Participant Factors That Contribute to Magnetic Resonance Imaging Motion Artifacts in Children With Mild Traumatic Brain Injury or Orthopedic Injury

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Abstract

Background: Motion can compromise image quality and confound results, especially in pediatric research. This study evaluated qualitative and quantitative approaches to motion artifacts detection and correction, and whether motion artifacts relate to injury history, age, or sex in children with mild traumatic brain injury or orthopedic injury relative to typically developing children. The concordance between qualitative and quantitative motion ratings was also examined.

Method: Children aged 8-16 years with mild traumatic brain injury (*n*=141) or orthopedic injury (*n*=73) were recruited from the emergency department and completed an MRI scan roughly 2 weeks post-injury. Typically developing children (*n*=41) completed a single MRI scan. T1- and diffusion-weighted images were visually inspected and rated for motion artifacts by trained examiners. Quantitative estimates of motion artifacts were derived from FreeSurfer and FSL.

Results: Age (younger > older) and sex (boys > girls) were significantly associated with motion artifacts on both T1- and diffusion-weighted images. Children with mild traumatic brain or orthopedic injury had significantly more motion-corrupted diffusion-weighted volumes than typically developing children, but mild traumatic brain injury and orthopedic injury groups did not differ from each other. The exclusion of motion-corrupted volumes did not significantly change diffusion tensor imaging metrics.

Discussion: Results indicate that automated quantitative estimates of motion artifacts, which are less labour-intensive than manual methods, are appropriate. Results have implications for the reliability of structural magnetic resonance imaging research and highlight the importance of considering motion artifacts in studies of pediatric mild traumatic brain injury.

Introduction

Pediatric mild traumatic brain injury (mTBI) is a major global public health concern that affects millions of children annually (Gilchrist et al., 2011; Langlois et al., 2006; Mayer et al., 2017; Ruff et al., 2009). Despite its high incidence and the potential vulnerability of the developing brain, no gold standard exists for clinical diagnosis or prognosis due to the absence of known biomarkers for mTBI (Lumba-Brown et al., 2018; Mayer et al., 2018; Yeates, Beauchamp, Craig, Doan, Zemek, Bjornson, Gravel, Mikrogianakis, Goodyear, Abdeen, Beaulieu, Dehaes, Deschenes, Harris, Lebel, Lamont, Williamson, Barlow, Bernier, Brooks, Emery, Freedman, Kowalski, Mrklas, Tomfohr-Madsen, & Schneider, 2017). Mounting evidence suggests that structural magnetic resonance imaging (MRI) techniques can potentially help identify biomarkers for pediatric mTBI (Mayer et al., 2018). However, MRI is highly susceptible to motion. When severe, motion artifacts can preclude data processing and analysis and result in data loss, and also bias quantitative estimates of brain structure and lead to reduced validity and/or misinterpretation of results. Motion artifact is particularly relevant to pediatric mTBI, both because motion is inversely associated with age in typically-developing (TD) children (Afacan et al., 2016; Alexander-Bloch et al., 2016; Blumenthal et al., 2002; Ducharme et al., 2016; Rosen et al., 2018; Satterthwaite et al., 2013), and because behaviors

associated with increased motion (e.g., impulsivity, hyperactivity; (Gerring et al., 1998; Lee et al., 2008) are also associated with increased susceptibility to injury (Alosco et al., 2014). Thus, understanding, quantifying, and appropriately mitigating motion in neuroimaging studies of pediatric mTBI is imperative.

A large number of quality assurance procedures exist for detecting and minimizing the influence of motion in neuroimaging data analysis. To date, most neuroimaging studies of pediatric mTBI have used manual approaches (i.e., visual inspection) to assess data quality. Automated approaches are more feasible in large studies, and have been found to be highly correlated with manual ratings of motion in T1-weighted images (Fischl, 2012; Rosen et al., 2018). While automated approaches are available to quantify motion in diffusion MRI, their applicability and generalizability to neurodevelopmental populations, such as children with mTBI, is unclear. Once motion is detected in an image, important methodological decisions must be made to minimize any potential bias on quantitative metrics. Prior studies have suggested that T1-weighted scans with severe motion artifacts should be excluded from further analyses so that the effects of true neurobiological phenomenon can be preserved (Rosen et al., 2018). For diffusion-weighted data, a common approach to correct for motion is to remove or replace motion-corrupted datapoints from raw, unprocessed images prior to subsequent processing and analysis (Benner et al., 2011; Elhabian et al., 2014; Soares et al., 2013). However, this approach has potential downsides, leading others to suggest that attempts to denoise images via gradient removal must also weigh the reliability of scalar estimates (Barrio-Arranz et al., 2015; Wang et al., 2012; Chen et al., 2015). Regardless, no study has examined the effect of this approach to motion correction in children, which has particularly important implications for structural neuroimaging research in pediatric mTBI.

The only study to our knowledge of motion artifacts in children with mTBI showed increased motion in younger relative to older children, but no differences by sex or compared to children with mild orthopedic injury (OI; Goodrich-Hunsaker et al., 2018). However, given the clear clinical and scientific implications, the participant factors that affect motion artifacts during acquisition need to be further examined in children with mTBI. Thus, the current study sought to examine motion artifacts in structural MRI scans, including both T1-weighted and diffusion images, and the factors that predict motion artifacts in children with mTBI or mild OI compared to a group of healthy TD children. The first study aim was to compare image quality and motion artifacts between groups, and to evaluate age and sex as predictors of motion artifacts. Based on prior research in other populations, we expected more motion in children with mTBI or OI than in TD children, with few differences between the injury groups (Goodrich-Hunsaker et al., 2018). We also expected greater motion in younger as compared to older children, and in boys as compared to girls (Goodrich-Hunsaker et al., 2018; Roalf et al., 2016; Rosen et al., 201). The second aim was to compare qualitative (manual) and quantitative (automated) approaches for detecting motion artifacts. We expected a significant correlation between qualitative and quantitative metrics of subject motion in T1-weighted images (Fischl, 2012; Rosen et al., 2018). In the absence of prior evidence regarding automated approaches to motion correction in diffusion MRI, an exploratory analysis was performed to evaluate qualitative and quantitative approaches for detecting motion artifacts in diffusion images. Finally, we examined the effect of removing diffusion-weighted image volumes (gradient directions) to minimize the effects of motion artifacts on common DTI metrics, specifically fractional anisotropy (FA)

and mean diffusivity (MD). We expected metrics to correlate strongly, with larger changes in estimates of FA than for MD values (Chen et al., 2015; Tijssen et al., 2009).

Methods

Study Design and Procedure

Data were drawn from two pediatric neuroimaging studies conducted on the same MRI scanner at the Alberta Children's Hospital in Calgary, AB between September 2016 and July 2019. Both studies were conducted with the approval of the conjoint health research ethics board at the University of Calgary; all participants provided informed assent when appropriate and parents or guardians provided written informed consent. The protocols for both studies are published elsewhere (Geeraert, Lebel, and Lebel 2019; Yeates, Beauchamp, Craig, Doan, Zemek, B. H. Bjornson, et al. 2017). In the interest of space, only the relevant methodology for the present study is described in detail below.

Children with mTBI or OI between the ages of 8.00-16.99 years were recruited and assessed as part of the Advancing Concussion Assessment in Pediatrics (A-CAP) study, a large multi-site study of pediatric mTBI that included a post-acute assessment with longitudinal follow-up (Yeates, Beauchamp, Craig, Doan, Zemek, B. H. Bjornson, et al. 2017). For both groups, acute injury signs and symptoms were assessed within 48 hours post-injury at the time of enrollment in the emergency department (ED) at Alberta Children's Hospital, where parents also completed demographic questionnaires. Injured children returned for a post-acute assessment that included a 3T MRI scan and was targeted for 10 days post-injury.

The TD comparison group was comprised of healthy children who were recruited from the community as part of a study of typical brain development in childhood and adolescence (Geeraert et al. 2019).

Participants

A total of 226 children (mTBI/OI = 150/76) were recruited as part of the larger A-CAP study. Of those enrolled, 191 (mTBI/OI = 130/61) children returned for the post-acute assessment. Children who returned for the post-acute assessment did not significantly differ from those who did not (mTBI/OI = 20/15) in terms of sex, race, or age at time of injury, all p 0.483. At the post-acute assessment, 147 children completed an MRI (mTBI/OI = 98/49). One child with MRI data withdrew from the parent study and was not included in this study. The children who returned for the post-acute assessment and completed the post-acute MRI did not significantly differ from participants who returned but did not complete an MRI (mTBI/OI = 32/12) in terms of premorbid or post-acute somatic or cognitive symptoms, race, sex, or age at time of injury, all p 0.289. Orthodontia and scheduling difficulties were the most common reasons that MRI was not completed.

Mild TBI group. Children in the mTBI group (n = 98) sustained a blunt head trauma resulting in at least one of the following three criteria, consistent with the World Health Organization (WHO) definition of mTBI: an observed loss of consciousness (LOC), a Glasgow Coma Scale (GCS) score of 13 or 14, or at

least one acute sign or symptom of concussion as noted by ED medical personnel on a standard case report form, such as post-traumatic amnesia (PTA), focal neurological deficits, vomiting, headache, dizziness, or other mental status changes (Carroll et al. 2004; Cassidy et al. 2004; Teasdale and Jennett 1974). Children were excluded if they demonstrated delayed neurological deterioration (i.e., GCS < 13), required neurosurgical intervention, or had LOC > 30 min or PTA > 24 hr.

Mild OI group. Children with OI (*n* = 49) were included if they sustained an upper or lower extremity fracture, sprain, or strain due to blunt force/physical trauma, associated with an Abbreviated Injury Scale (AIS) score 4 (Committee on Injury Scaling 1998). Children were excluded from the OI group if they had head trauma or symptoms of concussion, or any injury requiring surgical intervention or procedural sedation.

Exclusion criteria for both injury groups were any other severe injury that resulted in an AIS score > 4; prior concussion within the past 3 months; hypoxia, hypotension, or shock during or following the injury; history of previous TBI requiring hospitalization; premorbid neurological disorder or intellectual disability; injury resulting from non-accidental trauma; history of severe psychiatric disorder requiring hospitalization; or any MRI contraindications. Additional inclusion/exclusion criteria are described in the published study protocol (Yeates, Beauchamp, Craig, Doan, Zemek, B. H. Bjornson, et al. 2017).

TD group. Children in the TD group (*n* = 41) were recruited from the Calgary community. All had uncomplicated birth histories and were born between 37-42 weeks gestational age. Participants were excluded if they had a history of neurodevelopmental or intellectual disability, neurological or psychiatric disorder, or MRI contraindication (Geeraert et al. 2018, 2019). Of an initial 53 enrolled participants in the parent TD study, 12 were excluded from this study for having an age outside of the A-CAP study age range (i.e., age outside of 8.00-16.99 years).

Magnetic Resonance Imaging

All participants completed 3T MRI without sedation on the same General Electric MR750w 3T scanner with a 32-channel head coil (GE, Milwaukee, WI). Children in the mTBI and OI groups completed MRI 2-23 days post-injury (M = 8.93, Mdn = 8.62, SD = 3.51), with most scans (75%) completed 6-10 days post-injury. Time between injury and the post-acute MRI scan did not differ between the mTBI and OI groups (see **Table 1**).

Image acquisition. T1-weighted MRI data were acquired using a fast spoiled gradient echo brain volume (FSPGR BRAVO) in the axial plane with flip angle = 10, inversion time (TI)/repetition time (TR)/echo time (TE) = 600/8.25/3.2 ms, resolution = 0.8 mm, field of view (FOV) = 512 cm, contiguous slices = 226, and scan duration = 5:28 min. Diffusion-weighted images were acquired using a spin echo EPI sequence with 5 b = 0 s/mm^2 volumes and 30 gradient directions at b = 900 s/mm^2 , TR/TE = 12000/88-98 ms, resolution = 2.2 mm, FOV = 256 cm, contiguous slices = 57, and scan duration = 7:12 min.

Image processing. T1- and diffusion-weighted DICOM data were converted into NIfTI format using the dcm2niix tool in MRIcron (publicly available software; https://github.com/rordenlab/dcm2niix), and the bval and bvec files were automatically created from the raw diffusion-weighted DICOM headers. During conversion to NIfTI format, T1-weighted images were automatically reoriented to canonical space. Subsequent processing procedures were completed on a remote Linux computing cluster at the University of Calgary in AB, Canada. Cortical reconstruction of the T1-weighted image was performed for all subjects using FreeSurfer v6.0.0 (Fischl 2012).

Initial quality review. Initial visual review of both image types was conducted to identify and exclude any data with incidental findings (n = 2), scanner artifact such as aliasing or warping (T1/diffusion = 1/3), data collected without the default scan parameters (T1/diffusion = 1/10), and any incomplete or partially acquired images (T1/diffusion = 1/3). Therefore, a total of 183 (mTBI/OI/TD = 97/45/41) T1-weighted and 170 (mTBI/OI/TD = 89/42/39) diffusion-weighted datasets were included in subsequent analyses after the initial quality review.

Motion Artifacts

Qualitative Ratings of Motion Artifacts. After the initial review, all remaining datasets were manually inspected for motion in accordance with published protocols (Reuter et al. 2015; Roalf et al. 2016; Rosen et al. 2018). T1-weighted images were visually inspected by at least two trained analysts and rated using a 0-2 ordinal scale, with “0” assigned to images with gross artifacts that were considered unusable, “1” assigned to images with minor artifacts that were judged acceptable for analysis, and “2” assigned to images that were free from visible artifact and were considered to be of excellent quality. For diffusion-weighted images, each volume (gradient direction) was visually inspected for motion to determine the volumes to exclude. The diffusion-weighted images were then classified on a 0-2 rating scale based on total number of volumes with identified motion artifacts; scans that had >7 (i.e., > 25%) volumes with visible motion-related artifacts were rated unusable (rating of 0), scans that contained at 1-7 volumes with motion artifacts were rated acceptable (rating of 1), and scans with no volumes with motion artifacts were considered excellent quality (rating of 2). Exemplars for each MRI sequence are shown in **Figure 1**.

Quantitative Ratings of Motion Artifacts. The Euler number, which is automatically produced by the FreeSurfer processing pipeline, was used as a quantitative estimate of motion artifacts during T1-weighted MRI data acquisition. The Euler number captures the topological complexity of the reconstructed cortical surface by calculating the sum of the vertices and faces subtracted by the number of faces (Dale, Fischl, and Sereno 1999). This measure robustly correlated with manual ratings of motion artifacts in anatomical MRI data drawn from a large developmental neuroimaging study (Rosen et al. 2018). Euler numbers are negative, with higher values (i.e., closer to 0) indicating less motion.

The eddy tool from the FSL v6.0.1 Diffusion Toolbox (FDT diffusion) v5.0 was used to derive quantitative measures of motion artifacts during diffusion-weighted MRI data acquisition (Andersson and Sotiropoulos 2016). The *output.eddy_movement_rms* parameter was used as a measure of total

movement. This parameter estimates motion between volumes, calculated as the restricted root mean square (RMS) displacement of each voxel compared to the previous volume across the total number of voxels within the brain; it attempts to isolate RMS displacement caused by in-scanner motion from eddy current-related artifacts.

Diffusion Tensor Imaging

To determine whether the removal of diffusion-weighted volumes (gradients) with severe motion artifacts influenced DTI metrics, mean FA and MD values were estimated for the participants who had 1 bad volume on diffusion-weighted imaging (n = 68) in two ways: (i) from the uncorrected data (i.e., using all 35 volumes, including those identified as having gross motion artifacts) and (ii) from the corrected data (i.e., 35 volumes, excluding those identified as having gross motion artifacts).

The diffusion-weighted images were eddy current and motion corrected, skull-stripped, and tensor fitted using ExploreDTI v4.8.6 running on MATLAB v8.6.0 R2018a (MathWorks Inc., Natick, MA). T1-weighted images were brain-extracted using the Advanced Normalization Tools version 3.0.0.0.dev13-ga16cc (compiled January 18, 2019) volume-based cortical thickness estimation pipeline (antsCorticalThickness.sh) with the OASIS pediatric template from the MICCAI 2012 Multi Atlas Challenge (Tustison et al. 2014), and used for anatomical reference during skull-stripping. White matter pathways were derived for the genu, body, and splenium of the corpus callosum and for the left and right corticospinal tract and cingulum bundle using a semi-automated tractography approach. These tracts were chosen given that they run inferior-superior, left-right, and anterior-posterior. Average FA and MD were extracted within ExploreDTI for each tract for each participant.

Statistical Analyses

Demographic data were analyzed using analysis of variance (ANOVA) for continuous variables and chi-square techniques for categorical variables. Multiple multivariable logistic and linear regressions were used to investigate the relations of group (mTBI, OI, TD), age, sex, and their interactions to qualitative and quantitative estimates of motion. Non-significant (p > .05) interactions were removed from final models. Area under the curve (AUC) analyses were used to evaluate the concordance among qualitative and quantitative ratings. Linear mixed effects modeling and Pearson correlation were used to examine the effect of volume (gradient) removal on FA and MD values of selected white matter tracts, with motion correction status (uncorrected, corrected), hemisphere (or region for corpus callosum subregions), group, and their interaction included as fixed effects and participant as a random effect, with covariates sex and age.

A post-hoc power analysis, conducted using G*Power v3.1 (Faul et al. 2009), indicated that the current sample size (N = 188) was sufficiently powered (1-b = .95) to detect small effects (partial R^2 = .10) with 4 predictors at a critical F-value = 3.05 and = .05.

Results

Sample Characteristics

Sample characteristics and demographic data are presented in **Table 1**. The mTBI and OI groups did not differ significantly in age, sex, or Full-Scale IQ. The TD group had a lower proportion of White children, as compared to the mTBI and OI groups.

Motion Artifact in T1-Weighted Images

Qualitative motion ratings. Of the 183 images that passed the initial quality check, 19 T1-weighted images (10%) were rated as unusable (i.e., rated 0) due to severe motion artifacts (see **Table 2**). A multivariable logistic regression predicting qualitative ratings of usable (rated 1-2 for moderate to no motion artifact) versus unusable (rated 0 for severe motion artifacts) image quality from group, age, and sex was significant, $^{2}(4) = 9.51$, $p = .049$. Older children were more likely to have usable scans than younger children ($B = 0.29$, $p = .013$). Scan quality did not differ significantly by group or sex.

Euler number. Average Euler number for each group is provided in **Table 2**. To correct for negative skew, a log(-1*Euler number) transformation was performed prior to analysis. The multivariable linear regression, with predictors group, age, and sex, was significant for the transformed Euler number, $F(4, 178) = 10.66$, $p < 0.001$, $R^2 = .19$. Groups did not significantly differ in average Euler value, $F(2,178) = 1.74$, $p = .178$. Age and sex were significantly associated with Euler value (see **Figure 2a**). Younger children had lower raw Euler values (i.e., indicative of greater motion artifacts) compared to older children, $F(1,178) = 32.04$, $p < .001$, and boys had lower Euler values compared to girls, $F(1,178) = 7.09$, $p = .008$.

Average (transformed) Euler values were significantly associated with manual QA ratings (i.e., usable versus unusable), $B = -9.49$, $p < .001$, across groups, age, and sex. Euler values discriminated between usable and unusable T1-weighted images with high accuracy, AUC = 0.97, 95% CI = 0.94-0.99. A threshold of -370 corresponded with the best balance between specificity and sensitivity (both = 0.90), but resulted in a 10% false positive rate; a more stringent threshold of -310 resulted in sensitivity = .90 and specificity = 1.00 (0% false positive rate).

Motion Artifacts in Diffusion-Weighted Images

Qualitative motion ratings. Of the 170 diffusion-weighted images that passed initial quality review, 11 scans (6.5%) had > 7 volumes (gradient directions) with severe motion artifacts (**Table 2**). The total number of volumes (gradients) with severe motion artifacts per individual was examined using a multivariable Poisson regression with predictors group, age, and sex, $F(4, 167) = 8.52$, $p < .001$, Akaike's Information Criterion (AIC) = 801.39, as summarized in **Figure 2b**. The TD group had significantly fewer volumes with motion artifacts than children in the mTBI ($B = 0.78$, $p < .001$) and OI ($B = 0.73$, $p < .001$) groups; the mTBI and OI groups did not differ significantly ($B = 0.07$, $p = .717$). Older children had more bad volumes than younger children ($B = -0.28$, $p < .001$), and boys had more bad volumes than girls ($B = 0.50$, $p < .001$).

The multivariable logistic regression, with group, age, and sex as predictors, was significant for predicting usability ratings (i.e., 0 vs. 1 or 2; based on total number of volumes with motion artifacts) of diffusion-weighted images, $^2(4) = 26.34$, $p < .001$. The groups did not differ significantly in qualitative ratings based on the number of volumes with motion artifacts. However, age was significantly positively associated with qualitative motion ratings ($B = 0.71$, $p = .001$), and sex showed a non-significant trend ($B = -1.63, 9$, $p = .062$), indicating that younger children had poorer quality scans than older children and that boys tended to have lower quality scans than girls.

Restricted root mean squared (RMS) displacement. Descriptive statistics for restricted RMS displacement are shown for each group in **Table 2**. The inverse of restricted RMS displacement was used in analyses to correct for skewness of the raw data. The groups did not differ significantly for displacement, $F(2, 163) <1$, $p = .897$. However, younger children showed greater displacement than older children ($B = 0.56$, $p < .001$), and boys showed greater displacement than girls ($B = -1.44$, p = .009; **Figure 2c**). Restricted RMS displacement discriminated between the diffusion-weighted images that were considered usable versus unusable due to motion-related artifacts with high accuracy (AUC = 0.98, 95% CI = 0.96-1.00). A restricted RMS displacement threshold of 0.644 had excellent sensitivity (0.92) and a 0% false positive rate (specificity = 1.00).

Effect of Motion Correction (Volume Removal) on DTI Metrics

Pearson correlations were conducted for the DTI metrics derived for each region of interest from the corrected and uncorrected diffusion-weighted images that had at least one volume with motion artifacts ($n = 57$). Results are reported in **Table 3**. All of the correlations were large and statistically significant (all $p < .001$). Linear mixed effects modeling revealed that FA and MD did not significantly differ significantly as a function of motion correction status (uncorrected, corrected), group (mTBI, OI), hemisphere (or region for the corpus callosum subregions), or their interactions, accounting for the random effect of participant and covariates age at time of injury and sex. Motion correction status also was not influenced by DTI metric (FA, MD) or region (corpus callosum, corticospinal tract, cingulum bundle).

Discussion

Here, we show that motion artifacts relate to children's age, sex, and (to a lesser extent) injury history. We also showed that qualitative (manual) and quantitative (automated) approaches for detecting motion artifacts are highly correlated for both T1- and diffusion MR images, and that removing diffusion-weighted image volumes (gradient directions) to minimize the effects of motion artifacts had little effect on DTI metrics.

The overall pattern of results suggests that children with mTBI or OI were more similar than either group was to the TD children, but that the groups generally did not differ substantially in terms of motion artifacts (Beauchamp et al. 2017; Wilde et al. 2018). Specifically, children with mTBI or OI demonstrated increased motion artifacts in diffusion images compared to TD children. However, the groups did not

differ significantly in motion artifacts for the T1-weighted images or in quantitative estimates of diffusion-weighted images. The lack of differences between children with mTBI and OI is consistent with previous results (Goodrich-Hunsaker et al., 2018), though no previous studies compared motion in diffusion MRI sequences between TD children and children with mTBI or OI. The differences between the two injury groups and the TD group may reflect several factors, including the presence of pre-injury neurobehavioral characteristics that are associated with both increased motion artifacts and increased risk of childhood injury (Alosco et al. 2014; Gerring et al. 1998; Lee et al. 2008). These results highlight the importance of comparison group selection for neuroimaging research in pediatric mTBI, especially for DTI studies.

Unsurprisingly, age was the most robust predictor of motion artifacts in both anatomical and diffusion MRI sequences, with greater motion observed in younger as compared to older children. Younger children tend to exhibit high levels of restlessness, leading to greater motion (Makowski, Lepage, and Evans 2019). Our findings of greater motion artifacts in younger mTBI, OI, and TD children for diffusion-weighted images are consistent with results from MR studies of other pediatric populations (Afacan et al. 2016; Goodrich-Hunsaker et al. 2018; Makowski et al. 2019; Roalf et al. 2016; Satterthwaite et al. 2012; Yuan et al. 2009). Expected sex differences were also relatively robust, with greater motion artifacts in boys than girls. This is consistent with previous research in other pediatric populations (Alexander-Bloch et al. 2016; Roalf et al. 2016), and may be an especially important consideration for neuroimaging research in pediatric mTBI. mTBI is more prevalent in males than females, and some research suggests that females take longer to recover and report greater initial symptom severity than males after mTBI (Corwin et al. 2014, 2017; Eisenberg et al. 2013; Zemek et al. 2016). However, neuroimaging studies have not identified physiological underpinnings for these differences. The influence of both age and sex on motion may obscure biological markers of mTBI. Understanding and correcting for motion artifacts is therefore essential to delineate age- and sex-related differences in mTBI (Fakhran et al. 2014).

This study provides much-needed evidence regarding the generalizability of popular open-source tools for post-acquisition motion artifacts identification and correction in structural MR images (i.e., FreeSurfer and eddy from FMRIB Software Library). We observed high consistency across manual and automated approaches for motion estimation for both T1-weighted and diffusion MR images. This has significant implications for pediatric mTBI neuroimaging research, which is moving towards acquiring larger, more representative study samples at multiple timepoints post-injury that make manual techniques to assess data quality impractical (Mayer et al. 2018; Yeates, Beauchamp, Craig, Doan, Zemek, B. Bjornson, et al. 2017; Yue et al. 2013). Our results indicate that semi-automated methods for identifying motion artifacts in structural images are a practical solution to reduce the time and labour burden associated with manual ratings, although optimal cut-points for these methods may be study dependent. Our cut-points differed from those identified in a large sample of TD children (Roalf et al. 2016; Rosen et al. 2018). More specifically, those studies reported high sensitivity and specificity at a threshold (Euler = -217) that yielded low sensitivity (high percentage of false positives) in the current study.

Finally, we examined how the manual removal of volumes (gradients) for motion correction affects diffusion metrics. We identified nominal changes in FA and MD with gradient volume removal that did not differ significantly as a function of DTI metric, region, hemisphere, or group. Thus, conclusions based on results from either motion correction status would be largely similar. Manual rejection of volumes (gradients) was not associated with a significant inflation in FA values and MD did not prove to be more robust to manual removal of volumes than FA, which is inconsistent with previous research (Barrio-Arranz et al. 2015; Chen et al. 2015). The sensitivity of MD to signal-to-noise ratio (SNR) suggests that the raw and corrected images may have equitable SNRs at the currently chosen threshold for weighted gradient volume removal (i.e., < 25%; Barrio-Arranz et al. 2015). It is noteworthy that we cannot be certain of which values (raw or corrected) are more accurate. Additional research using phantoms with known structural properties is needed to address this question. Better yet would be to examine scans of TD children without motion or to use phantom scans to more directly examine the effect of volume removal to help determine which approach provides more reliable estimates of white matter microstructure since both approaches were highly correlated and did not differ between the groups.

Limitations. The current study did not account for the order of scan acquisition. Research suggests that scans acquired later in a scan session may have higher motion as compared to those acquired earlier (Rosen et al. 2018). We also did not examine behaviors such as hyperactivity and impulsivity that influence participant motion. Future research would benefit from examining these factors, and additional neurodevelopmental populations that may be influenced by them.

Conclusions

The current study provides a novel examination of participant characteristics that predict MRI motion artifacts in children with mTBI and mild OI, as compared to TD children. Overall results suggest that MRI studies of mTBI need to consider motion, particularly if comparing diffusion imaging results to TD children or testing for age and sex differences. Children with mTBI and mild OI exhibited more motion than TD children on some metrics, suggesting that the use of OI comparison groups in neuroimaging studies of pediatric mTBI may better control for confounding effects of motion. Finally, we found high levels of agreement between qualitative and quantitative methods for detecting motion artifacts, indicating that semi-automated methods of correcting for motion artifacts can be used to reduce the burden associated with qualitative ratings, making it practical to perform large neuroimaging studies of mTBI with representative samples collected at multiple timepoints, although thresholds for some quantitative metrics may be study specific.

Declarations

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Disclosure: The submitted work has not been published previously and is not being considered for publication elsewhere. Material has not been reproduced from prior publications, whether by the same or different authors.

Ethics approval: I verify that appropriate Institutional Review Board (IRB) approval has been obtained for the use of human or animal subjects. Study was conducted in accordance with the IRB at the University of Calgary: REB15-2296 for the A-CAP study and REB13-1346 for the adolescent study.

Consent to participate: I verify that all study participants and their caregivers provided written informed consent.

Availability of data and material: Data available upon reasonable request.

Code availability: Analysis code is available upon reasonable request.

References

1. Afacan, Onur, Burak Erem, Diona P. Roby, Noam Roth, Amir Roth, Sanjay P. Prabhu, and Simon K. Warfield. 2016. “Evaluation of Motion and Its Effect on Brain Magnetic Resonance Image Quality in Children.” *Pediatric Radiology* 46(12):1728–35. doi: 10.1007/s00247-016-3677-9.
2. Alexander-Bloch, Aaron, Liv Clasen, Michael Stockman, Lisa Ronan, Francois Lalonde, Jay Giedd, and Armin Raznahan. 2016. “Subtle In-Scanner Motion Biases Automated Measurement of Brain Anatomy from in Vivo MRI: Motion Bias in Analyses of Structural MRI.” *Human Brain Mapping* 37(7):2385–97. doi: 10.1002/hbm.23180.
3. Alosco, Michael L., Andrew F. Fedor, and John Gunstad. 2014. “Attention Deficit Hyperactivity Disorder as a Risk Factor for Concussions in NCAA Division-I Athletes.” *Brain Injury* 28(4):472–74. doi: 10.3109/02699052.2014.887145.
4. Andersson, Jesper L. R., and Stamatios N. Sotiropoulos. 2016. “An Integrated Approach to Correction for Off-Resonance Effects and Subject Movement in Diffusion MR Imaging.” *NeuroImage* 125:1063–78. doi: 10.1016/j.neuroimage.2015.10.019.
5. Barrio-Arranz, Gonzalo, Rodrigo de Luis-García, Antonio Tristán-Vega, Marcos Martín-Fernández, and Santiago Aja-Fernández. 2015. “Impact of MR Acquisition Parameters on DTI Scalar Indexes: A Tractography Based Approach.” *PLoS ONE* 10(10). doi: 10.1371/journal.pone.0137905.
6. Beauchamp, Miriam H., Catherine Landry-Roy, Jocelyn Gravel, Cindy Beaudoin, and Annie Bernier. 2017. “Should Young Children with Traumatic Brain Injury Be Compared with Community or Orthopedic Control Participants?” *Journal of Neurotrauma* 34(17):2545–52. doi: 10.1089/neu.2016.4868.
7. Blumenthal, Jonathan D., Alex Zijdenbos, Elizabeth Molloy, and Jay N. Giedd. 2002. “Motion Artifact in Magnetic Resonance Imaging: Implications for Automated Analysis.” *NeuroImage* 16(1):89–92.

doi: 10.1006/nimg.2002.1076.

8. Carroll, Linda, J. David Cassidy, Lena Holm, Jess Kraus, and Victor Coronado. 2004. “Methodological Issues and Research Recommendations for Mild Traumatic Brain Injury: The Who Collaborating Centre Task Force on Mild Traumatic Brain Injury.” *Journal of Rehabilitation Medicine* 36(0):113–25. doi: 10.1080/16501960410023877.
9. Cassidy, J. David, Linda J. Carroll, Paul M. Peloso, Jörgen Borg, Hans von Holst, Lena Holm, Jess Kraus, Victor G. Coronado, and WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. 2004. “Incidence, Risk Factors and Prevention of Mild Traumatic Brain Injury: Results of the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury.” *Journal of Rehabilitation Medicine* (43 Suppl):28–60.
10. Chen, Yiran, Olga Tymofiyeva, Christopher P. Hess, and Duan Xu. 2015. “Effects of Rejecting Diffusion Directions on Tensor-Derived Parameters.” *NeuroImage* 109:160–70. doi: 10.1016/j.neuroimage.2015.01.010.
11. Committee on Injury Scaling. 1998. *Abbreviated Injury Scale*. Arlington Heights, IL: Association for the Advancement of Automotive Medicine.
12. Corwin, Daniel J., Matthew F. Grady, Mark D. Joffe, and Mark R. Zonfrillo. 2017. “Pediatric Mild Traumatic Brain Injury in the Acute Setting.” *Pediatric Emergency Care* 33(9):643–49. doi: 10.1097/PEC.0000000000001252.
13. Corwin, Daniel J., Mark R. Zonfrillo, Christina L. Master, Kristy B. Arbogast, Matthew F. Grady, Roni L. Robinson, Arlene M. Goodman, and Douglas J. Wiebe. 2014. “Characteristics of Prolonged Concussion Recovery in a Pediatric Subspecialty Referral Population.” *The Journal of Pediatrics* 165(6):1207–15. doi: 10.1016/j.jpeds.2014.08.034.
14. Dale, Anders M., Bruce Fischl, and Martin I. Sereno. 1999. “Cortical Surface-Based Analysis.” *NeuroImage* 9(2):179–94. doi: 10.1006/nimg.1998.0395.
15. Ducharme, Simon, Matthew D. Albaugh, Tuong-Vi Nguyen, James J. Hudziak, J. M. Mateos-Pérez, Aurelie Labbe, Alan C. Evans, Sherif Karama, and Brain Development Cooperative Group. 2016. “Trajectories of Cortical Thickness Maturation in Normal Brain Development–The Importance of Quality Control Procedures.” *NeuroImage* 125:267–79. doi: 10.1016/j.neuroimage.2015.10.010.
16. Eisenberg, Matthew A., John Andrea, William Meehan, and Rebekah Mannix. 2013. “Time Interval between Concussions and Symptom Duration.” *Pediatrics* 132(1):8–17. doi: 10.1542/peds.2013-0432.
17. Fakhran, Saeed, Karl Yaeger, Michael Collins, and Lea Alhilali. 2014. “Sex Differences in White Matter Abnormalities after Mild Traumatic Brain Injury: Localization and Correlation with Outcome.” *Radiology* 272(3):815–23. doi: 10.1148/radiol.14132512.
18. Faul, Franz, Edgar Erdfelder, Axel Buchner, and Albert-Georg Lang. 2009. “Statistical Power Analyses Using G*Power 3.1: Tests for Correlation and Regression Analyses.” *Behavior Research Methods* 41(4):1149–60. doi: 10.3758/BRM.41.4.1149.

19. Fischl, Bruce. 2012. “FreeSurfer.” *NeuroImage* 62(2):774–81. doi: 10.1016/j.neuroimage.2012.01.021.
20. Geeraert, Bryce L., R. Marc Lebel, Alyssa C. Mah, Sean C. Deoni, David C. Alsop, Gopal Varma, and Catherine Lebel. 2018. “A Comparison of Inhomogeneous Magnetization Transfer, Myelin Volume Fraction, and Diffusion Tensor Imaging Measures in Healthy Children.” *NeuroImage* 182:343–50. doi: 10.1016/j.neuroimage.2017.09.019.
21. Geeraert, Bryce L., Robert Marc Lebel, and Catherine Lebel. 2019. “A Multiparametric Analysis of White Matter Maturation during Late Childhood and Adolescence.” *Human Brain Mapping* 40(15):4345–56. doi: 10.1002/hbm.24706.
22. Gerring, J. P., K. D. Brady, A. Chen, R. Vasa, M. Grados, K. J. Bandeen-Roche, R. N. Bryan, and M. B. Denckla. 1998. “Premorbid Prevalence of ADHD and Development of Secondary ADHD after Closed Head Injury.” *Journal of the American Academy of Child and Adolescent Psychiatry* 37(6):647–54. doi: 10.1097/00004583-199806000-00015.
23. Gilchrist, Julie, Karen Thomas, Likang Xu, Lisa C. McGuire, and Victor G. Coronado. 2011. “Nonfatal Traumatic Brain Injuries Related to Sports and Recreation Activities Among Persons Aged ≤19 Years — United States, 2001–2009.” *MMWR Morbity and Mortality WEekly Report* 60(39):1337–42.
24. Goodrich-Hunsaker, Naomi J., Tracy J. Abildskov, Garrett Black, Erin D. Bigler, Daniel M. Cohen, Leslie K. Mihalov, Barbara A. Bangert, H. Gerry Taylor, and Keith O. Yeates. 2018. “Age- and Sex-Related Effects in Children with Mild Traumatic Brain Injury on Diffusion Magnetic Resonance Imaging Properties: A Comparison of Voxelwise and Tractography Methods.” *Journal of Neuroscience Research* 96(4):626–41. doi: 10.1002/jnr.24142.
25. Langlois, Jean A., Wesley Rutland-Brown, and Marlena M. Wald. 2006. “The Epidemiology and Impact of Traumatic Brain Injury: A Brief Overview.” *The Journal of Head Trauma Rehabilitation* 21(5):375–78.
26. Lee, Li-Ching, Rebecca A. Harrington, Jen Jen Chang, and Susan L. Connors. 2008. “Increased Risk of Injury in Children with Developmental Disabilities.” *Research in Developmental Disabilities* 29(3):247–55. doi: 10.1016/j.ridd.2007.05.002.
27. Lumba-Brown, Angela, Keith Owen Yeates, Kelly Sarmiento, Matthew J. Breiding, Tamara M. Haegerich, Gerard A. Gioia, Michael Turner, Edward C. Benzel, Stacy J. Suskauer, Christopher C. Giza, Madeline Joseph, Catherine Broomand, Barbara Weissman, Wayne Gordon, David W. Wright, Rosemarie Scolaro Moser, Karen McAvoy, Linda Ewing-Cobbs, Ann-Christine Duhaime, Margot Putukian, Barbara Holshouser, David Paulk, Shari L. Wade, Stanley A. Herring, Mark Halstead, Heather T. Keenan, Meeryo Choe, Cindy W. Christian, Kevin Guskiewicz, P. B. Raksin, Andrew Gregory, Anne Mucha, H. Gerry Taylor, James M. Callahan, John DeWitt, Michael W. Collins, Michael W. Kirkwood, John Ragheb, Richard G. Ellenbogen, T. J. Spinks, Theodore G. Ganiats, Linda J. Sabelhaus, Katrina Altenhofen, Rosanne Hoffman, Tom Getchius, Gary Gronseth, Zoe Donnell, Robert E. O’Connor, and Shelly D. Timmons. 2018. “Diagnosis and Management of Mild Traumatic Brain Injury in Children: A Systematic Review.” *JAMA Pediatrics* 172(11):e182847. doi: 10.1001/jamapediatrics.2018.2847.

28. Makowski, Carolina, Martin Lepage, and Alan C. Evans. 2019. “Head Motion: The Dirty Little Secret of Neuroimaging in Psychiatry.” *Journal of Psychiatry & Neuroscience : JPN* 44(1):62–68. doi: 10.1503/jpn.180022.
29. Mayer, Andrew R., Mayank Kaushal, Andrew B. Dodd, Faith M. Hanlon, Nicholas A. Shaff, Rebekah Mannix, Christina L. Master, John J. Leddy, David Stephenson, Christopher J. Wertz, Elizabeth M. Suelzer, Kristy B. Arbogast, and Timothy B. Meier. 2018. “Advanced Biomarkers of Pediatric Mild Traumatic Brain Injury: Progress and Perils.” *Neuroscience & Biobehavioral Reviews* 94:149–65. doi: 10.1016/j.neubiorev.2018.08.002.
30. Mayer, Andrew R., Davin K. Quinn, and Christina L. Master. 2017. “The Spectrum of Mild Traumatic Brain Injury: A Review.” *Neurology* 89(6):623–32. doi: 10.1212/WNL.0000000000004214.
31. Reuter, Martin, M. Dylan Tisdall, Abid Qureshi, Randy L. Buckner, André J. W. van der Kouwe, and Bruce Fischl. 2015. “Head Motion during MRI Acquisition Reduces Gray Matter Volume and Thickness Estimates.” *NeuroImage* 107:107–15. doi: 10.1016/j.neuroimage.2014.12.006.
32. Roalf, David R., Megan Quarmley, Mark A. Elliott, Theodore D. Satterthwaite, Simon N. Vandekar, Kosha Ruparel, Efstathios D. Gennatas, Monica E. Calkins, Tyler M. Moore, Ryan Hopson, Karthik Prabhakaran, Chad T. Jackson, Ragini Verma, Hakon Hakonarson, Ruben C. Gur, and Raquel E. Gur. 2016. “The Impact of Quality Assurance Assessment on Diffusion Tensor Imaging Outcomes in a Large-Scale Population-Based Cohort.” *NeuroImage* 125:903–19. doi: 10.1016/j.neuroimage.2015.10.068.
33. Rosen, Adon F. G., David R. Roalf, Kosha Ruparel, Jason Blake, Kevin Seelaus, Lakshmi P. Villa, Rastko Ciric, Philip A. Cook, Christos Davatzikos, Mark A. Elliott, Angel Garcia de La Garza, Efstathios D. Gennatas, Megan Quarmley, J. Eric Schmitt, Russell T. Shinohara, M. Dylan Tisdall, R. Cameron Craddock, Raquel E. Gur, Ruben C. Gur, and Theodore D. Satterthwaite. 2018. “Quantitative Assessment of Structural Image Quality.” *NeuroImage* 169:407–18. doi: 10.1016/j.neuroimage.2017.12.059.
34. Ruff, R. M., G. L. Iverson, J. T. Barth, S. S. Bush, D. K. Broshek, and the NAN Policy and Planning Committee. 2009. “Recommendations for Diagnosing a Mild Traumatic Brain Injury: A National Academy of Neuropsychology Education Paper.” *Archives of Clinical Neuropsychology* 24(1):3–10. doi: 10.1093/arclin/acp006.
35. Satterthwaite, Theodore D., Mark A. Elliott, Raphael T. Gerraty, Kosha Ruparel, James Loughead, Monica E. Calkins, Simon B. Eickhoff, Hakon Hakonarson, Ruben C. Gur, Raquel E. Gur, and Daniel H. Wolf. 2013. “An Improved Framework for Confound Regression and Filtering for Control of Motion Artifact in the Preprocessing of Resting-State Functional Connectivity Data.” *NeuroImage* 64:240–56. doi: 10.1016/j.neuroimage.2012.08.052.
36. Satterthwaite, Theodore D., Daniel H. Wolf, James Loughead, Kosha Ruparel, Mark A. Elliott, Hakon Hakonarson, Ruben C. Gur, and Raquel E. Gur. 2012. “Impact of In-Scanner Head Motion on Multiple Measures of Functional Connectivity: Relevance for Studies of Neurodevelopment in Youth.” *NeuroImage* 60(1):623–32. doi: 10.1016/j.neuroimage.2011.12.063.

37. Teasdale, G., and B. Jennett. 1974. “Assessment of Coma and Impaired Consciousness. A Practical Scale.” *Lancet (London, England)* 2(7872):81–84.
38. Tijssen, Rob H. N., Jacobus F. A. Jansen, and Walter H. Backes. 2009. “Assessing and Minimizing the Effects of Noise and Motion in Clinical DTI at 3 T.” *Human Brain Mapping* 30(8):2641–55. doi: 10.1002/hbm.20695.
39. Tustison, Nicholas J., Philip A. Cook, Arno Klein, Gang Song, Sandhitsu R. Das, Jeffrey T. Duda, Benjamin M. Kandel, Niels van Strien, James R. Stone, James C. Gee, and Brian B. Avants. 2014. “Large-Scale Evaluation of ANTs and FreeSurfer Cortical Thickness Measurements.” *NeuroImage* 99:166–79. doi: 10.1016/j.neuroimage.2014.05.044.
40. Wilde, Elisabeth A., Ashley L. Ware, Xiaoqi Li, Trevor C. Wu, Stephen R. McCauley, Amanda Barnes, Mary R. Newsome, Brian D. Biekman, Jill V. Hunter, Zili D. Chu, and Harvey S. Levin. 2018. “Orthopedic Injured versus Uninjured Comparison Groups for Neuroimaging Research in Mild Traumatic Brain Injury.” *Journal of Neurotrauma* 36(2):239–49. doi: 10.1089/neu.2017.5513.
41. Yeates, Keith Owen, Miriam Beauchamp, William Craig, Quynh Doan, Roger Zemek, Bruce Bjornson, Jocelyn Gravel, Angelo Mikrogianakis, Bradley Goodyear, Nishard Abdeen, Christian Beaulieu, Mathieu Dehaes, Sylvain Deschenes, Ashley Harris, Catherine Lebel, Ryan Lamont, Tyler Williamson, Karen Maria Barlow, Francois Bernier, Brian L. Brooks, Carolyn Emery, Stephen B. Freedman, Kristina Kowalski, Kelly Mrklas, Lianne Tomfohr-Madsen, Kathryn J. Schneider, and Pediatric Emergency Research Canada (PERC). 2017. “Advancing Concussion Assessment in Pediatrics (A-CAP): A Prospective, Concurrent Cohort, Longitudinal Study of Mild Traumatic Brain Injury in Children: Protocol Study.” *BMJ Open* 7(7):e017012. doi: 10.1136/bmjopen-2017-017012.
42. Yeates, Keith Owen, Miriam Beauchamp, William Craig, Quynh Doan, Roger Zemek, Bruce H. Bjornson, Jocelyn Gravel, Angelo Mikrogianakis, Bradley Goodyear, Nishard Abdeen, Christian Beaulieu, Mathieu Dehaes, Sylvain Deschenes, Ashley Harris, Catherine Lebel, Ryan Lamont, Tyler Williamson, Karen Maria Barlow, Francois Bernier, Brian L. Brooks, Carolyn Emery, Stephen B. Freedman, Kristina Kowalski, Kelly Mrklas, Lianne Tomfohr-Madsen, and Kathryn J. Schneider. 2017. “Advancing Concussion Assessment in Pediatrics (A-CAP): A Prospective, Concurrent Cohort, Longitudinal Study of Mild Traumatic Brain Injury in Children: Study Protocol.” *BMJ Open* 7(7). doi: 10.1136/bmjopen-2017-017012.
43. Yuan, Weihong, Mekibib Altaye, Jen Ret, Vincent Schmithorst, Anna W. Byars, Elena Plante, and Scott K. Holland. 2009. “Quantification of Head Motion in Children During Various FMRI Language Tasks.” *Human Brain Mapping* 30(5):1481–89. doi: 10.1002/hbm.20616.
44. Yue, John K., Mary J. Vassar, Hester F. Lingsma, Shelly R. Cooper, David O. Okonkwo, Alex B. Valadka, Wayne A. Gordon, Andrew I. R. Maas, Pratik Mukherjee, Esther L. Yuh, Ava M. Puccio, David M. Schnyer, Geoffrey T. Manley, and TRACK-TBI Investigators. 2013. “Transforming Research and Clinical Knowledge in Traumatic Brain Injury Pilot: Multicenter Implementation of the Common Data Elements for Traumatic Brain Injury.” *Journal of Neurotrauma* 30(22):1831–44. doi: 10.1089/neu.2013.2970.

45. Zemek, Roger, Nick Barrowman, Stephen B. Freedman, Jocelyn Gravel, Isabelle Gagnon, Candice McGahern, Mary Aglipay, Gurinder Sangha, Kathy Boutis, Darcy Beer, William Craig, Emma Burns, Ken J. Farion, Angelo Mikrogianakis, Karen Barlow, Alexander S. Dubrovsky, Willem Meeuwisse, Gerard Gioia, William P. Meehan, Miriam H. Beauchamp, Yael Kamil, Anne M. Grool, Blaine Hoshizaki, Peter Anderson, Brian L. Brooks, Keith Owen Yeates, Michael Vassilyadi, Terry Klassen, Michelle Keightley, Lawrence Richer, Carol DeMatteo, and Martin H. Osmond. 2016. "Clinical Risk Score for Persistent Postconcussion Symptoms Among Children With Acute Concussion in the ED." *JAMA* 315(10):1014–25. doi: 10.1001/jama.2016.1203.

Tables

Table 1. Sample demographic and injury characteristics.

Variable	TD (*n* = 41)	OI (*n* = 49)	mTBI (*n* = 98)	*p*-value
Age (*M*±*SD* years)	12.34±2.41	12.63±2.32	12.65±2.39	.772
Full Scale IQ (*M*±*SD*)*	108.30±14.41	108.29±10.02	106.43±12.17	.614
Sex [*n* (%) male]	22 (54)	26 (53)	64 (65)	.247
Race [*n* (%) White]	25 (61)	38 (78)	77 (79)	.050
MRI days post-injury (*M*±*SD*)	- -	9.63±4.09	8.58±3.15	.087

Note. *Based on the Wechsler Abbreviated Scale of Intelligene-2nd Edition (WASI-II) 2-subtest score (Wechsler, 2011) administered at 3 months post-injury. M = Mean; SD = standard deviation; TD = typically developing; OI = orthopedic injury; mTBI = mild traumatic brain injury; MRI = magnetic resonance imaging.

Table 2. Summary of image QA results from manual ratings and qualitative estimates of in-scanner head motion.

	Group		
	TD	**OI**	**mTBI**
T1-weighted MRI			
Manual QA			
Rating [*n* (%)]			
0	2 (5)	4 (7)	13 (13)
1	19 (46)	17 (30)	36 (37)
2	20 (49)	36 (63)	48 (49)
Quantitative QA			
Euler Value (*M±SD*)*	-248.22103.98	-289.64126.69	-281.03131.00
Diffusion-weighted MRI			
Manual QA			
Rating [*n* (%)]			
0	0 (0)	5 (12)	6 (7)
1	13 (33)	13 (31)	35 (39)
2	26 (67)	24 (57)	48 (54)
Motion corrupted volume count (*M±SD*)	0.23±0.67	5.00±13.06	3.85±12.15
Quantitative QA			
Restricted RMS Displacement (M±SD)*	0.250.16	0.310.25	0.360.45

Note. *Raw values are reported. RMS = root mean square; TD = typically developing, OI = orthopedic injury; mTBI = mild traumatic brain injury; M = mean; SD = standard deviation.

Table 3. Summary statistics (Mean ± SD) and Pearson correlation coefficients (*r*) for the DTI metrics of each region of interest derived from corrected (unusable volumes excluded) and uncorrected (unusable volumes included) diffusion-weighted images for the scans that had 1, but < 8, gradient volumes with gross motion artifacts.

Tract	Fractional Anisotropy (FA)			Mean Diffusivity (MD) x 10^{-3} mm^2		
	Uncorrected	Corrected	*r*	Uncorrected	Corrected	*r*
Corpus Callosum	0.55±0.02	0.55±0.01	.892*	0.90±0.84	0.91±0.84	.933*
Corticospinal tract	0.56±0.02	0.56±0.01	.896*	0.76±0.02	0.75±0.02	.925*
Cingulum Bundle	0.46±0.02	0.47±0.02	.911*	0.84±0.03	0.84±0.03	.863*

Note. *$p < .001$.*

Figures

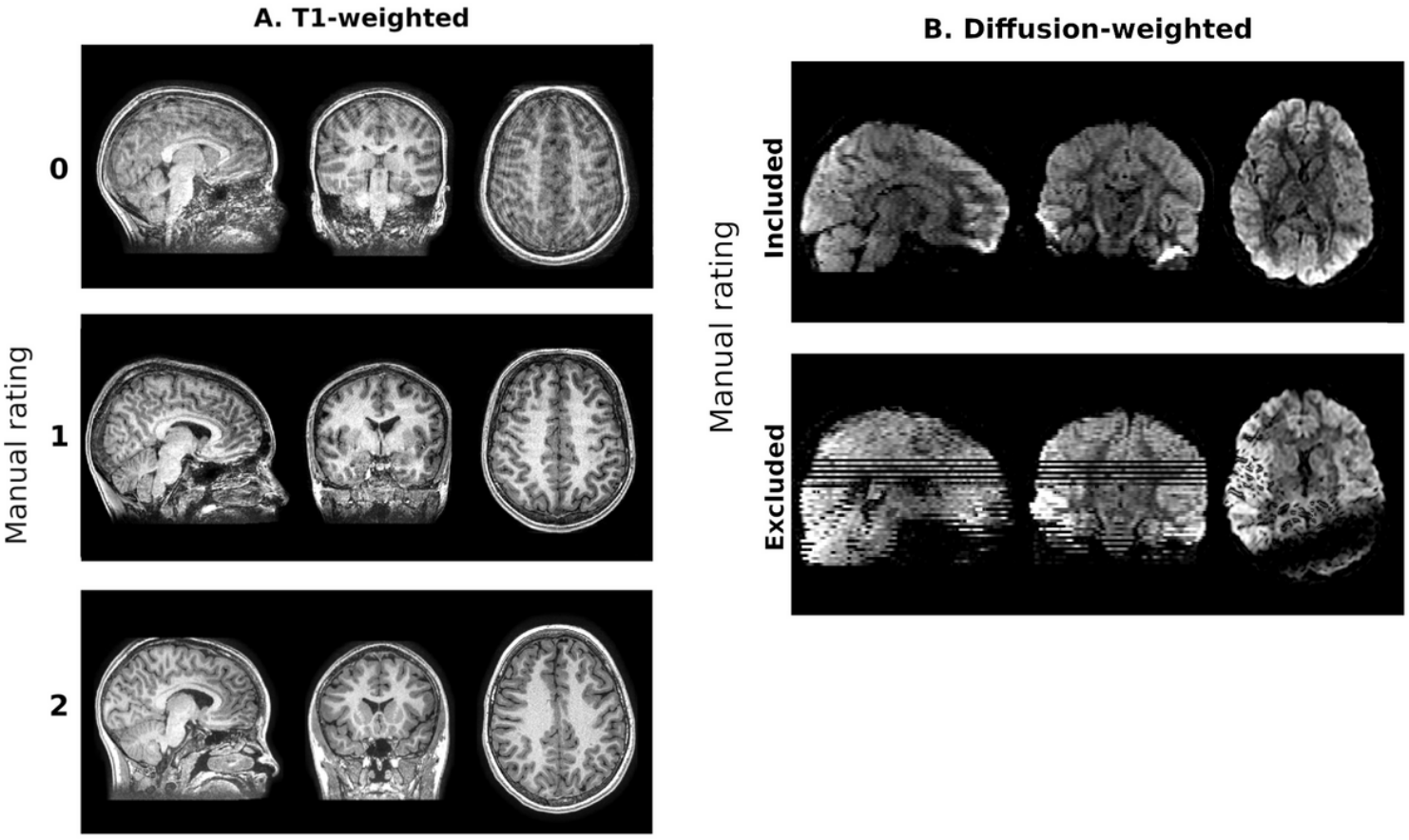

Figure 1

Examples of quality ratings for (a) T1- and (b) diffusion-weighted MRI images. T1-weighted images were rated from 0 (unusable due to gross motion artifacts) to 2 (excellent quality with no visible motion artifact). For the diffusion-weighted images, total volumes (gradient directions) with severe motion artifacts to exclude from “corrected” images were totaled and then used to classify images from 0 (unusable because ≥ 8 volumes excluded due to gross motion artifacts) to 2 (0 volumes excluded with visible motion artifact).

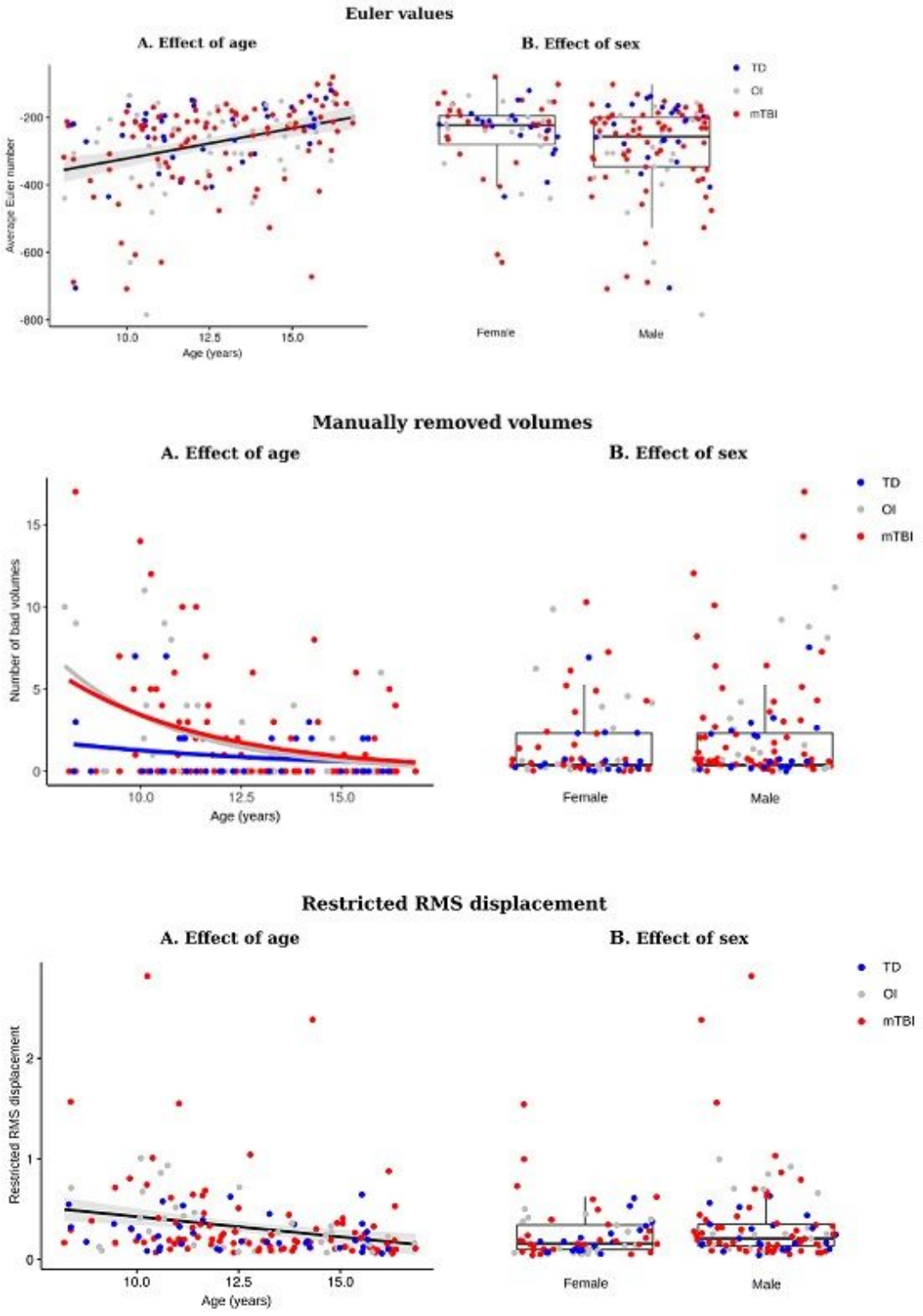

Figure 2

Graphs illustrating the effects of group, age (in years), and sex on a) Euler number, b) manual diffusion-weighted volumes, and c) restricted root mean square (RMS) displacement. a) Multiple linear regression results for Euler values showed a significant effect of (A) age (in years) and (B) sex on Euler number, indicating greater motion artifact (lower Euler values) in younger children and boys. Groups did not differ significantly in average Euler value. b) Poisson regression showing the relationship between (A) age and

number of manually identified DTI bad volumes, with significantly lower bad volume count in the TD group as compared to mTBI and OI children (A). Results also indicated a greater number of bad slices in boys compared to girls (B). Importantly, the group by age interaction was not statistically significant ($p > .05$) and was therefore trimmed from the final model. c) Results of multivariable linear regression showing that restricted RMS displacement was significantly associated with participant (A) age and (B) sex, with higher motion-related displacement at younger ages and in boys. Groups did not differ significantly in average restricted RMS displacement.