On the Robustness of Prospective Motion Correction for Clinical Routine

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Purpose: Despite the recent advances in prospective motion correction (PMC) for the correction of rigid body motion, the application of this technique to clinical routine still lacks behind [1]. External tracking and motion correction has been shown to be applicable to a wide range of sequences and to provide sufficient accuracy and precision to improve even data from cooperative volunteers. However, when used in patients, problems such as marker fixation and involuntary skin motion limit the abilities of PMC and can even lead to additional motion artifacts. The aim of this work was to address this last key barrier to help bring PMC to clinical routine.

Methods: All experiments were performed on a 3 T Magnetom Trio (Siemens Healthcare, Germany) using an optical in-bore system [2] to track head position. This system requires the fixation of a special encoded marker which allows position information in six degrees of freedom to be calculated from a single camera image. A turbo spin echo (TSE), a gradient echo (GRE), and an MP-RAGE sequence were modified to perform PMC.

In a first step, different marker fixation methods were tested. To provide an estimate of the relative motion between marker and skull, a short 3D GRE protocol (11 sec) was applied before and after each experiment correcting for any rigid body motion between them. The position difference resulting from maker motion was then measured using PACE [3]. Three different fixation approaches were tested (Fig. 1): double sided tape with a plastic stick (A), modeling clay (B), and a mouthpiece (C). The mouthpiece provides optimal fixation and is often used for volunteer scanning. However, for clinical routine a more comfortable option is needed. The two other fixations were comfortable for the volunteer and did not restrict normal breathing. Additionally, a filter model was developed to detect any motion pattern related to involuntary skin motion. This model is based on two Kalman filters. A fast filter is used to provide an accurate estimate of the actual marker position. However, if fast rotations around the marker axis are detected (which would mean a large un-physiologic motion of the back of the head), a slower filter is instead used to predict the new position. This filter model was developed and optimized based on a database of tracking data collected during a pilot patient study (50 subjects). When extreme motion is detected by the filter, the sequence is able to reject and reacquire the affected portion of the data. Several five minute TSE datasets (TR/TE:6500/87, 0.3×0.3×2mm³, 786×612matrix, 3 averages, GRAPPA 2, with PMC) were acquired with each fixation method. The volunteers were instructed to perform cooperatively. The prospective filter was tested in an in vivo experiment, where the volunteer was instructed to perform uncooperatively. This included not only motion but also skin twitching and touching the head coil with the marker. A four minute MP-RAGE protocol (TR/TE:6500/87, 0.3×0.3×2mm³, 786×612matrix, 3 averages, GRAPPA 2) with PMC was run three times: without PMC and with PMC with and without the filter. Double sided tape (Fig.1 A) was used as marker fixation.

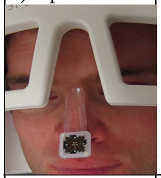
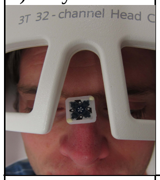
Fixation	Subject	Residual Error	
		Rotations (deg)	Translations (mm)
A)Tape	S1, cooperative	0.21	0.39
	uncooperative	1.52	0.81
	S2, cooperative	1.89	1.93
	uncooperative	0.82	1.86
	S3, cooperative	0.89	0.50
	uncooperative	0.78	0.52
	uncooperative	1.07	0.68
	mean, cooperative	1.00	0.94
	uncooperative	1.05	0.97
B) Clay	S1, cooperative	0.57	0.20
	uncooperative	0.61	0.31
	S2, cooperative	0.23	0.18
	uncooperative	0.81	0.74
	S3, cooperative	0.71	0.47
	uncooperative	1.43	0.87
	uncooperative	0.98	0.61
	mean, cooperative	0.50	0.28
	uncooperative	0.96	0.63
C) Mouthpiece	S1, cooperative	0.25	0.06
	uncooperative	1.15	0.44

Fig. 1: Three marker fixation approaches were compared by determining the residual error between two volumes after prospective motion correction. Each marker fixation technique was tested in 3 volunteers.

Results: Figure 1 shows the three possible marker fixations tested and the corresponding position difference measured before and after a five minute scan. The mouthpiece provides the best stability however, is not practical for patients. The other fixations are sufficiently comfortable however, the coupling seems not rigid enough for high resolution scanning and motion artifacts can be seen in some of the TSE data (Fig.2 A). Out of the presented options only the mouthpiece enables reliable high resolution acquisitions with PMC (Fig.2 C). Figure 3 shows tracking data collected during a in-vivo scan. During the first seconds head motion related to swallowing (1deg) can be seen folowed by two fast peaks indicating (3deg) skin motion. The blue line shows the unfiltered data, the green line displays the result after prospective filtering. The images presented in Fig. 4 show the results of the in-vivo MP-RAGE experiments. In (A) the experiment was performed without PMC and the uncorrected head motion leads to strong artifacts in the frontal part of the brain. In the second image (B), PMC was applied and corrects for head motion. However, the non rigid coupling between marker and skull introduces new motion artifacts especially at the back of the head. These were reduced when the filter model was applied (C). For quantification the average edge strength (AES,[4]) was calcultated for each dataset.

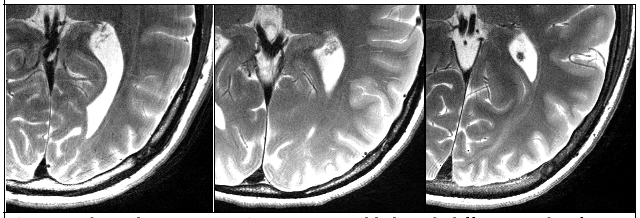


Fig. 2: High resolution images (TSE, PMC enabled) with different marker fixation on cooperative volunteers. A: Tape (S3), B: Clay (S2), C: Mouthpiece (S1)

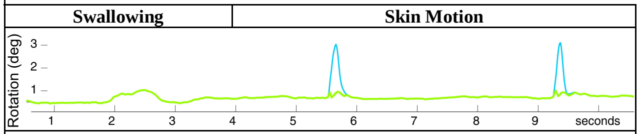
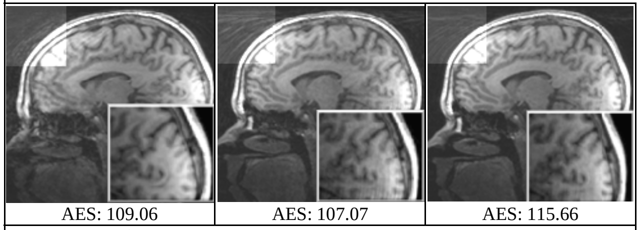


Fig. 3: Tracking data from an in vivo experiment involving fast head motion (e.g. swallowing) and voluntary skin motion. Unfiltered data (blue) is compared to the filtered data (green). The model detects skin motion and provides a position estimate during the corrupted sections.

Discussion: The comparison of the different marker fixation methods (Fig. 1 and Fig. 2) suggests the use of a mouthpiece for best results. However, for clinical routine a mouthpiece is not an option. Therefore a good solution to this problem is still missing. In Fig. 3 the output of the prospective filter is displayed (filtered data in green) compared to the original tracking data (blue). While fast head motion (e.g. swallowing) is still tracked by the filter, skin motion was successfully detected and a better position estimate was provided by the model. The data presented in Fig. 4 display the benefit possible through advanced filtering in this experiment with remarkably difficult conditions for PMC. The strong motion artifacts due to skin motion are prevented, while the correction of detected rigid body motion still provides a notable improvement over the uncorrected case. Comparison of the AES underlines this.



AES: 109.06 AES: 107.07 AES: 115.66

Fig. 4: Results from a volunteer instructed to behave uncooperatively (swallowing and skin motion). (A) No PMC (B) PMC without filter (C) PMC with filter. The average edge strength (AES) was calculated for quantification.

Conclusion: The coupling between tracking marker and the object of interest is crucial for the success of PMC and currently a limiting factor in the success of PMC in patients. The use of the new filter model lowers the requirements on the marker fixation as periods affected by non-rigid motion can be detected. This could greatly improve its robustness in clinical routine.

Acknowledgements: This work is a part of the INUMAC project supported by the German Federal Ministry of Education and Research, grant #01EQ0605. We thank Brian Armstrong and Todd Kusik for their assistance with the moiré phase tracking (MPT) system used in this work.

References: [1] Maclaren et al.,DOI10.1002/mrm.24314 [2]Maclaren et al.,PLOS ONE 2012 [3] Thesen et al.,MRM 2000Sep;44(3):457-65 [4] Aksoy et al.,MRM 67:1237–1251(2012)