Reliability of Objective Eye-Tracking Measures Among Healthy Adolescent Athletes

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Abstract

Objective: To determine the test–retest correlation of an objective eye-tracking device among uninjured youth athletes. **Design:** Repeated-measures study. **Setting:** Sports-medicine clinic. **Participants:** Healthy youth athletes (mean age = 14.6 ± 2.2 years; 39% women) completed a brief, automated, and objective eye-tracking assessment. **Independent variables:** Participants completed the eye-tracking assessment at 2 different testing sessions. **Main outcome measures:** During the assessment, participants watched a 220-second video clip while it moved around a computer monitor in a clockwise direction as an eye tracker recorded eye movements. We obtained 13 eye movement outcome variables and assessed correlations between the assessments made at the 2 time points using Spearman's Rho (r_s). **Results:** Thirty-one participants completed the eye-tracking evaluation at 2 time points [median = 7 (interquartile range = 6–9) days between tests]. No significant differences in outcomes were found between the 2 testing times. Several eye movement variables demonstrated moderate to moderately high test–retest reliability. Combined eye conjugacy metric (BOX score, $r_s = 0.529$, $P = 0.008$), the variance of the ratio for both eye movements in the horizontal ($r_s = 0.497$, $P = 0.013$) and vertical ($r_s = 0.446$; $P = 0.029$) movement planes along the top/bottom of the computer screen, and the variance of the left and right eye movement along the bottom segment of the computer screen ($r_s = 0.565$; $P = 0.004$) each demonstrated moderate between-test correlations. **Conclusions:** Automated and quantitative eye movement and conjugacy metrics provide relatively stable measurements among a group of healthy youth athletes. Thus, their inclusion as a visual tracking metric may be complementary to other visual examination techniques when monitoring concussion recovery across time.

Key Words: vision, disconjugacy, concussion, eye tracking

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INTRODUCTION

The clinical management of sport-related concussion varies across medical professionals.[1,2] Assessing symptoms is a key element to identification of the course of clinical recovery after a concussion; however, recent work suggests that physiologic dysfunction may continue even after symptoms have resolved.[3] Therefore, clinical assessment tools based on physiologic function that can be used during concussion evaluations may be useful in determining recovery from injury. There are, however, relatively few tests of physiologic function that are both clinically viable and reliable across multiple time points that are available for clinical use.

The visual system is commonly affected by sport-related concussion.[4,5] Accordingly, visual tests are recommended for use during clinical concussion evaluations.[6] Using simple clinical measures, researchers have identified that accommodative insufficiency, convergence insufficiency, and saccadic dysfunction occur in 29% to 51% of patients presenting to a specialized sport concussion clinic.[4] More sophisticated and robust measures of visual function are relatively quick and easy to use as an adjunct to standard vision examinations.[7] Using a visual tracking device and automated algorithm to detect the disruption of pathways responsible for eye movement control, reasonably high sensitivity and specificity have been reported after concussion.[8] Furthermore, visual disconjugacy has been identified among patients with concussion relative to uninjured controls.[7] The stability of measurements used to make these diagnoses across time, however, is unknown.

Measurements of neurocognitive abilities,[9] gait and balance control,[10,11] and vestibular-ocular motor function[12] are common components of concussion evaluations with established reliability metrics. To the best of our knowledge, however, the reliability of objective eye-tracking metrics obtained within a clinically viable protocol has not yet been reported. Identification of test stability over time will help

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clinicians to determine the amount of expected change that accompanies follow-up tests.

In addition to reliability concerns, pre-existing factors may affect postconcussion performance on many different concussion assessments. Specifically, a history of prior concussion[13,14] and attentional deficit disorder/attentional deficit hyperactivity disorder (ADD/ADHD)[15,16] have been documented to affect neurocognitive and balance control abilities. Their effect on visual tracking abilities as assessed by a quantitative test independent of a diagnosed concussion remains unknown, including among youth athletes. Therefore, the purpose of this investigation was to determine the test–retest correlation of an objective eye-tracking device among a sample of uninjured pediatric and adolescent athletes tested twice. Secondarily, we sought to determine whether pre-existing factors, such as a history of concussion and an attentional disorder (ADD or ADHD), were associated with altered visual tracking abilities.

METHODS

Study Design

We used a prospective, repeated-measures design of uninjured adolescent athletes to determine the reliability of eye-tracking measures over the course of 2 separate tests. The second test occurred 4 to 32 days after the initial examination to replicate the testing timeline that often accompanies postconcussion serial testing during the acute recovery phase. All testing took place in a dedicated room free from distracting visual or auditory stimuli. The test timeline was selected based on other test–retest studies that used a time interval between tests of 1 week and 1 month,[11,17–20] and to mimic the timeline that patients are often seen for care after a concussion.

Participants

As with previous work,[21,22] we recruited healthy adolescents aged 11 to 18 years from an injury prevention center, where they were completing an injury prevention evaluation, a personal training session, or a different study, or from children of hospital employees. We included participants who reported active participation in an organized sport. Exclusion criteria included a diagnosed concussion within the year before testing, significant sensory deficits (eg deafness or blindness), a psychiatric disorder, self-reported migraine history, or a history of use of a medication affecting the central nervous system any time within the 3 months before testing. We defined adolescence according to the definition provided by the World Health Organization as people between 10 and 19 years of age.[23]

Procedures

During the trial, participants watched a brief (220 seconds) clip of a video from internet sources such as "Myth Busters," "Finding Nemo," "Emperor's New Groove," "America's Got Talent," or replays of Olympic swimming events. Consistent with previous work,[7,8] eye movements were recorded while participants watched the visual stimulus using an Eyelink 1000 eye tracker at a fixed distance of 55 cm between the computer monitor and the participant's eyes. Participants sat in a height-fixed chair and rested their chin on a chin rest situated in a height-adjustable table to adjust for the seated height of participants and to limit movement during the test to the extent possible. During the trial, the stimulus video (approximately 1/9 of the area of the display monitor) played and moved in a clockwise direction along the outer edges of the monitor. Eye position was obtained at a frequency of 500 Hz. The 10 seconds at the beginning and end of the trial were discarded to reduce noise. All eye tracking took place with both eyes watching the visual stimulus throughout the trial, and no spatial calibration occurred to allow for the independent analysis of each pupil throughout the trial. The test administrator did not intervene during the trial.

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 over time, consistent with previously established methods[7] to create a box trajectory of each eye movement during the trial. For x coordinates, the sum of differences over time was used to calculate horizontal pupil movement, and the sum of differences for y coordinates over time was used to calculate vertical pupil movement. Total gaze disconjugacy was obtained by calculating the sum of differences for both x and y coordinates over time. When blinks occurred, 200 frames (0.4 seconds) before and after the event were removed to limit noise related to the blink event. After the trial, 89 metrics were automatically calculated using a computer algorithm independent of operator intervention and consistent with previous work.[7,8]

In addition, participants filled out a standardized questionnaire that documented presence and severity of concussion symptoms, and they self-reported whether they had a previous history of diagnosed concussions or a diagnosis of ADD or ADHD. Concussion symptoms were assessed using the Postconcussion Symptom Scale (PCSS), a standard evaluation form designed to assess the number of concussion symptoms present at the time of testing and their severity.[24] This scale is a part of the Sport Concussion Assessment Tool, Version 5[6], and instructs participants to rate each of the 22 concussion symptoms on a scale from 0 to 6.

Outcome Variables

We analyzed 13 eye-tracking outcome variables that preliminary data suggest are useful for concussion diagnoses among pediatric and adolescent patients, derived from an analysis taking into account 89 possible eye-tracking metrics (Table 1).[8] These metrics evaluated the distance the eye covered 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/SD of eye movement, and the ratio between eyes represents their ability to move in conjunction with one another.

Statistical Analysis

We compared the median values for each of the outcome variables between time points using Wilcoxon signed-rank tests. Because of the 13 comparisons made, we evaluated

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TABLE 1. Eye-Tracking Outcome Variables Measured at Separate Time Points

Variable	Variable Definition	Time 1: Median (IQR)	Time 2: Median (IQR)	*P*
Box score	Binary classifier developed using best-subset regression model, normalized and adjusted by a constant.[8]	5.6121 (3.8545 to 9.3795)	5.5347 (2.4764 to 9.8780)	0.27
Left eye skew: right box	Left eye mean skew along the right side of the box area	0.0012 (−0.0087 to 0.0083)	0.0017 (−0.0080 to 0.0109)	0.88
Left eye skew normalized: right box	Left eye mean normalized skew along the right side of the box area	0.0456 (−0.3204 to 0.3897)	0.0572 (−0.3019 to 0.3630)	0.95
Right eye skew: right box	Right eye mean skew along the right side of the box area	0.0014 (−0.0049 to 0.0078)	0.0018 (−0.0056 to 0.0148)	0.93
Right eye skew normalized: right box	Right eye mean normalized skew along the right side of the box area	0.0441 (−0.2142 to 0.3168)	0.0443 (−0.2187 to 0.4462)	0.95
L/R eye movement variance ratio X: top and bottom box	Variance of the ratio for the left and right eye along the X direction for the top and bottom of the box area	1.6267 (0.8022 to 2.8628)	1.3335 (0.7733,3.1854)	0.81
L/R eye movement variance ratio Y: top and bottom box	Variance of the ratio for the left and right eye along the Y direction for the top and bottom of the box area	2.3756 (0.4608 to 5.2109)	1.5185 (0.6471 to 7.1528)	0.24
Left eye distance: bottom box	The distance covered by the left eye along the bottom of the box area	0.0021 (0.0016 to 0.0028)	0.0020 (0.0016 to 0.0028)	0.17
Left eye distance: left box	The distance covered by the left eye along the left side of the box area	0.0024 (0.0018 to 0.0031)	0.0022 (0.0016 to 0.0027)	0.013
Left eye movement variance: top box	Mean variance of the left eye along the top of the box area	0.0130 (0.0077 to 0.0297)	0.0083 (0.0056 to 0.0177)	0.016
Right eye distance: bottom box	The distance covered by the right eye along the bottom of the box area	0.0022 (0.0017 to 0.0026)	0.0022 (0.0016 to 0.0029)	0.52
Right eye distance: right box	The distance covered by the right eye along the right side of the box area	0.0023 (0.0018 to 0.0028)	0.0024 (0.0019 to 0.0027)	0.67
L/R eye movement variance ratio X: bottom box	Variance of the left and right eye along the X direction of the bottom segment of the box area	0.0018 (0.0006 to 0.0029)	0.0014 (0.0007 to 0.0028)	0.65

IQR, interquartile range.

statistical significance at the threshold of $P < 0.004$ (0.05 divided by 13 comparisons). We assessed correlations between the 2 testing time points using Spearman's Rho using the following criteria to evaluate the strength of correlation: no correlation (0–0.19), low correlation (0.20–0.39), moderate correlation (0.4–0.59), moderately high correlation (0.6–0.79), and high correlation (≥0.8).[25] We assessed the effect of concussion history and ADD/ADHD on each eye-tracking outcome variable using multiple linear regression analyses. Finally, we assessed the correlation between the 2 testing time points for only those participants who did not have ADD/ADHD using Spearman's Rho. Statistical significance was evaluated as $P < 0.05$ for each regression analysis. Statistical analyses were performed with Statistical Package for the Social Sciences (SPSS version 24; IBM Inc, Armonk, NY).

Ethical Considerations

Before their first visit, we obtained parental and participant consent. The institutional review board approved the study protocol.

RESULTS

Thirty-one participants completed the study protocol. The majority were male and approximately one-quarter of the participants reported a history of concussion or ADD/ADHD (Table 2). Although the left eye distance covered along the left side of the box area decreased at the second time point, as did the mean variance of the left eye along the top of the box area, no outcome variable demonstrated a significant difference between the 2 time points after adjusting for multiple comparisons (Table 1).

The Box score calculation resulted in a moderate test–retest correlation. The 3 variables that included data from both left

TABLE 2. Participant Characteristics (n = 31)

Characteristic	Mean (SD) or N (%)
Age (yr)	14.6 (2.2)
Female sex	12 (39%)
Height (cm)	162.6 (13.1)
Mass (kg)	54.4 (14.7)
Previous concussion history	7 (23%)
Diagnosed ADD/ADHD	7 (23%)
Time between tests (d)	9.4 (6.7)
PCSS score: time 1	3.9 (8.6)
PCSS score: time 2	2.8 (6.9)

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and right eyes in conjunction (L/R eye movement variance ratio X: top and bottom box, L/R eye movement variance ratio Y: top and bottom box, and L/R eye movement variance ratio X: bottom box) were moderately correlated (Table 3). In addition, the measures of the left eye along the bottom and left areas of the box area were moderate to moderately highly correlated, whereas the remaining measures demonstrated low test–retest reliability (Table 3).

Those with ADD/ADHD demonstrated more left eye mean skew along the right, more left eye mean normalized skew along the right, a higher variance of the ratio for both eyes along the Y direction for the top and bottom of the screen, and more mean variance of the left eye along the top of the screen (Table 4). Concussion history was not significantly associated with any of the eye-tracking outcome variables (Table 4). Similar to the correlation results from all participants, Spearman's rho correlations were moderate to moderately high for 6 variables among the patients who did not report ADD/ADHD (Box score, L/R eye movement variance ratio X: top and bottom box, L/R eye movement variance ratio Y: top and bottom box, Left eye distance: bottom box, Left eye distance: left box, and L/R eye movement variance ratio X: bottom box; Table 5).

DISCUSSION

Data from our investigation indicate that several objective measures of eye tracking have acceptable test–rest reliability for the purposes of clinical evaluation of visual dysfunction. Furthermore, although concussion history did not affect visual tracking scores, those with ADD/ADHD had impaired scores on several outcome variables pertaining to more eye movement variability and visual disconjugacy relative to those without. Thus, although clinicians may be moderately confident in the ability of eye-tracking measures to provide consistent results across time, assessing those with attentional deficits may require additional interpretation and consideration, particularly in the presence of other conditions such as a recent concussion.

Using a similar experimental apparatus, Samadani et al[8] reported that a rapid, noninvasive, and automated setup can provide valuable clinical information pertaining to the visual system and its potential disruption after a concussion. Furthermore, this form of eye tracking has preliminarily been reported to detect concussion and convergence-related deficits among children.[26] Our data build upon this previous work because we evaluated the reliability of eye-tracking variables previously established as useful in concussion diagnoses[8] across 2 testing sessions. Although no significant median value differences were identified, the reliability analyses indicated that some measures are likely consistent across time, but others may not be. For example, those measures that used calculations derived from both left and right eyes each resulted in moderate to moderately high and significant test–retest correlations. Therefore, clinicians may use the eye-tracking metrics that consider both eyes with reasonably more confidence across multiple testing sessions than those that independently analyze the movement of a single eye. Furthermore, the predictable and constantly changing stimulus may be a useful method to detect deficits after a concussion.[8] By measuring pupillary movement over time in a rapid and noninvasive manner during a brief video, the task does not require language skills, potentially making it a more viable assessment method across diverse populations than other commonly used concussion evaluations.[2]

Recent studies have used visually based measures to demonstrate that a concussion significantly alters the visual system.[4,27] These techniques include vision-specific symptom inventories, visual acuity, eye alignment, fusional vergence, gross extraocular movements, smooth pursuits, near point of convergence, and horizontal and vertical saccades.[4,27] Each of these evaluative techniques are useful components of an examination of the visual system after a concussion. However, as many of the tests rely on a highly trained clinician and possess considerable variability of techniques and interpretation, their broad clinical use remains limited. Therefore, objective metrics that are tester-independent may allow for assessments by a greater number of clinicians without specialty training, remove inter-rater variability, and help to augment visual examinations, particularly in the context of sport-related concussion where early identification of persistent symptom risk may lead to earlier interventions and appropriate treatment pathway referral. The timing of our experimental design was consistent with previous work investigating the

TABLE 3. Correlation Between Assessments for Each Outcome Variable

Outcome Variable	Spearman Correlation	*P*	Reliability Rating
Box score	0.529	0.008	Moderate
Left eye skew: right box	0.036	0.87	None
Left eye skew normalized: right box	0.007	0.97	None
Right eye skew: right box	0.170	0.43	None
Right eye skew normalized: right box	0.086	0.69	None
L/R eye movement variance ratio X: top and bottom box	0.497	0.013	Moderate
L/R eye movement variance ratio Y: top and bottom box	0.446	0.029	Moderate
Left eye distance: bottom box	0.413	0.045	Moderate
Left eye distance: left box	0.611	0.002	Moderately high
Left eye movement variance: top box	0.261	0.22	Low
Right eye distance: bottom box	0.286	0.18	Low
Right eye distance: right box	0.342	0.10	Low
L/R eye movement variance ratio X: bottom box	0.565	0.004	Moderate

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TABLE 4. the Effect of Concussion History and ADD/ADHD on Each of the Eye-Tracking Outcome Measures at the First Time Point

Outcome Variable	Predictor Variable	β Coefficient	SE	95% CI	*P*
Box score	ADD/ADHD	1.903	3.191	−4.829 to 8.635	0.56
	Concussion history	−1.136	3.015	−7.498 to 5.225	0.71
Left eye skew: right box	ADD/ADHD	0.016	0.006	0.003 to 0.030	0.02*
	Concussion history	−0.005	0.006	−0.018 to 0.008	0.42
Left eye skew normalized: right box	ADD/ADHD	0.447	0.179	0.069 to 0.824	0.02*
	Concussion history	−0.105	0.169	−0.462 to 0.252	0.54
Right eye skew: right box	ADD/ADHD	0.009	0.007	−0.005 to 0.023	0.20
	Concussion history	−0.005	0.006	−0.018 to 0.009	0.48
Right eye skew normalized: right box	ADD/ADHD	0.123	0.182	−0.260 to 0.507	0.51
	Concussion history	−0.095	0.172	−0.457 to 0.268	0.59
L/R eye movement variance ratio X: top and bottom box	ADD/ADHD	1.383	1.081	−0.897 to 3.663	0.22
	Concussion history	−0.792	1.021	−2.946 to 1.363	0.45
L/R eye movement variance ratio Y: top and bottom box	ADD/ADHD	18.83	8.501	0.901 to 36.77	0.04*
	Concussion history	−13.28	8.033	−30.22 to 3.673	0.12
Left eye distance: bottom box	ADD/ADHD	−0.002	0.001	−0.004 to 0.001	0.19
	Concussion history	0.001	0.001	−0.001 to 0.003	0.34
Left eye distance: left box	ADD/ADHD	−0.001	0.002	−0.006 to 0.003	0.49
	Concussion history	−0.001	0.002	−0.005 to 0.003	0.62
Left eye movement variance: top box	ADD/ADHD	0.082	0.038	0.002 to 0.162	0.04*
	Concussion history	−0.052	0.036	−0.127 to 0.023	0.16
Right eye distance: bottom box	ADD/ADHD	−0.002	0.001	−0.004 to 0.001	0.26
	Concussion history	0.002	0.001	−0.001 to 0.005	0.10
Right eye distance: right box	ADD/ADHD	−0.001	0.001	−0.002 to 0.001	0.37
	Concussion history	0.001	0.001	−0.001 to 0.002	0.43
L/R eye movement variance ratio X: bottom box	ADD/ADHD	0.000	0.001	−0.003 to 0.002	0.91
	Concussion history	−0.001	0.001	−0.003 to 0.002	0.63

** ADD/ADHD was significantly associated with higher left eye skew: right box scores, left eye skew normalized: right box scores, L/R eye movement variance ratio Y direction: top and bottom box, and left eye movement variance: top box scores.*
CI, confidence interval; SE, standard error.

test–retest reliability of neurocognitive function of athletes[20] but was relatively short compared with longer term test–retest reliability studies.[28,29] Therefore, further work is needed for emerging technologies to assess reliability metrics in both the short-term and long-term, among both uninjured participants and participants who have sustained a concussion, and in larger samples across different age groups.

Pre-existing factors can alter postconcussion recovery trajectories.[30] In addition to several other factors, both ADD/ADHD[31,32] and a previous history of concussion[14,33] can influence concussion-related outcomes among adolescents and young adults. Furthermore, each of these factors has been associated with vision impairments.[34,35] Therefore, we expected that the presence of concussion history and ADD/ADHD would affect visual disconjugacy measures. Only ADD/ADHD, however, was significantly associated with the amount of left eye movement along the right side and top of the screen, as well as the ratio of eye movement along the top and bottom of the screen. It has been reported that ophthalmologic impairments (ie, visual acuity deficits, subnormal stereovision, or abnormal convergence) are prevalent among children with ADD/ADHD.[36] The disturbance of key visual structures during development, such as optic nerve morphological changes, has been identified as one potential reason for this observation[36] and may underlie the association with the measures of eye movement during a tracking task observed in our investigation. Although we found a significant association between ADD/ADHD and eye-tracking variables, the test–retest correlation did not significantly improve when we analyzed only the participants without ADD/ADHD. The value of eye-tracking assessments may be different for those with ADD/ADHD because of its influence on eye-tracking outcome variables, but it does not seem to affect the test–retest reliability to a significant degree.

Our study is not without limitations, and our findings should be placed in the context of them. Study participants were composed of a relatively small sample, leading to a possibility of error or bias. Future studies with larger samples should be conducted to further establish the psychometric properties of eye-tracking measurements. In addition, our participants were healthy individuals recruited from the local community surrounding the data collection site. Generalizability of these findings to postconcussion or other, perhaps younger or older, populations may not be warranted at this time and require further investigation. Furthermore, we did not assess eye dominance. Accordingly,

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TABLE 5. Correlation Between Assessments for Each Outcome Variable Among Participants Without ADD/ADHD (n = 24)

Outcome Variable	Spearman Correlation	*P*	Reliability Rating
Box score	0.421	0.07	Moderate
Left eye skew: right box	0.025	0.92	None
Left eye skew normalized: right box	0.004	0.99	None
Right eye skew: right box	0.284	0.24	Low
Right eye skew normalized: right box	0.230	0.34	Low
L/R eye movement variance ratio X: top and bottom box	0.500	0.03	Moderate
L/R eye movement variance ratio Y: top and bottom box	0.502	0.03	Moderate
Left eye distance: bottom box	0.451	0.05	Moderate
Left eye distance: left box	0.667	0.002	Moderately high
Left eye movement variance: top box	0.035	0.89	None
Right eye distance: bottom box	0.361	0.13	Low
Right eye distance: right box	0.291	0.23	Low
L/R eye movement variance ratio X: bottom box	0.667	0.002	Moderately high

the different results obtained from left and right eyes when analyzed independently may be affected by eye dominance, but we cannot determine this association through our study design.

In conclusion, the data from our investigation suggest that several objective, quantitative, and automated metrics of eye movement and conjugacy are reliable across 2 separate time points. Therefore, their use in concussion recovery monitoring may be warranted as an adjunct to a vision screen. The use of objective eye-tracking tests may be beneficial for objectively evaluating deficits within a comprehensive and multifaceted evaluation. Such metrics may be affected by the presence of ADD/ADHD.

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