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Objective Eye Tracking Deficits Following Concussion for Youth Seen in a Sports Medicine Setting

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Abstract

Quantification of visual deficits may help to identify dysfunction following concussion. We evaluated eye-tracking measurements among adolescents within 10 days of concussion and healthy control participants. Patients who reported to 2 tertiary care sport concussion clinics within 10 days of concussion completed an objective eye tracking assessment. Seventy-nine participants completed the study, 44 with concussion (mean age = 14.1 ± 2.2 years, 39% female) and 35 controls (mean age = 14.3 ± 2.4 years, 57% female). Right eye skew along the bottom of the screen was significantly higher for the concussion group compared to controls (median = 0.022 [interquartile range = –0.263, 0.482] vs 0.377 [interquartile range = –0.574, –0.031]; $P = .002$), but not the left eye. Among the variables investigated, right eye skew was altered for adolescents with a concussion. Visual function is an important component in the postconcussion evaluation, and identifying deficits soon after injury may allow for earlier specialist referral and intervention.

Keywords

pediatric, adolescent, mild traumatic brain injury, eye tracking, vision

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Sport-related concussion is an injury that is difficult to assess, as individuals who present for care of the injury report a heterogeneous array of complaints and behavioral problems.[1,2] Although symptoms are used for diagnosis and recovery assessment, most are not specific to a concussion, as many other conditions may be associated with the symptoms observed after a concussion.[2] Thus, researchers have sought to investigate physiologically based, objective markers of concussion to assist clinical decision making. Using techniques such as advanced imaging, electrophysiology, or fluid biomarkers, it appears that physiologic disruption continues beyond clinical recovery.[3] However, determining clinically pragmatic yet quantifiable methods to monitor postconcussion disruptions to brain function has been challenging for researchers.

Currently, it is recommended that clinical concussion evaluations assess several domains of function, such as cognitive function, sleep/wake disturbances, ocular function, vestibular function, and gait and balance testing.[1] According to a recent systematic review, ocular function represents a domain that has not been studied extensively in the context of sport-related concussion, but is an objective and promising indicator of patient status.[2] Empirical studies of vision in patients who have recently sustained a concussion remain an important research priority. Visual disturbances have been documented in recent investigations among the adolescent population with concussion.[4-8] Thus, quantifying the effect of concussion on vision in adolescents may help to specify areas of dysfunction.

Objective visual tracking methods have recently been developed to provide meaningful clinical information to assist with

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diagnosis of concussion or structural traumatic brain injury.[9-11] Because tailoring management plans based on the patient's most impaired findings can help clinicians move away from "one therapy for all" treatments,[12] the use of objective eye tracking may help identify otherwise clinically undetected deficits.[4,13] Detection of visual deficits may allow for early referral for intervention to reduce the likelihood of experiencing persistent postconcussion symptoms or to reduce overall symptom burden. Identifying visual deficits in a consistent manner, however, remains challenging because the deficits may be subtle and require a trained clinician.

Because of the heterogeneity of clinical presentation following concussion, it is important to develop objective tools that quantify patient performance reflective of physiologic function. Objective eye tracking represents one potential method that can be performed during a relatively brief protocol within the confines of an examination room.[9,10] Thus, the purpose of this study was to evaluate objective eye tracking measures among child and adolescent athletes who sustained a concussion within 10 days of examination and a group of healthy control participants. We hypothesized that eye movement variability would be higher for the concussion group compared to the control group.

Methods

Study Design

We conducted a cross-sectional and multisite study to measure eye tracking performance of athletes who were diagnosed with a concussion and uninjured controls. Data were collected at 2 separate sport concussion clinics associated with tertiary care regional children's hospitals between July 1, 2016, and January 31, 2018. After injury, concussion participants self-presented to the clinic, or were referred by an emergency department or primary health care provider.

Concussion was defined according to the consensus statement by the International Committee on Concussion in Sports as a brain injury caused by a direct blow to the head, face, neck, or elsewhere on the body, resulting in the rapid onset of impairment of neurologic function.[1] As such, those patients who experienced trauma to the head resulting in the onset of signs and symptoms were diagnosed with concussion. A board-certified sports medicine physician diagnosed each concussion participant with a concussion prior to enrollment in the study, and concussion participants were tested within 10 days of sustaining the concussion.

Participants

The 2 groups of participants included a concussion group and a control group. For the concussion group, inclusion criteria consisted of enrolling in the study within the first 10 days of injury and being between the ages of 8 and 18. Exclusion criteria consisted of a concurrent injury sustained at the time of concussion, history of permanent memory loss, significant sensory deficits (eg, deafness or blindness), or a history of psychiatric disorders. Only those who sustained a concussion during sports or by a mechanism involving forces similar to sports, such as falling from ground level or being injured during recreational activities, were included in the study. Patients with more severe injury mechanisms, such as falling from a height or sustaining motor vehicle collisions, were excluded. As with prior work,[14,15] we identified and recruited healthy adolescent control participants between the ages of 11 and 18 years involved in a program at a sports injury prevention center or were children of hospital employees. Exclusion criteria for the control group consisted of a diagnosed concussion within the year prior to testing, a concurrent injury limiting sport participation, history of permanent memory loss, significant sensory deficits (eg, deafness or blindness), or a history of psychiatric disorders. The institutional review board approved this study at both institutions. All participants and their parent/guardian assented/consented to participate in the study through a written informed consent procedure.

Eye Tracking Assessment

To assess visual function, participants completed an automated eye tracking assessment. During the assessment, they watched a brief (220-second) video clip from Internet sources (eg, clips from "Myth Busters," "Finding Nemo," "Emperor's New Groove," "America's Got Talent," or replays of Olympic swimming events). To limit movement during the trial, participants sat in a chair adjusted so their feet were flat on the ground, and placed their chin on a chin-rest mounted to a height-adjustable table so that it was fit to the seated height of participants. The stimulus video was displayed in approximately one-ninth of the display monitor area, moving in a clockwise direction along the outer edges of the monitor. Participants were instructed to watch the duration of the video while holding still. Test administrators did not intervene at any point during the trial.

Eye movements were recorded using an Eyelink 1000 eye tracker at a fixed distance of 55 cm between the computer monitor and the participant's eyes, consistent with prior work.[9,10] Eye position data (X and Y coordinates) from both eyes were obtained independently at 500 Hz. For each frame throughout the trial, the X (horizontal) and Y (vertical) pupil positions were tracked automatically, representing the 2 orthogonal components of the pupil reflection, in line with previously established methods[10,16] to create a box trajectory of each eye movement. The 10 seconds at the beginning and end of the trial were discarded to reduce potential noise from the eye tracking signal. The cameras recorded binocular pupil gaze coordinates in the horizontal and vertical planes of movement, and no spatial calibration occurred. The analysis consisted of calculation of how the eyes move over time in relation to one another and together, rather than their movement speed or accuracy relative to a target.[10] In prior work, the set of variables achieved an 88% sensitivity and 77% specificity in identifying concussion among a cohort of individuals seen in an emergency department.[9]

Following trial completion, 67 metrics were automatically calculated using commercially available software (Oculogica, Inc, New York, NY) independent of operator intervention, and as published previously.[9,10] We selected 17 variables to analyze within this investigation based on prior work that has used this experimental setup to define eye movement velocity, movement distance, or trajectory areas.[5,9] Many of these variables possess moderate levels of reliability among uninjured adolescent athletes,[16] and evaluate the distance the eye traverses during the trial, the variability of movement of each eye, and the ratio of the movement and variability of the 2 eyes moving together. The total distance covered refers to the amount of measured eye movement in each plane along each side (top, bottom, left, and right) of the computer monitor. Skew represents the amount of asymmetry around the mean of the eye trajectory, normalized skew is the

skew/standard deviation of eye movement, and the ratio between eyes represents their ability to move in conjunction with one another.

Symptom Assessment

All participants completed a clinical evaluation that included a symptom assessment using the Post-Concussion Symptom Scale (PCSS) or the Post-Concussion Symptom Inventory (PCSI), which are validated for use in adolescents with concussion to assess the number and severity of concussion symptoms present at the time of testing.[17,18] Participants rate each of the listed concussion symptoms on a scale from 0 to 6, where 0 indicates that the patient is not experiencing the listed symptom, and 6 indicates the maximum severity for that symptom. Because these 2 scales differ from one another to some degree, the summary scores were added for those items that are consistent between the 2 scales (eg, headache, light sensitivity, dizziness, fatigue). There were 18 included symptoms, rated on a scale from 0 to 6, resulting in a maximum score of 108.

Statistical Analysis

Continuous variables are presented as means ($\pm$standard deviation) and compared using independent samples *t* tests for normally distributed variables. For nonnormally distributed continuous variables, medians (interquartile ranges) are presented and between-group comparisons were made using Mann-Whitney *U* tests. Categorical variables are presented as the number present in the group and percentages of the total and were compared between groups using Fisher exact tests.

We first performed univariable comparisons for demographic, medical history, symptom ratings, and eye tracking metrics between the concussion and control groups. For eye tracking metrics, significance was adjusted to $P < .003$ to account for the multiple comparisons made. To identify the factors that were independently associated with concussion, we then performed a multivariable binary logistic regression analysis. Variables that appeared different between the 2 groups with a statistical probability of $P < .20$ were identified as potential predictors and included in the model.[19] We used a forward selection procedure to reduce redundancy and collinearity in the model, where each predictor was singularly added to the model, with a goal of identifying the clinical and eye tracking variables that were independently associated with sustaining a concussion. As with previous studies, the significance threshold of $P < .20$ for potential inclusion was selected to include a broad set of clinically relevant variables.[20,21] We assessed collinearity using condition indices and corresponding variance inflation factors (VIFs). A condition index >30 was determined to require individual collinearity assessments, which were performed using VIFs. Collinearity between 2 variables was detected with a VIF >2.5.[19,22]

Finally, to identify the association between symptoms and eye tracking, the eye tracking variables that were significantly associated with concussion were placed into a multiple linear regression model as the predictor variable, with overall symptom severity, symptom count, dizziness, and light sensitivity as the outcome variables, adjusting for potential confounders. Statistical significance was defined as a *P* value of <.05 or, for binary logistic regression analyses, an adjusted odds ratio (aOR) with a 95% confidence interval (CI) that did not contain one. All statistical analyses were conducted using Stata, version 15 (StataCorp, College Station, TX).

Table 1. Participant Characteristics.

Characteristic	Concussion group (n = 44)	Control group (n = 35)	*P* value
Age, y, mean (SD)	14.1 (2.2)	14.3 (2.4)	.75
Sex, female, n (%)	17 (39)	20 (57)	.12
Height, cm, mean (SD)	161.5 (13.6)	162.0 (13.6)	.87
Weight, kg, mean (SD)	56.5 (14.5)	54.3 (15.0)	.50
Prior concussion history, n (%)	22 (50)	7 (21)	.01*
Documented learning disability, n (%)	6 (14)	2 (6)	.29
ADD or ADHD diagnosis, n (%)	6 (14)	7 (20)	.55
History of migraine, n (%)	3 (7)	5 (14)	.46

Abbreviations: ADD, attention-deficit disorder; ADHD, attention-deficit hyperactivity disorder.

Table 2. Comparison of Overall and Vision-Related Symptoms Between Concussion and Control Groups.

Symptom	Concussion group, Median (interquartile range)	Control group, Median (interquartile range)	*P* value
Overall symptom severity	31 (20, 47)	1 (0, 5)	<.001*
Symptom count	12 (7.5, 15.5)	1 (0, 3)	<.001*
Dizziness rating	0.5 (0, 2)	0 (0, 0)	<.001*
Light sensitivity rating	3 (1, 4)	0 (0, 0)	<.001*

Results

A total of 79 participants completed the study, of which 44 were tested within 10 days of a concussion and 35 were controls. The concussion group was tested at a mean of 6.4 (SD = 2.5) days postinjury, and a significantly higher proportion reported a prior history of prior concussion relative to the control group (Table 1). Symptom resolution times were available for 29 (66%) of the concussion participants, and they reported a median symptom resolution time of 22 (interquartile range = 17-38) days postconcussion. The concussion group reported significantly greater overall symptom severity, total number of symptoms endorsed, and more severe dizziness and light sensitivity ratings than the control group (Table 2). Participant characteristics did not significantly differ between the 2 locations for age (14.1 ± 2.3 vs 14.7 ± 2.2 years; $P = .47$), sex (49% vs 30% female; $P = .32$), time of postinjury assessment (6.5 ± 2.5 vs 6.1 ± 2.6 days; $P = .64$), or overall visual function (BOX score = 8.3 ± 6.0 vs 10.2 ± 5.8; $P = .38$).

Univariable analysis of eye tracking metrics indicated that the concussion group demonstrated significantly higher normalized right eye skew along the bottom of the box using the

Table 3. Univariable Comparisons on the 16 Eye Tracking Metrics Between Concussion and Control Groups.

Metric	Concussion group, Median (interquartile range)	Control group, Median (interquartile range)	*P* value
Box score	8.37 (3.04, 12.6)	5.48 (3.90, 7.87)	.32
Left eye skew: right box	0.002 (–0.009, 0.012)	0.000 (–0.010, 0.007)	.57
Left normalized eye skew: right box	0.041 (–0.339, 0.459)	0.001 (–0.354, 0.299)	.61
Right eye skew: right box	–0.003 (–0.013, 0.010)	0.001 (–0.006, 0.007)	.49
Right normalized eye skew: right box	–0.081 (–0.340, 0.466)	0.042 (–0.231, 0.263)	.66
Left normalized eye skew: left box	0.247 (–0.101, 0.480)	–0.084 (–0.377, 0.296)	.03
Right eye skew: bottom of the box	0.001 (–0.010, 0.021)	–0.009 (–0.017, –0.001)	.02
Right normalized eye skew: bottom of the box	0.022 (–0.263, 0.482)	–0.377 (–0.574, –0.031)	.002*
Left normalized eye skew: bottom of the box	0.026 (–0.442, 0.300)	–0.249 (–0.622, 0.224)	.13
L/R eye movement variance ratio X: top and bottom box	1.194 (0.647, 2.166)	1.574 (0.847, 2.805)	.30
L/R eye movement variance ratio Y: top and bottom box	0.717 (0.321, 1.910)	2.402 (0.591, 4.985)	.02
Left eye distance: bottom box	0.003 (0.002, 0.004)	0.002 (0.001, 0.003)	.04
Left eye distance: left box	0.003 (0.002, 0.004)	0.002 (0.002, 0.003)	.16
Left eye movement variance: top box	0.012 (0.007, 0.025)	0.012 (0.010, 0.030)	.83
Right eye distance: bottom box	0.003 (0.002, 0.004)	0.002 (0.002, 0.003)	.04
Right eye distance: right box	0.003 (0.002, 0.003)	0.002 (0.002, 0.003)	.06
L/R eye movement variance ratio X: bottom box	0.003 (0.001, 0.007)	0.002 (0.001, 0.003)	.09

*$P < .003$.

Table 4. Multivariable Logistic Regression Results for the Independent Association Between Right Eye Skew Normalized Movement and Concussion.

Variable	Adjusted odds ratio	Standard error	95% confidence interval	*P* value
Right eye normalized skew: bottom of the box	7.84	5.43	2.02, 30.5	.003
Prior history of concussion	3.72	2.25	1.14, 12.2	.030

Table 5. The Effect of Eye Skew Along the Bottom of the Box (Predictor Variable) on Overall and Individual Concussion Symptoms (Outcome Variable) While Adjusting for Prior Concussion History Among Participants With a Concussion.

Outcome measure	β coefficient	Standard error	95% confidence interval	*P* value
Overall symptom severity	10.62	4.861	0.769, 20.47	.035
Number of symptoms endorsed	1.851	1.345	–0.867, 4.568	.18
Dizziness severity rating	0.127	0.438	–0.757, 1.012	.77
Light sensitivity severity rating	0.266	0.472	–0.687, 1.219	.58

eye tracking device compared to the control group (Table 3). In addition, we compared concussion and control groups for normalized left eye skew along the bottom of the box, with no significant differences detected between the concussion and control groups (Table 3). No other significant between-group differences were noted after performing the Bonferroni correction (Table 3).

After adjusting for potential confounding variables (prior history of concussion), normalized right eye skew bottom of the box metric was significantly associated with having sustained a concussion (Table 4). The eye movement variance ratio between the top and bottom of the box was removed from the logistic regression model because of collinearity with the other variables, resulting in a final model with only 2 variables (Table 4). In addition, the right eye skew normalized bottom of the box metric significantly predicted overall symptom severity among participants with concussion (Table 5), but was not significantly associated with any specific individual symptom ratings.

Discussion

The data from our multisite investigation suggest that eye skew, defined as the amount of asymmetry around the mean of the eye trajectory, is altered for adolescents within the first 10 days of a concussion relative to uninjured controls. Because vision is an important factor in identifying dysfunction following a concussion,[1] the use of objective methodologies may assist clinicians to identify otherwise unnoticed visual deficits.

Within the set of variables we examined between concussion and control groups, the variable with the strongest association with concussion was the skew deviation of the right eye, but not the left eye. The underlying mechanism for skew deviation is thought to involve a unilateral alteration within the neural pathways that connect the medulla and the mesencephalon.[23] In addition, this finding may reflect the underlying phenomenon of ocular dominance[24] where the right eye is dominant in the majority of people (68%)[25] and activates a larger area of the visual cortex compared with the nondominant side.[26] In binocular vision, the brain reconciles 2 competing visual images by choosing the dominant afterimage. The physiologic basis for this appears to be related to asymmetric

anatomic correlates in the fovea, observed in those with and without dyslexia.[27] This anatomic asymmetry and ocular dominance is lacking in dyslexia where both primary and mirror images appear to compete for attention, resulting in undetermined dominant image, potentially accounting for the clinical manifestations of dyslexia.[27] As such, the postconcussion alterations to eye movement may be subtle, and difficult to detect on clinical examination and may only be noted in the dominant eye, rather than binocularly or in the nondominant eye. Such subtle abnormalities in binocular visual function, including pursuits, saccades, or vestibulo-ocular system functioning may require the addition of objective eye movement recording devices made possible by technological advances to allow for a precise quantification of deficits.[28]

Although the skew deviation variable was associated with having sustained a concussion within the 10 days prior to evaluation, the majority of variables we investigated did not demonstrate differences between concussion and control groups. This may be due to the heterogeneity of concussion. Recently, it has been proposed that there are several subtypes of concussion, one of which involves ocular function.[29] This form of concussion can result in headache, fatigue, difficulties with vision tasks, pressure behind the eyes, or trouble focusing.[29] By grouping all concussion participants together, we may have combined participants with and without visual problems after concussion, thus reducing our ability to detect between-group differences for visual function. Given that it has been reported that 69% of patients have some form of visual problem on clinical evaluation,[4] it is likely that not all patients tested had vision-related problems within our sample. It is also possible that a subset of participants had underlying diagnosed or undiagnosed vision problems prior to their concussion that might account for differences in objective measures of eye movements after concussion. Clinical assessments for vision-related disorders, such as convergence insufficiency, accommodative insufficiency, and saccadic dysfunction each require evaluations by a professional skilled in visual examinations.[4] The use of objective eye-tracking technology that can quickly identify those with vision-specific disturbances after concussion may allow for earlier recognition and, when needed, specialist referral, potentially reducing the long-term effects of concussion. Thus, the inclusion of brief eye tracking assessments in addition to a thorough clinical evaluation may produce a well-rounded approach for determining vision-related deficits postconcussion.

Traditionally, eye movement deficits can be assessed clinically via a combination of symptom inventories, vision-specific symptom inventories, and physical examination findings during smooth pursuits, near point of convergence, visual acuity, eye alignment, or fusional vergence assessments.[4,13,30] Although these forms of evaluation have demonstrated utility, their clinical availability may be limited, as they rely on trained clinicians and results may potentially vary depending on administration conditions and interpretation of findings. Thus, objectively quantifying eye function through a brief protocol may assist with reducing between-examiner variability and increase the applicability of vision evaluations in the context of concussion care. Specifically, the lack of differences between testing sites in our investigation indicates that the protocol exhibits potential for useful comparisons between different clinical locations and settings.

Interestingly, while eye skew was significantly associated with the overall symptom burden of participants, no single vision-related symptom severity demonstrated an association with eye skew. This likely reflects the varying presentations of those in the concussion group, as not all reported significant visual problems, but all reported a relatively high overall symptom burden. Prior work performed in a different clinical setting (the emergency department) has identified a set of variables using a similar experimental protocol that distinguished between concussion and healthy participants.[9] Because our sample included those who were tested up to 10 days postinjury, rather than within hours of injury, it is not surprising that our findings differed from this prior study. In addition, our sample of control participants may have also differed, as we included a sample of relatively young individuals as healthy controls. Further work is required to determine which set of eye-tracking metrics are the most useful for acute diagnosis and longitudinal recovery tracking after concussion.

Our study had limitations and the findings should be interpreted in light of them. Although a multisite study, our participant sample was composed of patients who reported for care after a concussion to 1 of 2 specialized sport concussion clinics associated with a regional tertiary care hospital. Therefore, findings from this cohort of individuals may not be generalizable to other populations of individuals with concussion. In addition, the presence of attention-deficit disorder (ADD) or attention-deficit hyperactivity disorder (ADHD) may influence eye tracking performance.[16] The inclusion of some individuals with ADD or ADHD may have influenced our results, although the proportion of individuals with this diagnosis was not significantly different between concussion and control groups and, in fact, the diagnosis was more common in the control group, thereby biasing our results toward the null hypothesis. Our findings are specifically limited to young patients who present for care for concussion within this setting.

In conclusion, the normalized amount of asymmetry around the mean of the eye trajectory while watching a video was greater among adolescents who were tested within 10 days of a concussion than controls. This represents a potentially useful paradigm to allow clinicians across a variety of practice settings to identify vision-related problems after a concussion. However, further work is needed to validate and generalize these results to other populations.

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Author Contributions

DRH contributed to the conception and design, acquisition, analysis, and interpretation, and drafting of the manuscript. ANB contributed to the acquisition and interpretation of data and critically revising the

manuscript. EPS contributed to the acquisition and interpretation of data and critically revising the manuscript. OEP contributed to the acquisition and interpretation of data and critically revising the manuscript. WPM contributed to conception and study design, interpretation of data, and critically revising the manuscript. CLM contributed to conception and study design, interpretation of data, and drafting and critically revising the manuscript.

All authors gave final approval for submission of this manuscript for publication.

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Declaration of Conflicting Interests

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Ethical Approval

This study was approved by Boston Children's Hospital Protocol Number IRB-P00016317 Children's Hospital of Philadelphia Protocol Number 16-012722.

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