TracInnovations

Prospective Motion Correction of Functional MRI Using Markerless Tracking

Jesús Díaz Pereira[1], Malte Laustsen[1], Jakob Slipsager[1], Robert Frost[2,3], Patrick Fisher[4], Marta M Correia[5], José P Marques[6], Thomas Gaass[1]

[1]TracInnovations, Ballerup, Denmark, [2]Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Charlestown, MA, United States, [3]Department of Radiology, Harvard Medical School, Boston, MA, United States, [4]Copenhagen University Hospital, Rigshospitalet, Copenhagen, Denmark, [5]MRC-Cognition and Brain Sciences Unit, University of Cambridge, UK, [6] Donders Institute for Brain, Cognition and Behaviour, Radboud University, Nijmegen, The Netherlands

Functional MRI (fMRI) is a powerful tool for studying brain activity, but even slight head movements can degrade data quality, introducing artifacts and spurious results [1,2]. Conventional motion correction methods—such as realignment and regression—often fail, especially when motion aligns with task events or during single-slice imaging, where "spin-history" artifacts persist despite registration efforts [3].

Prospective motion correction (PMC), which adjusts imaging parameters in real time, offers a promising alternative. It has been shown to enhance fMRI sensitivity, particularly in high-resolution studies. For example, Huang et al. demonstrated that PMC improves pattern decoding accuracy by reducing motion-related noise [4].

However, PMC adoption is limited by the existing tracking technologies, which often require external markers or coil—solutions that can be uncomfortable or unsuitable in clinical contexts [5,6]. Markerless external optical systems like TracInnovations' TCL3 address this by using near-infrared imaging to create 3D facial point clouds for real-time tracking, offering a comfortable and efficient alternative.

In partnership with major MRI vendors, TracInnovations has developed a next-generation motion correction platform centered on the FDA-cleared and CE marked TCL3 system, which delivers continuous head pose updates and integrates directly with scanner software for seamless PMC [7,8].

Comfort Without Compromise

Patient discomfort—especially among children, older adults, and during long scans—often increases motion during MRI. Traditional tracking systems that require facial markers can be intrusive and are frequently unsuitable in clinical environments.
The TCL3 system eliminates this issue through a fully markerless approach using near-infrared light. This non-contact, invisible technology captures high-resolution facial depth maps at high frame rates, enabling continuous head pose estimation without compromising comfort.

High-Precision Tracking with Virtual Markers

TCL3 generates dense 3D point clouds (cf. Fig.1) of the face, creating thousands of "virtual markers" to track head position every 30 milliseconds. This method ensures high-precision motion correction without physical markers or facial model assumptions, making it effective for detecting even subtle head motion.

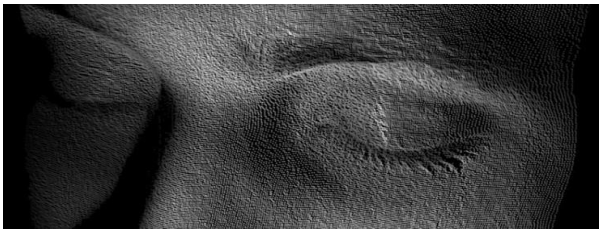

Fig. 1: 3D point cloud of a patient face consisting of thousands of single points.

Seamless Integration into Clinical Workflow

MRI environments demand a high degree of compatibility and operational simplicity. Recognising this, TracInnovations has designed the TCL3 system to integrate directly into the workflow of radiographers and clinical staff, without requiring modification of standard accessories or procedures. Its compact, non-contact setup and compatibility with a wide

range of patient positioning configurations make it well-suited to both research and routine clinical neurological applications.

Prospective and Retrospective Correction Options

Recognizing the complexity of human motion during MRI (cf. Fig. 2), TCL3 supports both real-time prospective (PMC) and retrospective motion correction (RMC). This flexibility allows tailored correction strategies for different imaging goals, whether temporal accuracy in fMRI or structural precision.

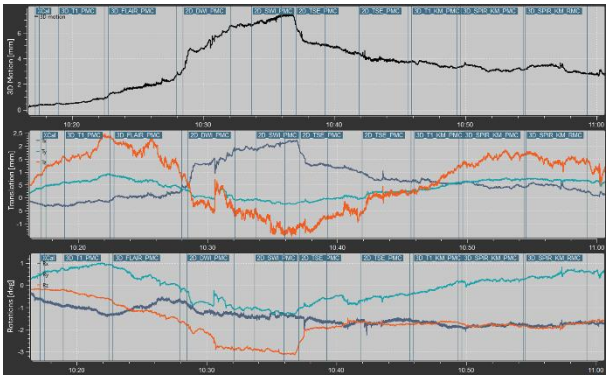

Fig. 2: Plots of rotational and translational motion in three degrees of freedom each, occurring during one complete scan session.

Evaluating Tracoline for Functional MRI: From Phantom to Human Studies

To explore the feasibility of using Tracoline-informed prospective motion correction (PMC) in functional MRI, we initiated studies designed in close collaboration with experts from the MRC Cognition and Brain Sciences Unit, University of Cambridge, the Donders Institute for Brain, Cognition and Behaviour, and the Neurobiology Research Unit at Copenhagen University Hospital.

The goal was to evaluate the performance of the TCL3 system—from stable phantom conditions to realistic human scenarios involving task-based fMRI. This allowed us to assess both the technical robustness and the practical benefits of PMC in representative use cases.

General Methods

All experiments employed the TCL3 system for head motion tracking, with real-time pose estimates processed via TracSuite 3.1. This enabled slice-by-slice prospective motion correction (PMC) during acquisition. Imaging was performed on a 3T Siemens Prisma scanner using an interleaved 2D-EPI BOLD sequence [9] and a 64-channel head/neck coil.

Post-acquisition, data was preprocessed using the *fMRIPrep* pipeline, which includes slice-time correction, rigid-body realignment, and spatial normalization to the MNI152 template [10]. Data quality was assessed both visually and quantitatively, focusing on framewise displacement (FD) and temporal signal-to-noise ratio (tSNR).

The protocol was collaboratively designed to align with clinical and research priorities, ensuring that both the technical evaluation and task paradigms supported real-world applicability.

Phantom Experiment: Establishing Baseline Signal Stability

To determine whether PMC introduces signal instability in the absence of motion, we conducted a controlled scan using a stationary water phantom. Two 150-volume BOLD runs (TR = 1260 ms, 3 mm isotropic, no acceleration) were acquired with PMC turned on and off, respectively.

Voxel-wise tSNR - defined as the mean signal over time divided by its temporal standard deviation—was calculated from the raw data.

As shown in Fig. 3, tSNR maps for both conditions were visually indistinguishable, exhibiting uniform signal across the phantom. Corresponding histograms confirmed near-identical distributions, with no significant differences in mean or variance. These results confirm that Tracoline-informed PMC does not degrade signal quality in the absence of motion, establishing a critical baseline for its use in dynamic studies.

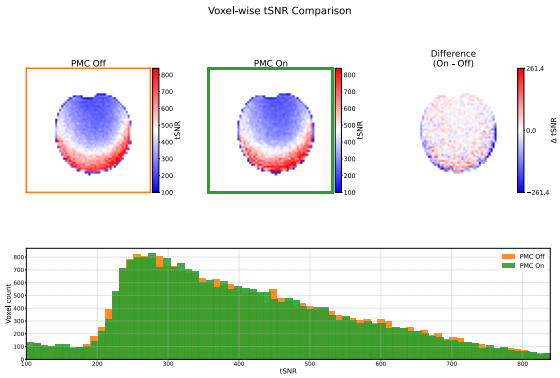

Fig. 3: tSNR maps from a still phantom scan with PMC Off (top left) and PMC On (top middle). The histogram (bottom) shows overlapping tSNR distributions for both conditions, confirming signal consistency.

Volunteer Experiment: Assessing PMC Under Low-Motion Conditions

Following phantom validation, we investigated whether Tracoline's markerless PMC improves fMRI signal stability under low-motion conditions—a key scenario for high-resolution imaging.

A healthy adult volunteer underwent two BOLD runs while viewing a flickering checkerboard stimulus in a block design, instructed to remain still throughout [4]. Scans (3 mm isotropic, TR = 1260 ms, 650 volumes, no GRAPPA/multiband) were acquired with PMC disabled and enabled, respectively.

Signal Quality Assessment

Voxel-wise tSNR was computed from the raw BOLD data. Despite minimal head motion in both runs (per tracking data), Fig. 4 shows higher tSNR across cortical regions with PMC enabled, indicating enhanced signal stability.

Histograms further supported this, showing a rightward shift and narrower spread in the PMC On condition—reflecting lower temporal variance and improved signal reliability.

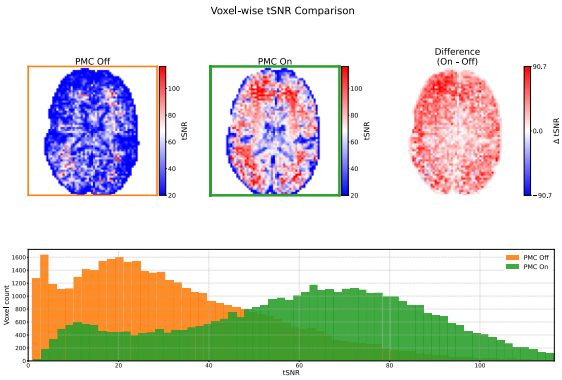

Fig. 4: tSNR maps and histograms from a visual task fMRI scan in a healthy volunteer. PMC On (top middle) shows improved signal homogeneity and in the histogram (bottom) a shift toward higher tSNR values relative to PMC Off, despite minimal gross motion in both runs.

Retrospective Realignment: Motion Estimates

To evaluate PMC's effect on head motion, we applied retrospective rigid-body realignment using *fMRIPrep*. Translational and rotational parameters, along with framewise displacement (FD), were extracted per volume.

As shown below in Fig. 5, the PMC Off scan displayed minor but cumulative motion drift. In contrast, the PMC On scan showed flatter traces and consistently lower FD, indicating reduced intra-scan motion and improved stability.

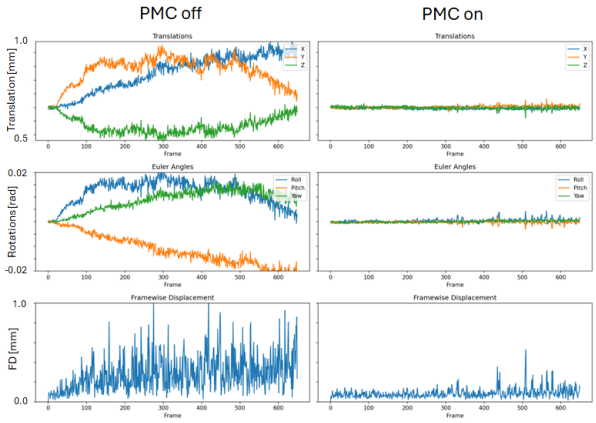

Fig. 5: Retrospective motion estimates (translations, rotations, and FD) from a volunteer fMRI scan with PMC Off (left) and PMC On (right). PMC reduces residual motion variability, even in a low-motion scenario.

Discussion and Outlook

These preliminary findings show that Tracoline-informed PMC reduces subtle head motion and improves signal stability in fMRI, even in low-motion conditions. Although the volunteer was instructed to remain still, retrospective realignment and FD metrics revealed minor drift mitigated by PMC. tSNR analyses further confirmed improved temporal stability with Tracoline-informed PMC enabled.

While the improvements were modest—expected in a low-motion scenario—they were consistent and measurable, demonstrating PMC's capacity to enhance data quality beyond what conventional quality control metrics might capture.

Activation maps were deliberately excluded from this initial assessment due to their susceptibility to confounding factors such as task compliance, baseline differences, and hemodynamic variability. Instead, the focus was on objective, generalizable metrics—tSNR and motion parameters—more appropriate for early-stage technical validation.

Looking ahead, a larger volunteer cohort (n = 10–15) will enable statistical validation and group-level analysis, including activation outcomes. This will allow for more comprehensive evaluation across different tasks and motion profiles and assess PMC's robustness and generalizability.

Overall, these early results support the feasibility of integrating markerless PMC into standard fMRI workflows. As the study expands, we aim to better characterize its impact on activation reliability and reproducibility—key goals for both clinical and cognitive neuroscience applications.

References

1. Haller S, Bartsch AJ. Pitfalls in fMRI. *Eur Radiol*. 2009;19(11):2689–706.
2. Van Dijk KRA, Sabuncu MR, Buckner RL. The influence of head motion on intrinsic functional connectivity MRI. *Neuroimage*. 2012;59(1):431–8.
3. Yancey SE, Rotenberg DJ, Tam F, Chiew M, Ranieri S, Biswas L, et al. Spin-history artifact during functional MRI: Potential for adaptive correction. Medical Physics. 2011 Jul 25;38(8):4634–46.
4. Huang P, Carlin JD, Alink A, Kriegeskorte N, Henson RN, Correia MM. Prospective motion correction improves the sensitivity of fMRI pattern decoding. *Hum Brain Mapp*. 2018;39(10):4018–31.
5. Todd N, Josephs O, Callaghan MF, Lutti A, Weiskopf N. Prospective motion correction of 3D echo-planar imaging data for functional MRI using optical tracking. *Neuroimage*. 2015;113:1–12.
6. Forman C, Aksoy M, Hornegger J, Bammer R. Self-encoded marker for optical prospective head motion correction in MRI. *Med Image Anal*. 2011;15(5):708–19.
7. Slipsager JM, Glimberg SL, Højgaard L, Paulsen RR, Wighton P, Tisdall MD, et al. Comparison of prospective and retrospective motion correction in 3D-encoded neuroanatomical MRI. *Magn Reson Med*. 2021;87(2):629–45.
8. Eichhorn H, Frost R, Kongsgaard A, Kettless K, Slipsager J, Glimberg S, et al. Evaluating the performance of markerless prospective motion correction and selective reacquisition in a general clinical protocol for brain MRI. *PsyArXiv (OSF Preprints)*. 2022 Nov 9.
9. Frost R, Wighton P, Karahanoğlu FI, Robertson RL, Grant PE, Fischl B, et al. Markerless high-frequency prospective motion correction for neuroanatomical MRI. *Magn Reson Med*. 2019;82(1):126–44. Available from: https://pubmed.ncbi.nlm.nih.gov/30821010/
10. Esteban O, Markiewicz CJ, Blair RW, Moodie CA, Isik AI, Erramuzpe A, et al. fMRIPrep: a robust preprocessing pipeline for functional MRI. *Nat Methods*. 2019;16(1):111–6. Available from: https://www.nature.com/articles/s41592-018-0235-4