The Association between Baseline Eye Tracking Performance and Concussion Assessments in High School Football Players

Jessie R. Oldham, PhD,[1,2]* Christina L. Master, MD,[3,4] Gregory A. Walker, MD,[5,6] William P. Meehan, III, MD,[1,2,7] and David R. Howell, PhD, ATC[5,6]

SIGNIFICANCE: Concussions are complex injuries that require a multifaceted testing battery. Vision impairments are common after concussion, but it is unknown exactly how eye tracking may be affected after injury and how it is associated with other clinical concussion assessments.

PURPOSE: This study aimed to (1) examine the relationship between eye tracking performance (BOX score) and other common concussion evaluations, (2) identify if eye tracking adds novel information that augments baseline concussion evaluations, and (3) examine the effect of age, concussion history, and attention-deficit/hyperactivity disorder on eye tracking and other ophthalmological measures.

METHODS: A total of 102 male high school football athletes (age, 16.0 years; 95% confidence interval, 15.8 to 16.2 years) completed a series of visual and neurocognitive tests during their pre-season baseline assessment. The main outcome measures were BOX score, near point of convergence (NPC) distance, binocular accommodative amplitude (BAA) distance, Standardized Assessment of Concussion score, and Immediate Post-Concussion Assessment and Cognitive Testing composite scores.

RESULTS: BOX score was not significantly associated with symptoms, Standardized Assessment of Concussion score, NPC distance, BAA distance, or any Immediate Post-Concussion Assessment and Cognitive Testing composite scores. Age, concussion history, attention-deficit/hyperactivity disorder, and number of prior years playing football were not significantly associated with BOX score or NPC distance, but there was a significant association between concussion history and greater BAA distance (β = 1.60; 95% confidence interval = 0.19 to 3.01; $P < .03$). The BOX score cutoff of 10 resulted in a 12% false-positive rate.

CONCLUSIONS: Eye tracking was not significantly associated with the commonly used clinical concussion assessments. These results suggest that an objective eye tracking variable may be a valuable addition to the current concussion battery.

Optom Vis Sci 2021;98:826–832. doi:10.1097/OPX.0000000000001737

Author Affiliations:
[1]The Micheli Center for Sports Injury Prevention, Waltham, Massachusetts
[2]Division of Sports Medicine, Department of Orthopedics, Boston Children's Hospital, Boston, Massachusetts
[3]Sports Medicine and Performance Center, Division of Orthopedics, Children's Hospital of Philadelphia, Philadelphia, Pennsylvania
[4]University of Pennsylvania Perelman School of Medicine, Philadelphia, Pennsylvania
[5]Sports Medicine Center, Children's Hospital Colorado, Aurora, Colorado
[6]Department of Orthopedics, University of Colorado School of Medicine, Aurora, Colorado
[7]Department of Pediatrics and Orthopedic Surgery, Harvard Medical School, Boston, Massachusetts
*Jessie.Oldham@childrens.harvard.edu

Concussions are complex multifaceted injuries that have clinicians implementing varied practice patterns beyond the examination room and encompassing the entire medical field.[1,2] Although symptom evaluation is an integral component of concussion diagnosis, assessment, and treatment, a true physiologic window of recovery has yet to be identified. Recent evidence suggests that physiological impairments persist beyond symptom recovery.[3] Therefore, clinically feasible tools that objectively evaluate physiological function at baseline and during concussion recovery would add important clinical information to treating clinicians.

Concussion evaluations traditionally consist of symptom, neurocognitive, and balance assessments. Within-patient designs, where post-injury performance is compared with an assessment before the injury, commonly referred to as a baseline examination, have been purported by some researchers as the best concussion evaluation model.[4] However, the latest International Consensus Statement on Concussion in Sport states that neuropsychological baseline testing, although advantageous, is not necessary to interpret post-injury performance, which could be extrapolated to other assessments.[5] Thus, the use of normative values has been met with encouraging results.[6] Furthermore, establishing false-positive rates for concussion tests helps clinicians understand test limitations. False-positive rates have been published from other concussion assessments to identify the specificity of a measure when interpreting the relative value of a test. For example, one study exploring the tandem gait test reported that current recommendations for passing the test (e.g.,

<14 seconds) resulted in an overall false-positive rate of 2%, suggesting its utility as a screening measure for post-concussion evaluations.[7]

Data supporting vision and oculomotor assessments in the evaluation of concussions are emerging. Clinically assessed post-concussion visual disturbances are common among children after concussion.[8] Up to 51% of adolescents presenting to a specialized concussion clinic have accommodative insufficiency, convergence insufficiency, and/or saccadic dysfunction, with 46% presenting with multiple diagnoses.[8] Near point of convergence and binocular accommodative amplitude are two ophthalmic measures that seem to have utility in the assessment and management of concusssion.[9,10] The King-Devick test, a timed assessment of horizontal saccades commonly used in concussion evaluations, has been associated with other concussion measures (e.g., concentration or reaction time), and such overlap promotes a role for vision tests within multifaceted baseline concussion batteries.[11] A knowledge gap exists for the exact value of eye tracking performance for concussion assessment, its correlation with other concussion assessment tools, and potential augmentative value.

New technologies have enabled researchers and clinicians to objectively track visual function using relatively portable assessments. Researchers have found that an objective eye tracking assessment can distinguish between concussed and control subjects[12] and detect convergence and accommodative abnormalities after concussion.[10] The BOX score, generated by a proprietary algorithm used by the EyeBOX (Oculogica Inc., New York, NY), is a measure of ocular dysmotility associated with brain injury and is useful as a diagnostic tool in pediatric concussion.[13,14] As with the King-Devick test, further information is warranted to define relationships existing between objectively assessed visual function and other concussion tests, such as neurocognitive functioning. In addition, patient-specific factors such as age, history of concussion, and/or attention-deficit/hyperactivity disorder may affect performance on baseline concussion tests, but their effect on visual function remains relatively understudied.

The purposes of our investigation were to (1) examine the relationship between eye tracking performance (i.e., BOX score) and other commonly administered concussion evaluations; (2) identify if eye tracking adds novel information that augments baseline concussion evaluations; (3) examine the effect of age, concussion history, and attention-deficit/hyperactivity disorder on BOX score, near point of convergence distance, and binocular accommodative amplitude distance; and (4) identify the false-positive rate of different cutoff thresholds for the BOX score among a cohort of healthy adolescent football athletes tested before the beginning of their season.

METHODS

Study Design and Participants

We conducted a cross-sectional study to assess concussion test characteristics of uninjured adolescent athletes who were undergoing routine pre-season baseline examinations. Participants were recruited from a single high school and, upon enrollment in the study, completed a series of visual and neurocognitive tests. Inclusion criteria consisted of being between the ages of 14 and 18 years and anticipated participation in football in the upcoming season. Exclusion criteria included a concussion sustained within 1 year of the assessment date or any unresolved concussion manifestations; any visual disorder that would interfere with normal ability to complete the eye tracking, near point of convergence assessments, or binocular accommodative amplitude assessments; and any cognitive disorder that would interfere with traditional concussion neurocognitive evaluations. Participants with correct lenses were not excluded. Before the study started, institutional review board approval was obtained. All participants and parents/guardians if the participant was younger than 18 years provided written informed consent to participate before enrollment.

Clinical Examination

Participants completed the Standardized Assessment of Concussion to evaluate neurocognitive functioning and neurologic status.[15] This test has been used throughout many investigations of sport-related concussion and is used in the majority of pre-season baseline examinations.[1,2] We used the Standardized Assessment of Concussion version included in the Sport Concussion Assessment Tool—Third Edition because the Sport Concussion Assessment Tool—Fifth Edition was not available at the time of testing.[15] During the Standardized Assessment of Concussion, participants completed evaluations of orientation (5 points), immediate memory (15 points), concentration (5 points), and delayed memory (5 points) that result in a total composite score up to a maximum of 30.[15]

To determine near point of convergence, a measure of the distance from an individual's eyes where binocular vision is maintained in the absence of diplopia,[16] participants were instructed to focus on a target (the letter "X" printed in size 14, Times New Roman font) attached to the end of a tongue depressor while slowly advancing the visual target to the tip of their nose from a distance of roughly 30 cm. Once participants reported diplopia or if the study administrator observed outward deviation of the eye, they were instructed to stop moving the target. As with some previous studies, near point of convergence was recorded, using a tape measure, as the distance from the tip of the nose to the target.[9,17–19] Three separate trials were conducted consecutively, and the mean of the three trials was used in further analysis. We also assessed binocular accommodative amplitude, which measures an individual's ability to focus as an object is slowly moved toward the eyes, whereas near point of convergence measures the distance at which an individual can maintain single vision. As previously described,[10] binocular accommodative amplitude is a useful component of an ophthalmic examination and is defined as the measure of a patient to accommodate an object as it slowly moves toward the eyes, operationally defined here as the point at which clear focus on the visual target is blurred. This can be accomplished binocularly, as opposed to monocularly, during the near point of convergence procedure. Both tests were performed on all participants by trained research staff.

Eye Tracking Protocol

To objectively assess eye tracking performance, participants viewed a brief (220-second) video while their eye movements were recorded. This procedure has been described in depth previously and has demonstrated utility to identifying post-concussion vision problems with an acceptable level of test-retest reliability among uninjured adolescents.[10,12,13,20] During the assessment, an Eyelink 1000 (SR Research, Ontario, Canada) eye tracker recorded continuous eye movement at a fixed distance of 55 cm between the participants' eyes and the computer monitor (aspect ratio 4:3), and eye position data were recorded at 500 Hz. For each trial frame, the horizontal and vertical pupil positions were tracked to create a box trajectory that subsequently created a BOX score. This is a

novel approach in which the system is temporarily calibrated based on the timing of the eye tracking to the moving visual target. The pupils are individually captured by the eye tracker before the start of the task, but the eye tracking measurements are based on the position of the pupil relative to the timing of the moving visual stimulus and its known position in the space within the monitor. This provides a novel opportunity to capture the movement of each pupil individually, which allows for a comparison between eyes to determine the level of conjugacy during the eye tracking task. The stimulus video was one-ninth of the computer monitor area and played while moving clockwise around the outer edges of the computer monitor. 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. Both the afferent stimulus presentation and eye tracking were binocular, and pupil position was tracked via automated software (Oculogica Inc., New York, NY) to plot horizontal and vertical movements during the trial. The stimulus traveled in distinct horizontal and vertical components during the visual task as the target traveled around the perimeter of the monitor at a pre-determined velocity. From this, several variables were then calculated automatically to facilitate further analysis.[10,12–14,20] This analysis calculated how the eyes moved in relation to one another over time together as opposed to accuracy relative to a target.[12,21] No operator intervention occurred during the test procedure.

Neurocognitive Evaluation Protocol

To assess neurocognitive function, participants completed the computerized Immediate Post-Concussion Assessment and Cognitive Testing. During this commonly used clinical concussion test,[1] participants complete a series of different tests described previously[22] to produce a set of composite outcome scores. The test battery was originally designed to reduce practice effects through randomizing stimulus presentation. Furthermore, to measure additional clinical features of study participants, participants completed a concussion symptom checklist within the computerized neurocognitive assessment, where self-reported symptom severity was rated on a 0-to-6 scale for 22 common symptoms of concussion. Any individuals who received an invalid computerized neurocognitive test were excluded.

Outcome Variables

To facilitate a multifaceted approach to baseline concussion testing, we calculated several variables from the assessments described previously for use in further analyses. Within the eye tracking protocol, we used the BOX score metric, a binary classifier (<10, normal; ≥10, abnormal) based on the sensitivity and specificity relative to a clinical reference standard of concussion.[14] The BOX score was developed using a best subset regression model, and normalized and adjusted by a constant that has been used previously for diagnostic purposes in pediatric concussion with sound reliability and uses metrics such as how well the eyes move together and how quickly the eyes move in concert.[10,13,14] From the clinical visual examination, we used near point of convergence breakpoint distance, measured in centimeters, and binocular accommodative amplitude distance, measured in centimeters, as our outcome variables of interest in subsequent analyses. The Standardized Assessment of Concussion total score ranged from 0 to 30, and the total symptom score obtained from the computerized neurocognitive test report ranged from 0 (no symptoms) to 132 (maximum severity on all symptoms). Finally, the neurocognitive domain scores of interest included verbal memory composite score, verbal memory composite score, visual motor speed composite score, and reaction time composite score.

Statistical Analysis

Continuous outcome variables are reported as means (95% confidence intervals), and categorical variables are reported as the number included with corresponding percentage. We first calculated summary descriptive statistics for each of our outcome variables of interest. To accomplish our first objective, we constructed a linear multivariable regression model. Our outcome variable was the BOX score, and predictor variables included total symptom severity score, Standardized Assessment of Concussion score, near point of convergence distance, binocular accommodative amplitude distance, and the four neurocognitive composite variables of interest (verbal memory, visual memory, visual motor speed, and reaction time). To accomplish our second objective, we constructed another series of multivariable linear regression models. The outcome variables included the eye tracking variables included in our investigation (BOX score, near point of convergence distance, and binocular accommodative amplitude distance), and predictor variables included age, history of concussion, attention-deficit/hyperactivity disorder, and years playing football. Finally, to accomplish our third purpose, investigating different pass/fail cutoff threshold values for the BOX score, we calculated the percentage of healthy athletes who failed to complete the objective eye tracking examination at the specified thresholds (i.e., false-positives). Because the recommended BOX score cutoff is 10, we evaluated the following cutoff thresholds: 4, 6, 8, 10, and 12. Any missing data were treated as such, and no imputations were performed. All statistical tests were two-sided and performed using Stata version 15 (StataCorp, College Station, TX).

TABLE 1. Demographic and medical history characteristics

Variable	Values
Age (y), mean (95% confidence intervals)	16.0 (15.8–16.2)
Sex (male), n (%)	102 (100)
ADHD, n (%)	13 (13)
Concussion history, n (%)	18 (18)
Race*, n (%)	
White	78 (78)
Hispanic/Latino	11 (11)
White and Hispanic/Latino	4 (4)
White and American Indian	3 (3)
African American	1 (1)
American Indian	1 (1)
White and African American	1 (1)
Middle Eastern	1 (1)
Years playing football, mean (95% confidence intervals)	1.8 (1.3–2.2)

*Two participants did not respond to questions pertaining to race.
ADHD = attention-deficit/hyperactivity disorder.

TABLE 2. Summary of performance on clinical measures and neurocognitive test performance

Variable	Mean (95% confidence interval)
Clinical test variables	
Symptom severity	2.7 (1.2–4.2)
SAC	25.3 (24.7–25.8)
NPC (cm)	3.3 (2.8–3.8)
BAA (cm)	6.5 (6.0–7.0)
Neurocognitive test variables	
Verbal memory composite	80.3 (77.9–82.7)
Visual memory composite	73.4 (70.7–76.1)
Visual processing speed composite	35.1 (33.7–36.5)
Reaction time composite	0.61 (0.59–0.63)
Objective eye tracking variable	
BOX score	4.7 (3.8–5.6)

BAA = binocular accommodative amplitude; NPC = near point of convergence; SAC = Standardized Assessment of Concussion.

RESULTS

A total of 102 male high school football athletes participated in the study. Participants were 16 years of age on average, and a small proportion reported being diagnosed with attention-deficit/hyperactivity disorder or a history of concussion (Table 1). The majority (63%) reported having played football for at least 1 year before the evaluation. During the baseline examination, symptom severity was within normal limits, and mean Standardized Assessment of Concussion, near point of convergence, and binocular accommodative amplitude values were within expected ranges for this population (Table 2).

Multivariable linear regression results indicated that symptoms, Standardized Assessment of Concussion score, near point of convergence distance, binocular accommodative amplitude distance, and any of the computerized neurocognitive composite outcome variables were not significantly associated with the BOX score (Fig. 1). Although age, concussion history, attention-deficit/hyperactivity disorder, and prior years of playing football were not significantly associated with BOX scores or near point of convergence distance (Figs. 2A, B), concussion history was significantly associated with greater binocular accommodative amplitude distance (Fig. 2C). The average BOX score among all participants was 4.7. The BOX score pass/fail threshold of 10 resulted in a 12% false-positive rate (Table 3). As the BOX score cutoff values increased beginning at 4, the false-positive rate decreased (Table 3).

DISCUSSION

Our results suggest that objective eye tracking methodology evaluates a distinct physiological domain independent from those commonly assessed at baseline. Therefore, eye tracking may be a

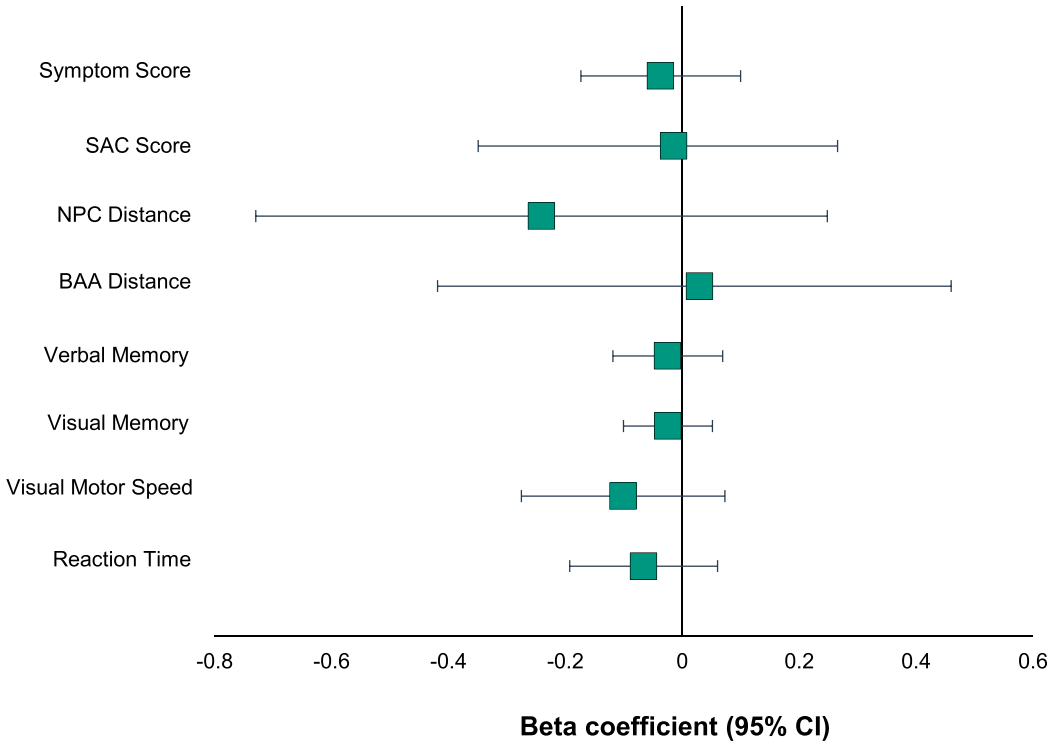

FIGURE 1. Results from the multivariable regression model describing the relationship between clinical measures and neurocognitive test performance (predictor variables) and BOX scores (outcome variable). There were no predictor variables that were significantly associated with BOX score performance. BAA = binocular accommodative amplitude; CI = confidence interval; NPC = near point of convergence; SAC = Standardized Assessment of Concussion.

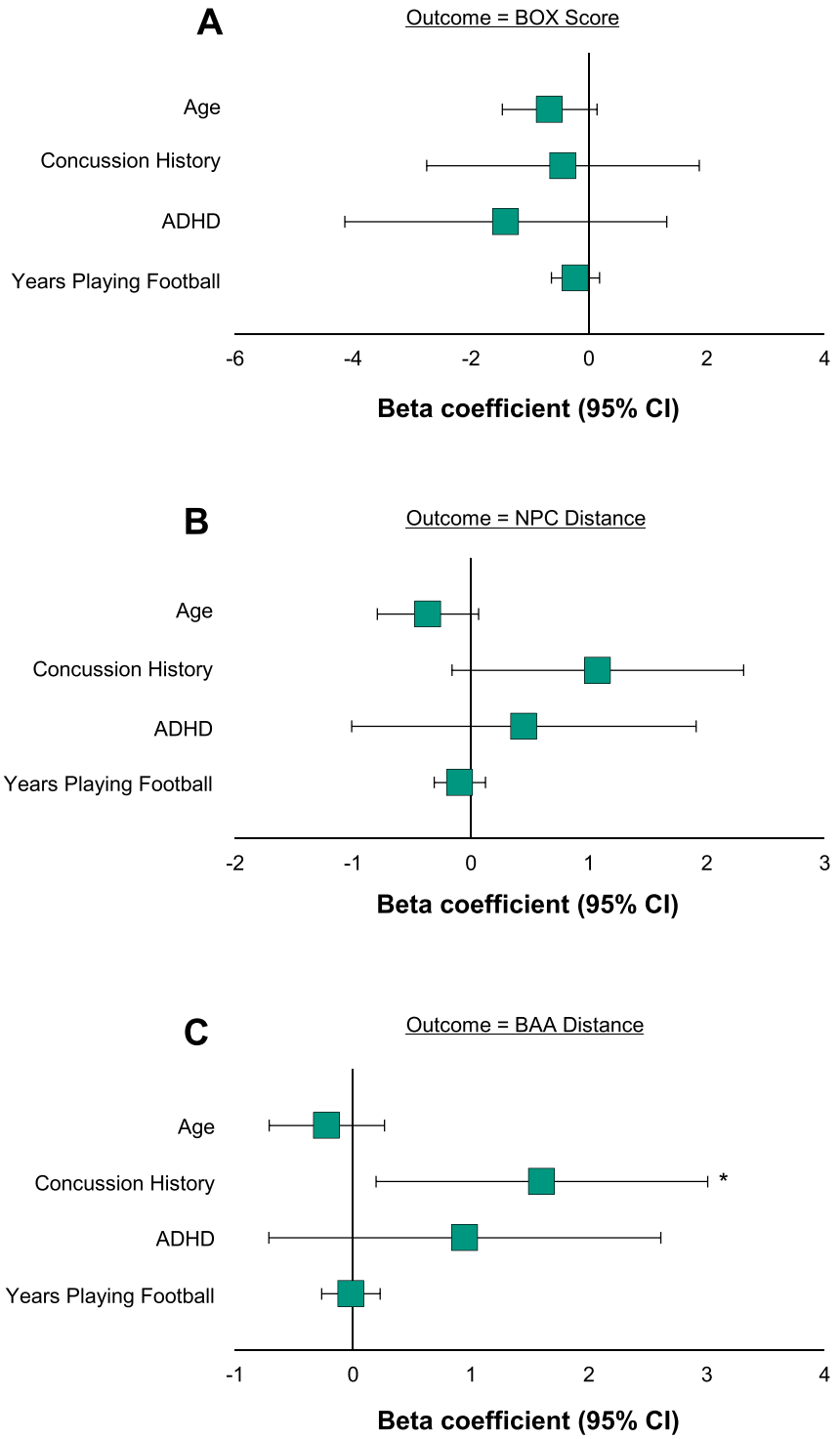

FIGURE 2. The association between patient characteristics and visual examination outcomes: (A) BOX score, (B) near point of convergence (NPC) distance, and (C) binocular accommodative amplitude (BAA) distance. *Concussion history was significantly associated with a greater BAA distance ($\beta = 1.60$; 95% confidence interval, 0.19 to 3.01; $P = .03$).

useful addition to the current clinical concussion battery. Concussion history and attention-deficit/hyperactivity disorder were not associated with the BOX score; however, concussion history was significantly associated with binocular accommodative amplitude distance. This finding suggests that certain domains of visual function either remain impaired beyond concussion recovery or are perhaps associated with an increased risk of sport-related concussion. The cross-sectional design of this study, however, limits our ability to tell which of these possibilities is most likely.

TABLE 3. False-positive rate of the BOX score, a binary classifier for determining the likelihood of disconjugate eye movements, set at various threshold levels

BOX score cutoff threshold	Higher than cutoff threshold (n/N)	% False-positive rate
4	38/102	37
6	23/102	23
8	17/102	17
10	12/102	12
12	9/102	9

The BOX score was not significantly associated with symptoms, Standardized Assessment of Concussion, or computerized neurocognitive outcomes, all of which are frequently used concussion clinical assessments. In addition, there was no significant relationship between BOX score and the vision-based clinical variables (near point of convergence, binocular accommodative amplitude) measured in this investigation. This lack of overlap suggests that eye tracking may address a unique physiological domain not currently evaluated by other commonly used concussion assessments. Furthermore, eye tracking has successfully and reliably identified abnormal convergence and accommodation in a concussed adolescent population.[10] Therefore, an objective eye tracking marker, such as BOX score, may be considered as a useful addition to a baseline multifaceted concussion examination.

A similar investigation of the King-Devick test also found few substantial relationships between measures in collegiate athletes.[11] There were significant associations between the King-Devick and cognitive components (Standardized Assessment of Concussion concentration, computerized neurocognitive visual motor speed, and computerized neurocognitive reaction time) but not with symptoms, psychological distress, or balance.[11] The relationship between faster King-Devick performance and better scores on the computerized neurocognitive visual motor speed and reaction time has been observed in a number of populations[11,23]; however, we did not find this to be the case with BOX score. This lack of association between the BOX score and neurocognitive composite scores suggests that eye tracking is assessing a construct that is independent of neurocognitive function and may be a valuable addition to the existing clinical battery.

Individuals diagnosed with attention-deficit/hyperactivity disorder,[24] as well as a previous history of concussion,[25] seem to be at risk for prolonged concussion symptoms. In addition, attention-deficit/hyperactivity disorder and concussion history have been associated with vision problems.[26] However, attention-deficit/hyperactivity disorder was not associated with any of our visual metrics (BOX, near point of convergence, binocular accommodative amplitude), which is consistent with prior work showing no significant relationship between BOX score and healthy adolescents diagnosed with attention-deficit/hyperactivity disorder or those with a concussion history.[13] This is an important distinction, as young athletes with attention-deficit/hyperactivity disorder have shown differences in baseline computerized neurocognitive scores.[27] Therefore, the eye tracking battery described in this study may comprise a more effort-independent analysis when compared with other frequently used concussion clinical assessments. Ophthalmologic impairments are not uncommon in a child/adolescent population, and otherwise healthy adolescent athletes diagnosed with attention-deficit/hyperactivity disorder have displayed alterations in left eye movements (left eye skew, left eye movement variance) during eye tracking tasks[28]; however, those specific eye tracking variables were not analyzed in this investigation.

Collegiate hockey players with a lifetime history of concussion did not seem to differ in their accommodative amplitude compared with the players with no concussion history; however, the concussion history group did have a significantly larger near point of fixation disparity, a measure of convergence insufficiency.[29] Although, in our study, concussion history had no association with BOX score or near point of convergence, we did find a significant association between concussion history and greater binocular accommodative amplitude distance (Fig. 2C). Successful accommodation occurs when an individual can maintain focus on an object of interest, and it is frequently impaired in patients with a concussion because of the number of neural pathways associated with the accommodative system that are disrupted after injury.[30] Abnormal accommodative amplitude was found to be a predictor of prolonged concussion recovery in a pediatric cohort.[31] Although we investigated a healthy adolescent population, the association between concussion history and binocular accommodative amplitude could be indicative of subclinical, unresolved ophthalmic dysfunction or subclinical visual dysfunction that may increase the risk for injury. Football is a collision sport, so it is also possible that this association results from exposure to repetitive head impacts. Similarly, near point of convergence has been shown to be a sensitive indicator of subclinical damage and recovery, independent of symptoms, in high school football players.[32] However, both the effect of head impact exposure on binocular accommodative amplitude and the effect of binocular accommodative amplitude on concussion risk are unknown and warrant further exploration.

A cutoff of 10 is considered the pass/fail threshold for the BOX score, with a BOX score <10 being classified as normal and a BOX score ≥10 considered abnormal. In this investigation, we found a cutoff of 10 to have a 12% false-positive rate (Table 3). Lowering the BOX score cutoff threshold down to 8 could compromise the specificity, as it resulted in a false-positive rate of 17%. Conversely, increasing the BOX threshold up to 12 dropped the false-positive rate down to 9%. Nonetheless, all three false-positive rates are below what has been previously reported for other concussion assessments, including common neurocognitive tests, which range from 22 to 46% in collegiate athletes.[33] Male and female athletes have shown to differ in their false-positive rates on other clinical concussion measures.[7] Therefore, future investigations are necessary to examine the false-positive rates of the BOX score in female athletes, as we only investigated male athletes in our study.

This study was not without limitations. The data are cross-sectional and from a single high school and therefore may not be generalizable to other populations (e.g., post-concussion, college athletes, and youth athletes). Furthermore, the participants in this study were all male football players, so future research should aim to investigate any eye tracking differences between sexes and differences between sport types (collision/contact/noncontact). As such, our findings cannot be extrapolated to other populations. Our study only measured near point of convergence from the tip of the nose, whereas others have measured from the forehead.[34,35] Therefore, our findings may not be generalizable to other measurements of near point of convergence. Head impact exposure over the course of a single season did not seem to impair oculomotor performance in youth football players, but additional research is necessary to investigate the role of sport type in visual outcomes.[36]

In conclusion, eye tracking was not significantly associated with any of the commonly currently used clinical concussion assessments in high school football players. These findings suggest that an objective eye tracking variable, like the BOX score, is effort independent and could be a useful addition to the current concussion battery, providing clinicians with an objective tool to identify visual impairments that are not currently being evaluated. Future research is needed to examine the utility of eye tracking in other populations.

ARTICLE INFORMATION

Submitted: November 12, 2020

Accepted: March 28, 2021

Funding/Support: None of the authors have reported funding/support.

Conflict of Interest Disclosure: The authors declare no conflicts of interest related to this study. WPM receives royalties from (1) ABC-CLIO publishing for the sale of his books, *Kids, Sports, and Concussion: A Guide for Coaches and Parents*, and *Concussions*; (2) Springer International for the book *Head and Neck Injuries in Young Athlete*; and (3) Wolters Kluwer for working as an author for UpToDate. His research is funded, in part, by philanthropic support from the National Hockey League Alumni Association through the Corey C. Griffin Pro-Am Tournament and the National Football League. DRH receives research support from the Eunice Kennedy Shriver National Institute of Child Health & Human Development (R03HD094560) and the National Institute of Neurological Disorders and Stroke (R01NS100952 and R41NS103698) of the National Institutes of Health. He has previously received research support from a research contract between Boston Children's Hospital, Cincinnati Children's Hospital Medical Center; EIMindA Ltd.; and the Eastern Athletic Trainers Association, Inc.

Author Contributions and Acknowledgments: Conceptualization: CLM, WPM, DRH; Formal Analysis: JRO; Investigation: JRO, CLM, WPM, DRH; Methodology: JRO, DRH; Supervision: WPM, DRH; Writing – Original Draft: JRO, DRH; Writing – Review & Editing: JRO, CLM, GAW, WPM, DRH.

The eye tracking device was provided by Oculogica Inc.

REFERENCES

1. Baugh CM, Kroshus E, Stamm J, et al. Clinical Practices in Collegiate Concussion Management. Am J Sports Med 2016;44:1391–9.

2. Buckley TA, Burdette G, Kelly K. Concussion-management Practice Patterns of National Collegiate Athletic Association Division II and III Athletic Trainers: How the Other Half Lives. J Athl Train 2015;50:879–88.

3. Kamins J, Bigler E, Covassin T, et al. What Is the Physiological Time to Recovery After Concussion? A Systematic Review. Br J Sports Med 2017;51:935–40.

4. Harmon KG, Clugston JR, Dec K, et al. American Medical Society for Sports Medicine Position Statement on Concussion in Sport. Br J Sports Med 2019;53:213–25.

5. McCrory P, Meeuwisse W, Dvořák J, et al. Consensus Statement on Concussion in Sport—The 5th International Conference on Concussion in Sport Held in Berlin, October 2016. Br J Sports Med 2017;51:838–47.

6. Schmidt JD, Register-Mihalik JK, Mihalik JP, et al. Identifying Impairments After Concussion: Normative Data versus Individualized Baselines. Med Sci Sports Exerc 2012;44:1621–8.

7. Howell DR, Oldham JR, Meehan WP, 3rd, et al. Dual-task Tandem Gait and Average Walking Speed in Healthy Collegiate Athletes. Clin J Sport Med 2019;29:238–44.

8. Master CL, Scheiman M, Gallaway M, et al. Vision Diagnoses Are Common After Concussion in Adolescents. Clin Pediatr (Phila) 2016;55:260–7.

9. Mucha A, Collins MW, Elbin RJ, et al. A Brief Vestibular/Ocular Motor Screening (VOMS) Assessment to Evaluate Concussions: Preliminary Findings. Am J Sports Med 2014;42:2479–86.

10. Bin Zahid A, Hubbard ME, Lockyer J, et al. Eye Tracking as a Biomarker for Concussion in Children. Clin J Sport Med 2020;30:433–43.

11. Clugston JR, Houck ZM, Asken BM, et al. Relationship between the King-Devick Test and Commonly Used Concussion Tests at Baseline. J Athl Train 2019;54:1247–53.

12. Howell DR, Brilliant AN, Storey EP, et al. Objective Eye Tracking Deficits Following Concussion for Youth Seen in a Sports Medicine Setting. J Child Neurol 2018;33:794–800.

13. Howell DR, Brilliant AN, Master CL, et al. Reliability of Objective Eye-tracking Measures among Healthy Adolescent Athletes. Clin J Sport Med 2020;30:444–50.

14. Samadani U, Li M, Qian M, et al. Sensitivity and Specificity of an Eye Movement Tracking-based Biomarker for Concussion. Concussion 2015;1:CNC3.

15. Sport Concussion Assessment Tool, 3rd ed. Br J Sports Med 2013;47:259–62.

16. Raghuram A, Cotter S, Gowrisankaran S, et al. Post-concussion: Receded Near Point of Convergence Is Not Diagnostic of Convergence Insufficiency. Am J Ophthalmol 2019;206:235–44.

17. Pearce KL, Sufrinko A, Lau BC, et al. Near Point of Convergence After a Sport-related Concussion: Measurement Reliability and Relationship to Neurocognitive Impairment and Symptoms. Am J Sports Med 2015;43:3055–61.

18. Elbin RJ, Sufrinko A, Anderson MN, et al. Prospective Changes in Vestibular and Ocular Motor Impairment After Concussion. J Neurol Phys Ther 2018;42:142–8.

19. Santo AL, Race ML, Teel EF. Near Point of Convergence Deficits and Treatment Following Concussion: A Systematic Review. J Sport Rehabil 2020;29:1179–93.

20. Howell DR, Myer GD, Brilliant A, et al. Quantitative Multimodal Assessment of Concussion Recovery in Youth Athletes. Clin J Sport Med 2021;31:133–8.

21. Samadani U, Ritlop R, Reyes M, et al. Eye Tracking Detects Disconjugate Eye Movements Associated with Structural Traumatic Brain Injury and Concussion. J Neurotrauma 2015;32:548–56.

22. Iverson GL, Lovell MR, Collins MW. Interpreting Change on ImPACT Following Sport Concussion. Clin Neuropsychol 2003;17:460–7.

23. Marinides Z, Galetta KM, Andrews CN, et al. Vision Testing Is Additive to the Sideline Assessment of Sports-related Concussion. Neurol Clin Pract 2015;5:25–34.

24. Mautner K, Sussman WI, Axtman M, et al. Relationship of Attention Deficit Hyperactivity Disorder and Postconcussion Recovery in Youth Athletes. Clin J Sport Med 2015;25:355–60.

25. Morgan CD, Zuckerman SL, Lee YM, et al. Predictors of Postconcussion Syndrome After Sports-related Concussion in Young Athletes: A Matched Case-control Study. J Neurosurg Pediatr 2015;15:589–98.

26. DeCarlo DK, Swanson M, McGwin G, et al. ADHD and Vision Problems in the National Survey of Children's Health. Optom Vis Sci 2016;93:459–65.

27. Zuckerman SL, Lee YM, Odom MJ, et al. Baseline Neurocognitive Scores in Athletes with Attention Deficit-spectrum Disorders and/or Learning Disability. J Neurosurg Pediatr 2013;12:103–9.

28. Grönlund MA, Aring E, Landgren M, et al. Visual Function and Ocular Features in Children and Adolescents with Attention Deficit Hyperactivity Disorder, with and without Treatment with Stimulants. Eye (Lond) 2007;21:494–502.

29. Poltavski DV, Biberdorf D. Screening for Lifetime Concussion in Athletes: Importance of Oculomotor Measures. Brain Inj 2014;28:475–85.

30. Green W, Ciuffreda KJ, Thiagarajan P, et al. Static and Dynamic Aspects of Accommodation in Mild Traumatic Brain Injury: A Review. Optometry 2010;81:129–36.

31. Master CL, Master SR, Wiebe DJ, et al. Vision and Vestibular System Dysfunction Predicts Prolonged Concussion Recovery in Children. Clin J Sport Med 2018;28:139–45.

32. Zonner SW, Ejima K, Fulgar CC, et al. Oculomotor Response to Cumulative Subconcussive Head Impacts in US High School Football Players: A Pilot Longitudinal Study. JAMA Ophthalmol 2019;137:265–70.

33. Resch J, Driscoll A, McCaffrey N, et al. ImPact Test-retest Reliability: Reliably Unreliable? J Athl Train 2013;48:506–11.

34. Maples WC, Hoenes R. Near Point of Convergence Norms Measured in Elementary School Children. Optom Vis Sci 2007;84:224–8.

35. Scheiman M, Gallaway M, Frantz KA, et al. Nearpoint of Convergence: Test Procedure, Target Selection, and Normative Data. Optom Vis Sci 2003;80:214–25.

36. Munce TA, Dorman JC, Thompson PA, et al. Head Impact Exposure and Neurologic Function of Youth Football Players. Med Sci Sports Exerc 2015;47:1567–76.