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
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. 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. 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. 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 MRI research and highlight the importance of considering motion artifacts in studies of pediatric mild traumatic brain injury.

Keywords Mild traumatic brain injury · Orthopedic injury · Structural magnetic resonance imaging · Motion artifacts · Quality assurance

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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 (Lumb-Brown et al., 2018; Mayer et al., 2018; Yeates et al., 2017a, b). Mounting evidence suggests that structural magnetic resonance imaging (MRI) techniques can potentially help identify biomarkers for pediatric mTBI (Mayer et al., 2018; Ware et al., 2020a, b). 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 in children with neurodevelopmental disorders (Engelhardt et al., 2017). Furthermore, behaviors (e.g., impulsivity, hyperactivity) that can increase susceptibility of injury (Alosco et al., 2014) have been associated with increased motion (Gerring et al., 1998; Lee et al., 2008), albeit inconsistently across known studies (Engelhardt et al., 2017). Thus, understanding, quantifying, and appropriately mitigating motion in neuroimaging studies of pediatric mTBI is imperative.

Many 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; Chen et al., 2015; Ling et al., 2012; Wang et al., 2012). 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 with mTBI or orthopedic injury (OI), but there were no differences by sex or between the groups (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 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., 2018). 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 diffusion tensor imaging (DTI) metrics, specifically fractional anisotropy (FA) and mean diffusivity (MD). We expected uncorrected and corrected (i.e., volumes with motion artifacts removed) DTI metrics to correlate strongly, with larger changes in estimates of FA than for MD values after correction (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 et al., 2019; Yeates et al., 2017b). In the interest of space, only the relevant methodology for the present study is described in detail below. 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. 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.

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 et al., 2017b). 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 (see Table 1).

The TD comparison group was comprised of uninjured, 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; see Table 1).

### Participants

A total of 226 children (mTBI/OI = 150/76) were recruited as part of the larger A-CAP study. Of those enrolled, 191 children (85%; mTBI/OI = 130/61) 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 \( p \geq 0.483 \). At the post-acute assessment, 147 children completed an MRI (77%; 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

| Variable | TD \((n=41)\) | OI \((n=49)\) | mTBI \((n=98)\) | \(p\) value |
|----------|--------------|--------------|----------------|-------------|
| Age+ \(M \pm SD\) years | 12.34 \(\pm\) 2.41 | 12.63 \(\pm\) 2.32 | 12.65 \(\pm\) 2.39 | .772 |
| Full Scale IQ score* \(M \pm SD\) | 108.30 \(\pm\) 14.41 | 108.29 \(\pm\) 10.02 | 106.43 \(\pm\) 12.17 | .614 |
| Sex \([n\%(\text{male})]\) | 22 \(\% 54\) | 26 \(\% 53\) | 64 \(\% 65\) | .247 |
| Race \([n\%(\text{White})]\) | 25 \(\% 61\) | 38 \(\% 78\) | 77 \(\% 79\) | .050 |
| MRI days post-injury \(M \pm SD\) | – | 9.63 \(\pm\) 4.09 | 8.58 \(\pm\) 3.15 | .087 |
| Mechanism of injury \([n\%]\) | – | – | – | .040 |
| Fall | 27 \(\% 55\) | – | 34 \(\% 37\) | |
| Bicycle related | 6 \(\% 12\) | – | 3 \(\% 3\) | |
| Motor vehicle collision | 0 \(\% 0\) | – | 1 \(\% 1\) | |
| Struck object | 7 \(\% 14\) | – | 29 \(\% 31\) | |
| Struck person | 7 \(\% 14\) | – | 24 \(\% 26\) | |
| Other | 7 \(\% 2\) | – | 1 \(\% 1\) | |
| Unknown | 1 \(\% 2\) | – | 1 \(\% 1\) | |
| Injury setting \([n\%]\) sport/recreational play | – | 42 \(\% 86\) | 78 \(\% 80\) | .964 |
| Total HBI parent \((M \pm SD)\) | – | 7.45 \(\pm\) 7.72 | 19.43 \(\pm\) 12.05 | <.001 |
| Reliable change total HBI \([n\%]\) symptomatic | – | 3 \(\% 6\) | 43 \(\% 44\) | <.001 |
| Loss of consciousness \([n\%]\) | – | – | – | – |
| Yes | 0 \(\% 0\) | – | 17 \(\% 17.9\) | |
| Unknown | 1 \(\% 2.0\) | – | 12 \(\% 12.6\) | |
| GCS score \([n\%]\) score = 15 | – | 49 \(\% 100\) | 89 \(\% 97.8\) | – |
| Extracranial injury \([n\%]\) | – | – | – | .035 |
| Fracture | 24 \(\% 49\) | – | 3 \(\% 3\) | |
| Laceration | 1 \(\% 2\) | – | 3 \(\% 3\) | |
| STI | 18 \(\% 37\) | – | 7 \(\% 7\) | |
| Undetermined STI vs. Fracture | 2 \(\% 4\) | – | 1 \(\% 1\) | |

* Age at injury for the mTBI and OI groups. *Based on the Wechsler Abbreviated Scale of Intelligence-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, \(STI\) soft tissue injury.
for the post-acute assessment and completed the post-acute MRI (see Table 1) 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 \( p \geq 0.289 \). 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 & 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 hours. Children with mTBI who also sustained extracranial (i.e., orthopedic) injuries at the time of the mTBI \((n = 14; 14\%)\) were included if the injury was associated with an Abbreviated Injury Scale (AIS) score \( \leq 4 \) (Committee on Injury Scaling, 1998).

**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 AIS score \( \leq 4 \) (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 et al., 2017b).

**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 and 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 MRI without sedation on the same General Electric MR750w 3T scanner with a 32-channel head coil (GE, Milwaukee, WI). Children with mTBI or OI completed MRI 2–23 days post-injury \((M = 8.93, \text{Mdn} = 8.62, SD = 3.51)\), 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 = 12,000/88–98 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/ordenlab/dcm2niix), and the timg 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 (2 children with mild OI), 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 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 Fig. 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 et al., 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 & 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 (DTI)** For the participants who had diffusion-weighted scans that contained 1–7 weighted volumes with motion artifacts (i.e., acceptable; rating of 1), corrected images were constructed by removing weighted volumes with severe motion artifacts. The uncorrected scans (i.e., 35 volumes regardless of identified motion artifacts) and corrected scans (i.e., the 28–34 volumes without gross motion artifacts in weighted volumes) images were corrected for eddy currents and motion, skull-stripped, and tensor fitted using ExploreDTI v4.8.6 running on MATLAB v8.6.0

![Fig. 1 Examples of (a) quality ratings for T1- and (b) visible motion artifacts in 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, volumes (gradient directions) with severe motion artifacts were identified and counted to classify images from 0 (unusable because > 7 volumes with gross motion artifacts excluded) to 2 (excellent quality because no volumes with visible motion artifacts excluded)](image-url)
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 (Reynolds et al., 2019). 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 for both corrected and uncorrected scans.

**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.

To determine whether the removal of (weighted) diffusion-weighted volumes with severe motion artifacts influenced DTI metrics in the children with mTBI and OI, intraclass correlation coefficients (ICC) were used to compare DTI metrics (i.e., FA and MD) between the uncorrected data (using all 35 volumes regardless of motion artifacts) and the corrected data (28–34 volumes without gross motion artifact).

**Power analysis**

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-β = .95) to detect small effects (partial $R^2 = .10$) with 4 predictors at a critical F-value = 3.05 and α = .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, $\chi^2(4) = 9.51$, $p = .049$. Older children were more likely to have usable scans than younger children ($β = 0.29$, $p = .013$). 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, $F(4, 178) = 10.66, p < .001$, $R^2 = .19$. 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 Fig. 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 quality ratings (i.e., usable versus unusable), $β = −9.49$, $p < .001$, 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 = .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 Fig. 2b. The TD group had significantly fewer volumes with motion artifacts than children in the mTBI ($β = 0.78$, $p < .001$) and OI ($β = 0.73$, $p < .001$) groups, but the mTBI and OI groups did not differ significantly ($β = 0.07$, $p = .717$). Older children had more bad volumes than younger children ($β = −0.28$, $p < .001$), and boys had more bad volumes than girls ($β = 0.50$, $p < .001$).

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, $\chi^2(4) = 26.34, p < .001$. 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 ($\beta = 0.71$, $p = .001$), and sex showed a non-significant trend ($\beta = -1.63$, 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 ($\beta = 0.56$, $p < .001$), and boys showed greater displacement than girls ($\beta = -1.44$, $p = .009$; Fig. 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 ($\geq 0.92$) and a 0% false positive rate (specificity = 1.00).

**Effect of volume removal on DTI metrics**

As reported in Table 3, there was strong (0.75 ≤ ICC < 0.90) to excellent (ICC ≥ 0.90) agreement between FA and MD values calculated from uncorrected and corrected diffusion scans. The one exception was of moderate agreement (ICC = 0.59) between uncorrected and corrected FA of the splenium of the corpus callosum.

To examine whether number of volumes moderated agreement between uncorrected and corrected DTI values, we conducted a median split on number of volumes removed ($M = 3.05$, $Mdn = 3$, $SD = 1.83$). There were 27 children with mTBI and OI who had 1–3 motion-corrupted volumes and 17 children with 4–7 motion corrupted volumes. With a few exceptions, results showed strong (0.75 ≤ ICC < 0.90) to excellent (ICC ≥ 0.90) agreement between uncorrected and corrected FA and MD values (see Supplementary Table 1). However, there was poor (ICC < 0.50) to moderate (i.e., < 0.75) agreement between uncorrected and corrected FA and MD values of the cingulum bundle (right FA ICC = 0.64), corticospinal tract (left MD ICC = 0.67), and splenium of the corpus callosum (FA ICC = 0.34; MD ICC = 0.69) when 4–7 volumes were removed.

**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)

### Table 2

| 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 ($M \pm SD$)* | −248.22 ± 103.98 | −289.64 ± 126.69 | −281.03 ± 131.00 |
| Diffusion-weighted MRI Manual QA Rating [n (%)] |               |               |               |
| 0           | 0 (0)         | 5 (12)        | 6 (7)        |
| 1           | 12 (31)       | 12 (29)       | 32 (36)      |
| 2           | 27 (69)       | 25 (60)       | 51 (57)      |
| Motion corrupted volume count ($M \pm SD$) | 0.23 ± 0.67  | 5.00 ± 13.06  | 3.85 ± 12.15 |
| Quantitative QA Restricted RMS displacement ($M \pm SD$)* | 0.25 ± 0.16 | 0.31 ± 0.25 | 0.36 ± 0.45 |

*Raw values are reported. RMS root mean square; TD typically developing, OI orthopedic injury, mTBI mild traumatic brain injury, M mean, SD standard deviation, QA quality assurance*
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
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 et al., 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 boys than girls, 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 et al., 2017a, b; 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. For example, our cut-points differed from those identified in a large sample of TD children (Roalf et al., 2016; Rosen et al., 2018). Specifically, Rosen et al., 2018 reported high sensitivity and specificity at a Euler threshold of −217 in TD children (N= 1065; 51% female; age mean = 14.90, SD = 3.70 years) enrolled in the Philadelphia Neurodevelopmental Cohort (PNC). However, a threshold of −310 provided much better sensitivity in the current sample. The cut-point for the

| Table 3 | Summary statistics and intra-class correlation coefficients (ICC) for the DTI metrics of each region of interest derived from uncorrected (i.e., 30 weighted volumes, including those with motion artifacts) and corrected (i.e., 23–29 weighted volumes, excluding those with motion artifacts) for the 44 participants who had scans that were rated as acceptable (i.e., rating of 1) for motion artifacts | Region of Interest | Hemisphere/Sub-region | Uncorrected M ± SD | Corrected M ± SD | ICC (lower, upper 95% CI) |
|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|------------------------|------------------|------------------|------------------|
| Fractional Anisotropy (FA) | Corticospinal tract | Left | 0.45 ± 0.02 | 0.45 ± 0.02 | 0.95 (0.90, 0.02) | | Cingulum bundle | Left | 0.48 ± 0.02 | 0.48 ± 0.02 | 0.82 (0.69, 0.02) | | Right | 0.55 ± 0.02 | 0.55 ± 0.02 | 0.90 (0.83, 0.02) | | Right | 0.57 ± 0.02 | 0.57 ± 0.02 | 0.91 (0.85, 0.02) | | Corpus callosum | Average | 0.55 ± 0.02 | 0.55 ± 0.02 | 0.91 (0.84, 0.02) | | Genu | 0.52 ± 0.02 | 0.52 ± 0.02 | 0.98 (0.93, 0.02) | | Body | 0.55 ± 0.02 | 0.55 ± 0.02 | 0.95 (0.89, 0.02) | | Splenium | 0.59 ± 0.02 | 0.59 ± 0.02 | 0.95 (0.89, 0.02) | | Mean Diffusivity (MD) × 10⁻³ mm² | Cingulum bundle | Left | 0.81 ± 0.03 | 0.81 ± 0.03 | 0.95 (0.91, 0.03) | | Right | 0.80 ± 0.03 | 0.80 ± 0.03 | 0.96 (0.93, 0.03) | | Corticospinal tract | Left | 0.76 ± 0.02 | 0.76 ± 0.02 | 0.85 (0.74, 0.02) | | Right | 0.75 ± 0.02 | 0.74 ± 0.02 | 0.91 (0.84, 0.02) | | Corpus callosum | Average | 0.84 ± 0.03 | 0.84 ± 0.03 | 0.92 (0.86, 0.03) | | Genu | 0.86 ± 0.03 | 0.86 ± 0.03 | 0.97 (0.92, 0.03) | | Body | 0.83 ± 0.03 | 0.82 ± 0.03 | 0.96 (0.93, 0.03) | | Splenium | 0.84 ± 0.04 | 0.84 ± 0.04 | 0.76 (0.60, 0.04) |

M Mean, SD standard deviation
PNC study was established using data collected on a 3T Siemens Tim Trio scanner using a 32-channel head coil and in another test sample with a different 3T Siemens Tim Trio scanner using an 8-channel head coil. In contrast, the current study acquired data using a 3T GE system with a 32-channel head coil. Thus, we cannot be certain if the difference in cut-points is a function of scanner type, sample characteristics, or some other study feature.

Finally, we examined how the manual removal of motion-corrupted volumes affects diffusion metrics. Metrics generally showed strong agreement between corrected and uncorrected values, indicating that conclusions from either corrected or uncorrected scans would be largely similar. However, lower agreement was found for scans with more volumes removed (i.e., 4–7) compared to fewer (i.e., 1–3 volumes). Overall, the DTI metrics of the splenium of the corpus callosum appeared to be the most susceptible to volume removal. Notably, we cannot be certain which values (raw or corrected) are more accurate. Additional research using phantoms with known structural properties is needed to address this question.

**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 than compared to those acquired earlier (Rosen et al., 2018). Here, the protocol order differed between the A-CAP study (i.e., mTBI/OI groups) and the study of TD children, and some sequences were repeated when motion or other artifacts were apparent. Children with mTBI and OI completed diffusion- and T1-weighted imaging after resting-state functional MRI, whereas diffusion-weighted and then T1-weighted imaging were collected prior to additional sequences in TD children. Thus, the time between the start of the scan and diffusion-weighted imaging was ~14 min for children with mTBI and OI and ~8 min for TD children; and T1-weighted imaging was ~28 min for children with mTBI and OI and ~16 min for TD children. The sequences did not differ by study. Finally, we did not examine behaviors such as hyperactivity and impulsivity that may influence participant motion. Future research would benefit from examining these factors. However, we note that behaviors that are common in children with attention deficits and hyperactivity do not always account for motion above the effects of age (Engelhardt et al., 2017).

**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. Group differences were minimal but did 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’s age and sex were more associated with motion than the comparison group (OI vs TD), and thus warrant consideration during scan acquisition. 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.

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**Data availability** Data available upon reasonable request.

**Code availability** Analysis code is available upon reasonable request.

**Declarations**

**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.

**Conflicts of interest/Competing interests** None of the authors have a conflict of interest to declare.

**Conflict of interest** 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.

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