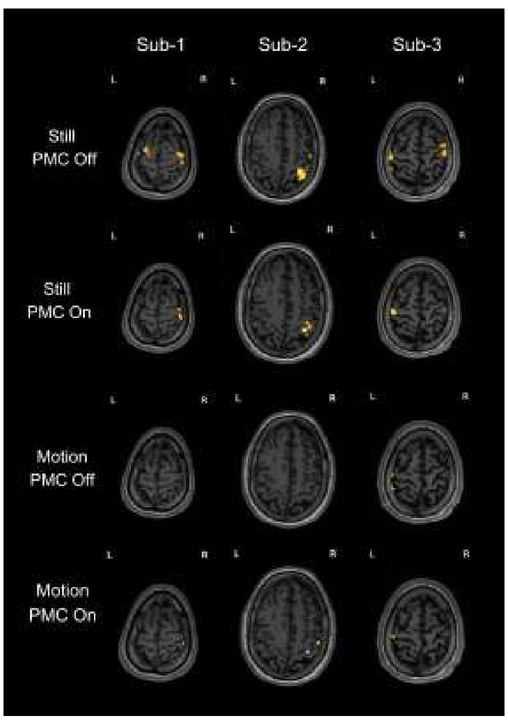
Figures



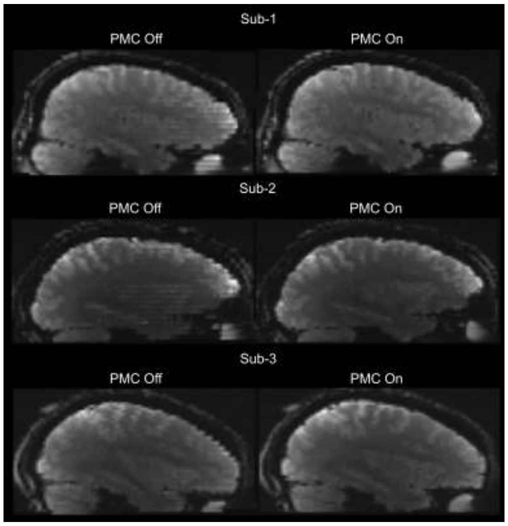
Recorded motion parameters from Sub 1-3 during acquisitions with intentional head motion and Prospective Motion Correction (PMC) Off and On.



Temporal Signal to Noise Ratio (tSNR) maps calculated from acquisitions with Prospective Motion Correction (PMC) On and Off for Sub 1-3. Retrospective motion correction has been applied to both acquisitions prior to calculations of the tSNR.



Activation maps for three subjects (Sub-1 and Sub-2: right-handed, Sub-3: left-handed) performing motor task under three conditions: Still PMC Off, Motion PMC Off, and Motion PMC On. With PMC Off under motion, motor cortex activation is reduced or absent. When PMC is On with motion, expected activation reappears, especially in Sub-1 and Sub-2, demonstrating PMC's effectiveness in preserving functional activation under movement. Results are Bonferroni-corrected and thresholded at $p < 0.05$.



Sagittal slices of volumes acquired on Sub 1-3 representative of image quality with PMC-off and PMC-on during heavy breathing. Individual slices appear non-contiguous and with varying intensity in the PMC-off scan due to uncorrected in-plane motion and contrast differences resulting from spin-history of overlapping slices. The per-slice correction with PMC-on ensures both more contiguous slices and more homogenous signal across slices