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Real-time motion analytics during brain MRI improve data quality and reduce costs

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ABSTRACT

Head motion systematically distorts clinical and research MRI data. Motion artifacts have biased findings from many structural and functional brain MRI studies. An effective way to remove motion artifacts is to exclude MRI data frames affected by head motion. However, such post-hoc frame censoring can lead to data loss rates of 50% or more in our pediatric patient cohorts. Hence, many scanner operators collect additional 'buffer data', an expensive practice that, by itself, does not guarantee sufficient high-quality MRI data for a given participant. Therefore, we developed an easy-to-setup, easy-to-use Framewise Integrated Real-time MRI Monitoring (FIRMM) software suite that provides scanner operators with head motion analytics in real-time, allowing them to scan each subject until the desired amount of low-movement data has been collected. Our analyses show that using FIRMM to identify the ideal scan time for each person can reduce total brain MRI scan times and associated costs by 50% or more.

1. Introduction

Head motion represents one of the greatest obstacles to collecting quality brain MRIs in humans. Head motion distorts both structural (T1-weighted, T2-weighted, etc.) and blood-oxygenation level dependent (BOLD) functional MRI data (task-driven [fMRI], resting state functional connectivity [rs-fcMRI]) (Power et al., 2012, 2013, 2015; Reuter et al., 2015; Satterthwaite et al., 2012, 2013; Siegel et al., 2016; Siegel et al., 2014; Van Dijk et al., 2012; Yan et al., 2013; Yendiki et al., 2014). It has been shown that even sub-millimeter head movements (i.e., micro-movements) systematically alter structural and functional MRI data (Fair et al., 2012; Power et al., 2012; Satterthwaite et al., 2012; Van Dijk et al., 2012; Yan et al., 2013). Hence, much effort has been devoted to developing various effective post-acquisition methods for the removal of head motion artifacts from BOLD data (Behzadi et al., 2007; Burgess et al., 2016; Ciric et al., 2017; Di Martino et al., 2014; Griffanti et al., 2014; Jo et al., 2013; Kundu et al., 2013; Muschelli et al., 2014; Patel et al., 2014; Power, 2017; Power et al., 2012, 2013, 2015; Pruim et al., 2015a; Pruim et al., 2015b; Salimi-Khorshidi et al., 2014; Satterthwaite et al., 2012, 2013; Siegel et al., 2014; Van Dijk et al., 2012).

Head movement from one MRI data frame to the next, rather than absolute movement away from the reference frame, accounts for the most significant BOLD signal distortions (Ciric et al., 2017; Power et al., 2012; Satterthwaite et al., 2012; Van Dijk et al., 2012). Motion related artifacts are strongly correlated with measures of framewise displacement (FD), which represent the sum of the absolute head movements in all six rigid body directions from frame to frame. Recently, Ciric et al. directly compared the 14 most commonly used motion removal methods (Ciric

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et al., 2017). Their benchmarking showed that post-hoc frame censoring techniques which remove data frames with FD values above a certain threshold are very effective for removing the residual relationship between motion and brain connectivity, as well as the distance dependence of this artifact. However, frame-censoring BOLD data based on FD comes at a steep price, because it necessarily involves data loss.

In our own pediatric patient cohorts, frame censoring excluded over 50% of rs-fcMRI data collected when using strict frame censoring criteria (FD > 0.2 mm, Supplementary Fig. 1; e.g (Greene et al., 2016).). The accuracy of MRI measures improves with longer data acquisition periods (Laumann et al., 2015). Hence, a minimum number of data frames are required to obtain reliable estimates (Dosenbach et al., 2010), leaving investigators committed to frame-censoring with a difficult choice – lose the participant completely or collect more data. This 'overscanning,' required to remove distance-dependent motion artifact while maintaining sample sizes, has drastically increased the cost and duration of brain MRIs.

Recently developed structural MRI sequences with so-called prospective motion correction use a similar frame-censoring approach to reduce the deleterious effects of head motion. These MRI sequences pair each structural data acquisition with a fast, low resolution snap shot of the whole brain (echo-planar image = EPI), which is then used as a marker or navigator for head motion (Alhamud et al., 2015, 2016; Benner et al., 2011; Brown et al., 2010; Frost et al., 2016; Kuperman et al., 2011; Reuter et al., 2015; Stoeckel et al., 2014; Taylor et al., 2016; Tisdall et al., 2012, 2016; White et al., 2010). These motion-correcting structural sequences calculate relative motion between successive navigator images and use this information to mark the linked structural data frames for exclusion and reacquisition. In this manner, structural data frames are censored, which also increases the duration and cost of structural MRIs.

For both structural and functional MRI, access to real-time information about in-scanner head movement could greatly reduce the costs of MRI by eliminating the need for overscanning. Real-time motion monitoring would allow scanner operators to continue each scan until the desired number of low-movement data frames have been acquired (scanning-to-criterion). Even for investigators who do not implement frame censoring approaches, real-time motion monitoring would provide immediate, valuable information about scan quality. For example, access to accurate real-time FD data would enable scanner operators to intervene early on, if subjects are moving too much.

On many MRI scanners, operators can view EPI data (e.g. BOLD) on the console as they are being reconstructed. Unfortunately, the human eye cannot reliably detect the minute head movements (0.2 mm summed across all directions) that negatively affect MRI data. Thus, watching the raw EPI images on the console as they are being acquired is inadequate for making decisions about ongoing scans. Attempts have been made to acquire real-time proxies for FD using expensive cameras and lasers (Van Essen et al., 2013). Unfortunately, such proxies of head movement are only poorly correlated with FD because they cannot distinguish movements of the face and scalp from brain movement.

To simultaneously improve MRI data quality and reduce costs, we developed the easy-to-use Framewise Integrated Real-time MRI Monitoring (FIRMM) software suite, which calculates and displays FD values and summary motion statistics for brain MRI data in real time (Fig. 1, Supplementary Mov. 1). We focused on functional MRI data to develop and validate FIRMM, but it can be customized to monitor head motion during specialized structural MRI sequences that utilize navigators for motion correction.

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.neuroimage.2017.08.025.

FIRMM's accuracy and cost savings were verified using several large rs-fcMRI data sets from different patient and control cohorts (1134 total scan sessions). First we characterized head movement (FD) for our Autism Spectrum Disorder (ASD), Attention Deficit Hyperactivity Disorder (ADHD), Family History of Alcoholism (FHA) and Control cohorts, using an Offline, post-hoc processing stream (Fair et al., 2012). Next we validated the accuracy of the FIRMM FD values by comparing them to those derived from the Offline processing stream. We then calculated the time savings generated when using FIRMM to scan to criterion. Finally, we tested FIRMM's real-world utility and durability in a new cohort of 29 children and adolescents.

2. Materials and methods

2.1. FIRMM software suite

FIRMM is built using several software packages, each with a specific purpose, to make installation and usage easier and more reliable. Installation requires a Docker-capable Linux system. Operation on Ubuntu 14.04 and CentOS 7 operating systems have both been tested and work well. Installation is accomplished via a downloadable shell script which retrieves and installs FIRMM's components. After installation FIRMM is launched with a shell script tailored to use a pre-built Docker image. FIRMM's components are the compiled MATLAB (R2016b) binary backend which only requires an included MATLAB compiler runtime to run, shell scripts for image processing, a Docker image containing image processing software dependencies, and a Django web application front end. The compiled MATLAB binary backend monitors an incoming folder waiting for a new subfolder that has the current date and contains images created within the last few minutes. The backend does shell script image processing only on new functional images. The required image processing software is already installed and configured inside the Docker image. Results are visually displayed in the Django web application frontend as plots and tables in a Chromium web browser.

2.2. Real-time processing of DICOM images

As soon as each frame/volume of EPI (echo planar imaging) data is acquired and reconstructed into DICOM format, it is transferred to a pre-designated folder that the FIRMM software monitors for new images. On Siemens scanners, rapid DICOM transfer can be achieved by selecting the 'send IMA' option in the ideacmdtool utility (requires 'advanced user' mode). On Siemens scanners one can also use an MS-DOS batch script to add start 'FIRMM' and stop 'FIRMM' buttons to the scanner operating system. This package is a standalone script that can be downloaded with FIRMM.

FIRMM reads the DICOM headers and uses the header information to enter data sequentially into a job queuing system. DICOMs are processed in the temporal order they were acquired. FIRMM converts DICOMs into 4dfp format prior to any further processing. FIRMM realigns EPI data using the 4dfp cross_realign3d_4dfp algorithm (Smyser et al., 2010). The cross_realign3d_4dfp algorithm run by FIRMM has been optimized for computational speed, thus frame-to-frame image intensity normalization has been disabled and the realigned data are not written out, only the alignment parameters. Alternative alignment algorithms operating on NIfTI format data can also be utilized and will be made available in future releases. The EPI images do not undergo pre-processing steps typically utilized in offline data analyses. For EPI images with a spatial resolution smaller than 4 mm^3, data are down-sampled to 4 mm^3 prior to realignment to increase processing speed.

2.3. Estimation of head realignments

Each data frame (volume) is aligned to the first frame of the run through a series of rigid body transforms, T_i, where i indexes the spatial registration of frame i to a reference of frame 1, starting with the second frame. Each transform is calculated by minimizing the registration error:

$$\varepsilon_i = \left(s\bar{I}_i(T(\vec{x}))^{-} - I_1(\vec{x})\right)^2,$$

such that $I(\vec{x})$ is the image intensity at locus $\vec{x}$ and s is a scalar factor that compensates for fluctuations in mean signal intensity, spatially