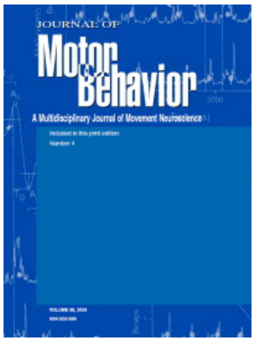

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RESEARCH ARTICLE

Eye Movement Differences in Contact Versus Non-Contact Olympic Athletes

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ABSTRACT. The purpose of this study was to investigate the difference in oculomotor functioning between Olympic-level contact and non-contact sports participants. In total, 67 male and female Olympic-level contact ($n = 27$) and non-contact ($n = 40$) athletes completed oculomotor tasks, including Horizontal Saccade (HS), Circular Smooth Pursuit (CSP), Horizontal Smooth Pursuit (HSP), and Vertical Smooth Pursuit (VSP) using a remote eye tracker. No significant differences for sex or age occurred. Each variable indicated higher scores for contact compared to non-contact athletes ($p < .05$) except for VSP Pathway differences and CSP Synchronization. A logistic regression was performed to determine the degree that HS measures, CSP synchronization, and VSP pathway predicted sport type. The model was significant, $\chi^2(6) = 37.08$, $p < .001$, explaining 57.4% of the variance and correctly classified 88.1% of cases. The sensitivity was 87.5% and specificity was 88.9%. CSP synchronization did not increase the likelihood of participating in a contact sport. This was the first study to identify oculomotor differences between Olympic athletes of contact and non-contact sports, which adds to the growing evidence that oculomotor functioning may be a reliable, quick, real-time tool to help detect mTBI in sport.

Keywords: oculomotor, eye tracking, concussion, sports, traumatic brain injury

Introduction

Concussion, a form of mild Traumatic Brain Injury (mTBI), is a complex pathophysiological process induced by traumatic biomechanical forces affecting the brain (McCrory et al., 2009). Concussions are often a product of sports activities that create strong forces near or around the head, ultimately causing rapid acceleration and deceleration of the brain. An estimated 1.6 to 3.8 million sports-related TBIs occur annually in the United States (Langlois et al., 2006), with 75% of individuals treated in hospitals representing mTBIs or concussions (Faul et al., 2010). This estimate is likely low, both because individuals with TBI often do not seek treatment and because clinicians often have difficulty diagnosing mTBI (Hunt et al., 2016).

The difficulty in diagnosing mTBI in athletes may stem from the subjective, self-report nature of assessments. Most diagnostic tools for mTBI employ a combination of three assessment tools, neurological, vestibular, and oculomotor, for sideline concussion testing (McCrory et al., 2009). Subjective measurements by clinicians, however, are likely to miss subtle changes in neuropsychological function. Importantly, subjective measures also provide athletes ample opportunity to falsify information, namely, to remain a part of a team. Furthermore, despite their convenience, self-report and subjective assessment may have limited long-term benefits, especially when considering that neuropsychological inefficiencies may persist even after symptoms diminish (Ventura et al., 2015).

One method of more objectively assessing mTBI in athletes that is gaining momentum is vision and oculomotor movement diagnosis (Hunfalvay et al., 2019). Researchers have found that the visual system is vulnerable to the effects of brain injury, with 50% of the brain's connectivity related to vision (Felleman & Van Essen, 1991) and up to 90% of concussed patients demonstrating visual difficulties (Sussman et al., 2016). Thus, if objective methods of visual performance can complement existing TBI screening methods, then decreases in neural functioning could be identified quicker, thereby contributing to long-term health benefits.

Eye tracking technology is a promising objective measurement tool for detecting mTBI in athletes (Snegireva et al., 2018) because it delivers precise, objective eye movement measurements several times per second (Hunfalvay et al., 2019; Murray et al., 2019). In recent years, eye-tracking technology has advanced immensely, allowing researchers to detect oculomotor measurements that help quickly diagnose brain dysfunction. Oculomotor measures encompass three eye movement types: fixations, saccades, and smooth pursuit (Land & Tatler, 2009). Fixations involve maintaining gaze on a single location of high visual acuity (Komogortsev & Karpov, 2013). Saccades are quick eye movements between fixation points (Møllenbach et al.,

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2013) that can provide information about several markers of concussion, including attention, executive function, and memory (Ventura et al., 2015). Smooth pursuit involves an individual closely tracking a moving object (Møllenbach et al., 2013). Interestingly, researchers report that military recruits with concussive symptoms had larger saccadic positioning errors and abnormalities in pursuit velocities compared to asymptomatic controls, indicative of possible brain dysfunction (Cifu et al., 2015). In a systematic review of the oculomotor assessment evidence to identify and monitor recovery from mTBI, Hunt et al. suggested that saccades, smooth pursuit, and vergence help detect mTBI changes, but cautioned that the strength of the evidence was not yet enough to provide clinical recommendations (2016). More recently, Hunfalvay and colleagues have offered additional support for using oculomotor measurements (including saccades and smooth pursuit) to detect neural deficits after TBI (Hunfalvay et al., 2019; 2020; 2021).

Researchers have found that oculomotor measurements can reliably differentiate between mTBI and healthy individuals. For example, Hunfalvay et al. used eye tracking tests on 287 participants with either no, mild, moderate, or severe TBI and found that vertical and horizontal saccade performance differed in patients with no TBI compared to those with mild, moderate, or severe TBI (2019). Other researchers identified that TBI patients have faster visual reaction speeds but slower processing than athletes or the general population (Lange et al., 2018). Researchers have also found that mTBI patients had significantly worse smooth pursuit in an eye tracking tests (Maruta et al., 2010) and extra position errors along with decreased predictive smooth pursuits (Armstrong, 2018) relative to normal participants. Recently, Hunfalvay et al. found that circular, horizontal, and vertical tracking tasks using eye tracking technology could detect differences in individuals with mTBI and those without TBI (2021). Furthermore, Hunfalvay et al. also combined four oculomotor variables (i.e., saccade, smooth pursuit, fixation, and simple reaction time) to determine the resultant effect to identify mTBI (2020). Hunfalvay et al. found that the "Brain Health EyeQ" tests identified mTBI individuals 75.3% of the time (2020). These studies indicate that oculomotor movements are adversely affected in individuals with mTBI compared to healthy controls and that mTBI can be predicted with objective eye tracking technology.

mTBI can occur easily within sports because of the incidental and often purposeful body contact among competitors, but the incidence of mTBI may depend on the type of sport (i.e., contact versus non-contact). Furthermore, it is estimated that fifty percent of mTBI are unreported, which can increase the risk of future cognitive impairment or further injury (Wallace et al., 2017). For this study, contact sports (e.g., boxing & wrestling) are defined as sports where competition consists of direct fighting (and continuous body contact) between two competing athletes to win a contest (Cynarski & Kudłacz, 2008). For non-contact sports, we used Rice et al.' categorization, which states that non-contact sports (e.g., cycling & swimming) comprise infrequent or inadvertent body contact, with physical altercations being outside the rules of competition (Rice et al., 2008). Since contact sports involve frequent body contact, especially to the head region, it might be expected that mTBI is more frequent in all contact sports. However, past work has suggested that the rate of injury from boxing is often less than that of other contact and non-contact sports when calculated per 1000 h of training and competition (Zazryn et al., 2006). Nevertheless, contact sport athletes are generally still at increased risk of sustaining a mTBI, with wrestling making up the largest chunk of mTBI emergency department visits (Lemme et al., 2020). Despite this increased risk for mTBI among contact sport athletes, there is limited research comparing different types of sports and rates of mTBI, with no known studies directly comparing rates of mTBI among contact and non-contact sport athletes.

Though limited research exists comparing sport-type and mTBI rates, previous research has demonstrated oculomotor differences in athletes with mTBI relative to healthy athletes. For example, researchers compared 10 NCAA Division I athletes with a concussion with 10 healthy control collegiate athletes on a sport-like anti-saccade postural control task (Murray et al., 2017). They found that athletes with a concussion had greater gaze resultant distance (the distance eyes moved in the horizontal or vertical direction), prosaccade errors (directional errors or the inability to suppress prosaccades), and mean horizontal velocity relative to healthy athlete controls, indicating that 24–48 h post-concussion athletes had worse gaze stability than healthy control athletes (Murray et al., 2017). Other researchers have found that athletes with mTBI have lengthy latencies and worse positioning errors on memory-guided and anti-saccades tasks compared to normal volunteers (Johnson et al., 2015). In a 2018 correlational study, researchers investigated the association between pre-season oculomotor performance (e.g., prosaccade, self-paced saccade, and smooth pursuit) using an eye tracker and in-season head impact occurrence in ice hockey (Kiefer et al., 2018). The results provided preliminary evidence for the positive link between inefficient oculomotor performance and head injuries during an ice hockey season (Kiefer et al., 2018). Studies such as these indicate that there may be eye movement abnormalities in athletes who have been concussed in contact sports. Other sport types, however, have had limited investigation. Results from a study examining vestibular and oculomotor function in contact sport athletes as compared to an active control group indicated that contact sports had increased oculomotor abnormalities relative to the control group (Brown et al., 2022). Limitations of the 2022 Brown et al. study, however, include that mixed martial arts and Muay Thai athletes from local clubs made up the sample, as opposed to Olympic-level athletes. Similarly, control participants were active individuals, defined as doing physical activity for greater than 15 min at least three times per week. This is an exercise threshold far below that of an Olympic athlete's control, thus failing to capture the extent of oculomotor differences that may occur in Olympic athletes who train longer and compete more. This information reveals links between oculomotor inefficiencies after concussion compared to healthy controls; still, limited research has compared this relationship between sport types (e.g., contact vs. non-contact) especially in circumstances in which one sport type has higher risk of unreported mTBI.

Given the underreporting of mTBI, it is vital to identify situations in which athletes may be at increased risk for head injury. As previously discussed, it is generally thought that contact sport athletes are at increased risk of mTBI given the requirements of their sport, however there is a gap in research examining mTBI rates between contact and non-contact sports. As shown in previous research, oculomotor behavior differences have been identified in concussed athletes as compared to healthy athletes. Thus, the purpose of the current study was to investigate differences in oculomotor behavior between Olympic-level contact and non-contact sports participants with no diagnosed concussions. We hypothesized that there would be significant differences in eye tracking movements (e.g., saccades and smooth pursuit) between contact and non-contact sport athletes, despite a lack of diagnosed concussions, indicating an indirect link between brain health and sport type.

Methods

This study's sample comprised 67 participants aged between 18 and 49 (M_{age} = 27.34, SD_{age} = 6.40). Participants were both female ($n = 27$) and male ($n = 40$) athletes who trained at an Olympic Training Center in the United States and either participated in a contact or non-contact sport. Contact sports included boxing ($n = 11$), judo ($n = 2$), taekwondo ($n = 3$), and wrestling ($n = 11$). Non-contact sports included cycling ($n = 10$), fencing ($n = 1$), gymnastics ($n = 4$), shooting ($n = 8$), skiing ($n = 1$), swimming ($n = 7$), and track and field ($n = 9$). All the participants reported having no diagnosed concussions before testing.

Participants were excluded from the study if they met any of the following prescreening conditions: neurological disorders (e.g., Parkinson's disease); diagnosed head injury, vision-related issues that prevented successful calibration (Bellmann et al., 2004) of all 9-points (e.g., extreme tropias, phorias) (Thompson et al., 2006), static visual acuity greater than 20/400 (Bellmann et al., 2004), cataracts (Hunfalvay et al., 2020), or consumption of drugs or alcohol within 24 h of testing. No participants were excluded from the study.

For testing, we used a RightEye system (Bethesda, MD, USA) which included a Tobii Dynavox, i15 all-in-one system and RightEye software. The screen dimensions were 12" wide x 9" high and placed at a distance between 60 cm from the participant's face. The system was fitted with a Tobii 90 Hz remote eye tracker, wired keyboard, and mouse. The tasks were identical to other research (Murray et al., 2019), except that vertical saccades were not measured in the current study. Thus, for brevity, we provide methodological differences only. Participants' heads were unconstrained during the tasks. Furthermore, previous work by Murray et al. (2019) demonstrated the specificity and sensitivity of these measures which guided our selection of the variables found here. Participants completed a series of oculomotor testing tasks, including Horizontal Saccades (HS), Circular Smooth Pursuit (CSP), Horizontal Smooth Pursuit (HSP), and Vertical Smooth Pursuit (VSP). Each test used a black background with white dot(s).

The HS task was self-paced (see Hunfalvay and colleagues' 2019 piece for more details) and participants looked at a countdown of three, two, one, which was in the center of the monitor before moving their eyes back and forth between two stationary dots, which were 1 degree in diameter and 10 cm apart (see Figure 1). The participants' goal was to 'target each dot' on the left and right of the monitor as quickly and accurately as possible.

The measures from the HS test included: HS Bandwidth, HS missed, HS on target, and HS saccade number (see Table 1 for descriptions).

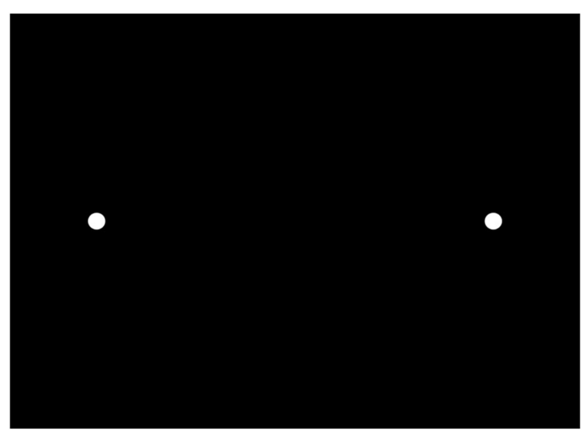

FIGURE 1. Horizontal saccade target.

TABLE 1. Oculomotor measures, definition, and relationship to performance.

Variable measure	Definition	Relationship to performance
HS Bandwidth	HS Bandwidth refers to a tally of x, y coordinates that appear beyond the targets to the right side. These “hits” are tallied across the length of the test and are reported as a total number of targets overshot. Bandwidth refers to the distance from eye gaze point to dot, with 2 degrees of visual angle at a viewing distance of 56 cm.	Lower HS Bandwidth indicates a better result.
HS Missed	HS missed is recorded when no target is hit and the user has passed the center of the monitor in the direction of the target.	Lower HS Missed indicates better performance.
HS on Target	HS on target refers to a tally of x, y coordinates within the left and right targets. These “hits” are tallied across the length of the test and are reported as a total number of target hits. On-target refers to the accuracy of the saccade and proximity of eye gaze point to the dot on the monitor when fixating.	Higher HS on Target indicates better performance.
HS Number	HS saccade number refers to the total number of saccades throughout the testing session.	Higher HS Saccade Number indicates more “hits” on a target by the eye.
HSP Variance	HSP variance refers to the average variance from the ideal pathway and is calculated in three segments of the pathway: middle, left/right, or up/down.	HSP Variance ideal score is 0.0, with closer scores to 0.0 indicating closer to the ideal pathway.
CSP Synchronization	CSP synchronization is how far off on the X plane (coordinate) the user’s eyes deviate during the test.	CSP Synchronization scores ranged from 0.0 to 1.0 with perfect synchronization with the target being 1.0.
VSP Pathway Differences	VSP pathway differences refer to the average difference in distance between the right and left eye gaze pathways in the top side of the monitor.	VSP Pathway Differences score is 0.0, with closer scores to 0.0 indicating closer to the ideal pathway.

Abbreviations: Horizontal Saccades (HS), Circular Smooth Pursuit (CSP), Horizontal Smooth Pursuit (HSP), and Vertical Smooth Pursuit (VSP).

The Circular Smooth Pursuit (CSP) task involved participants being asked to follow the dot, on the screen (i.e., a monitor), as accurately as possible with their eyes, as the dot moved around in a circle. Horizontal Smooth Pursuit (HSP) and Vertical Smooth Pursuit (VSP) tasks followed the same protocol as the CSP task, except that the dot moved horizontally during HSP and vertically during VSP. The measures for these tests were HSP variance and VSP pathway differences.

Participants were recruited through providers at a United States Olympic Committee center. The study was conducted in accordance with the tenets of the Declaration of Helsinki and the study protocols were approved (Approval # UMCIRB 22-000993) by the University Institutional Review Board (i.e., Ethics Committee). After the study was explained to participants and informed consent was obtained, participants completed a prescreening questionnaire and the RightEye acuity vision screening, where they identified 4-shapes at 4 mm diameter. If any of the prescreening questions were answered positively or if any of the vision screening shapes were not correctly identified, then the participant was excluded from the study.

Qualified participants who successfully passed the 9-point calibration sequence completed the eye-tracking tests. All testing was conducted by vision specialists (e.g., optometrists and ophthalmologists). All vision specialists received and passed the RightEye training which included how to run the system and how to determine if there is an issue with eye tracking, education, and protocol procedures prior to testing to ensure testing was performed accurately and consistently. Head movements are minimized by the design of the eye tracker in which the participants must maintain their head position within a virtual headbox at 60 cm from the screen. In addition, the participant was instructed to keep their head still. If excessive head movements were noted or if the participant moved outside the headbox then the test is repeated. No test was repeated. In addition, the researchers did observable that all participants were able to maintain a still head position. Written instructions on the screen and animations were provided before eye tracking tests to introduce standardized testing procedures. At the completion of the testing protocol, participants were debriefed before departing.

Data was processed with RightEye software that included automated filtering of blinks. All statistical analyses were performed using IBM SPSS Statistical Package version 28.0. Normality was assessed by dividing *Skewness* by the *S.E. of Skewness*, and *Kurtosis* by the *S.E. of Kurtosis*. Independent t-tests were used to examine both sex and group differences in HS Bandwidth, HS missed, HS on target, HS saccade number, HSP variance, CSP synchronization, and VSP pathway accuracy variables. The alpha level was set at $p < .05$, with Cohen's d used to determine effect size where .1 to .3 is considered small, .3 to .5 is considered moderate, and > .5 is considered large (Cohen, 1988). Pearson correlations were performed to examine relationships between these variables and age and to screen for multicollinearity. Logistic regression was used to assess the relationship between contact and non-contact groups and measures. Receiver Operating Characteristics (ROC) curve analyses were performed to determine the threshold score for each predictor in the logistic regression.

Results

There were no sex differences for any of the oculomotor variables and age was unrelated to the measures ($p > .05$). Therefore, sex and age were excluded from subsequent analyses. Data were inspected for normality using the $Z_{skewness}$ and $Z_{kurtosis}$ scores. The normality tests were non-significant for all tests; therefore parametric tests were used. Sport group-related independent t-tests were significant for each variable except CSP Synchronization and VSP Pathway Differences (see Table 2). Effect sizes were large, ranging from .5 to .68.

Correlations between eye tracking variables were low ranging from −0.02 to 0.34. Therefore, all eye tracking variables were included in the subsequent regression analysis.

The logistic regression entering all individual predictor variables indicated the model was significant, $\chi^2(6) = 37.08$, $p < .001$, explaining 57.4% (Nagelkerke R^2) of the variance and correctly classifying 88.1% of cases. The sensitivity was 87.5% and the specificity was 88.9%. Increasing HS Bandwidth, HS missed, and HSP variance increased the likelihood of being in a contact sport, while VSP Pathway and CSP synchronization did not. ROC analysis was significant for each HS variable (Table 3).

TABLE 2. Descriptive statistics for oculomotor variables by sport type.

	Contact sport athletes ($n = 27$)		Non-Contact sport athletes ($n = 40$)				
Variables	*M*	*SD*	*M*	*SD*	*t*	*p*	*Cohen's d*
HS Bandwidth	2.96	1.48	1.92	1.52	2.77	.01	.68
HS Missed	1.19	1.39	0.55	.96	2.22	.03	.55
HS on Target	6.59	3.58	4.35	3.27	2.65	.01	.66
HS Saccade Composite	10.74	3.38	6.82	1.90	2.71	.001	.86
HSP Variance	13.64	9.53	9.79	6.15	2.01	.05	.50
CSP Synchronization	0.95	0.02	0.90	0.01	1.90	.06	.47
VSP Pathway Differences	1.24	4.04	−0.09	3.35	1.49	.14	.37

Abbreviations: Horizontal Saccades (HS), Circular Smooth Pursuit (CSP), Horizontal Smooth Pursuit (HSP), and Vertical Smooth Pursuit (VSP).

TABLE 3. Logistic regression analysis results predicting sport type and ROC analyses.

Variables	Wald	*p*	Exp(B)	*ROC*	*p*	Coordinates
HS Bandwidth	8.38	.004	2.19	0.70	0.006	2.00
HS Missed	4.93	.026	2.07	0.66	0.030	0.25
HS on Target	7.40	.007	1.34	0.69	0.011	5.25
HSP Variance	6.10	.014	1.16	0.63	0.076	–
CSP Synchronization	7.84	.005	0.00	0.40	0.192	–
VSP Pathway Differences	4.71	.030	1.24	0.41	0.385	–

Abbreviations: Horizontal Saccades (HS), Circular Smooth Pursuit (CSP), Horizontal Smooth Pursuit (HSP), and Vertical Smooth Pursuit (VSP).

Discussion

The current study aimed to examine differences in oculomotor behavior between Olympic-level contact and non-contact sport athletes. Given the burgeoning research indicating that oculomotor measurements can differentiate mTBI and healthy participants (Hunfalvay et al., 2019; Maruta et al., 2010) or mTBI and healthy athletes (Brown et al., 2022; Murray et al., 2017), we hypothesized (and largely found) significant differences in self-paced horizontal saccades, and circular, vertical, and horizontal smooth pursuit eye movements between sport type, with contact sports participants having more inefficient oculomotor functioning.

Results indirectly indicate that Olympic athletes in contact sports have reduced oculomotor efficiencies compared to non-contact sport Olympic athletes, which concurs with Brown et al. (2022) who found that 40% of contact sport participants presented with at least one oculomotor impairment compared to 13% of the healthy controls. In our study, contact sport athletes exhibited more saccadic activity, as demonstrated by a greater number of overall saccades (HS Saccade Number), and displayed higher eye movement variability (as demonstrated by variance scores) than non-contact sport athletes. More saccadic activity indicated more movement of the eyes, however, this movement is weighed against speed and, in turn, the efficiency of the activity. The contact group moves quickly but with a lack of oculomotor control. This is exhibited by the combination of higher HS saccade numbers coupled with increased variability (shown through standard deviations and HSP variance). The number of saccades for the non-contact group indicates more precise oculomotor behavior, indicated by lower variance, which is most evident when viewing the HSP variance scores, VSP pathway differences, and with lower and fewer overall saccades numbers (and with lower standard deviations). These results are consistent with past research that indicated that show signs of individuals with poor oculomotor control (Lange et al., 2018). Furthermore, this work highlights the potential measurable neuropsychological dysfunction in individuals who may have experienced unreported concussive and sub-concussive head impacts.

Hunt et al. (2016) cautioned the use of saccadic, smooth pursuit, and vergence for the clinical detection of mTBI since their systematically reviewed papers were somewhat exploratory and not yet convincing enough for clinical recommendations. Our paper, however, adds to the already increasing evidence (Hunfalvay et al., 2019, 2020, 2021) that saccade and smooth pursuit movements may detect mTBI in populations that are at greater risk for concussive or sub-concussive impact. Clearly, sports with more contact have higher potential for mTBI being underreported. Given extensive advancements in eye tracking technology since Hunt et al. (2016) was published, this study provides compelling evidence for the use of oculomotor measurements for detecting neuropsychological inefficiencies, such as mTBI, in sport practices.

Despite our best efforts to ensure a robust study design, some limitations should be mentioned, which may aid in directing future research. One limitation was the small sample size. Aside from the size, the sample was unique in that it featured Olympic-level athletes from different sport types, which has not yet been done, providing valuable insight that is otherwise unavailable. Nevertheless, future research could provide more robust evidence for these differences by using a larger sample with similarly elite athletes. We were also unable to measure the extent to which participants had suffered repeated head contact, and thus, we can only imply from the results that eye movement differences were a consequence of potential head impacts. The ability to use oculomotor measures to detect mTBI and concussion is continually evolving. That being said, future research could also link these oculomotor inefficiencies as a result of sport type to performance outcomes and to symptoms, which would provide a more direct connection between how these eye movement differences affect the player.

Conclusions

This was the first study to identify oculomotor differences in Olympic athletes of contact and non-contact sports, which adds to the growing evidence that oculomotor functioning may be a reliable, quick, real-time tool to help detect concussion or TBI in sports. It is pertinent to note that these differences were identified in athletes with no diagnosed concussions. As such, further safety precautions should incorporate eye movement technology and oculomotor metrics to more precisely detect mTBI or concussions and reduce the long-term effects of head injuries in contact sports.

Disclosure Statement

Melissa Hunfalvay is a full-time employee with RightEye and has relevant affiliations and financial involvement. The remaining authors have no conflict of interest.

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REFERENCES

Armstrong, R. A. (2018). Visual problems associated with traumatic brain injury. *Clinical & Experimental Optometry*, *101*(6), 716–726. https://doi.org/10.1111/cxo.12670

Bellmann, C., Feely, M., Crossland, M. D., Kabanarou, S. A., & Rubin, G. S. (2004). Fixation stability using central and pericentral fixation targets in patients with age-related macular degeneration. *Ophthalmology*, *111*(12), 2265–2270. https://doi.org/10.1016/j.ophtha.2004.06.019

Brown, D. A., Leung, F. T., Evans, K., Grant, G., & Hides, J. A. (2022). Vestibular and oculomotor function in male combat sport athletes. *Journal of Science and Medicine in Sport*, *25*(6), 524–528. https://doi.org/10.1016/j.jsams.2022.02.004

Cifu, D. X., Wares, J. R., Hoke, K. W., Wetzel, P. A., Gitchel, G., & Carne, W. (2015). Differential eye movements in mild traumatic brain injury versus normal controls. *The Journal of Head Trauma Rehabilitation*, *30*(1), 21–28. https://doi.org/10.1097/HTR.0000000000000036

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.

Cynarski, W. J., & Kudłacz, M. (2008). *Injuries in martial arts and combat sport: A comparative study* (Vol. 4, pp. 91–97). Archives of Budo.

Faul, M., Wald, M. M., Xu, L., & Coronado, V. G. (2010). *Traumatic brain injury in the United States: Emergency department visits, hospitalizations, and deaths, 2002–2006*. Centers for Disease Control and Prevention, National Center for Injury Prevention and Control.

Felleman, D. J., & Van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. *Cerebral Cortex*, *1*(1), 1–47. https://doi.org/10.1093/cercor/1.1.1-a

Hunfalvay, M., Murray, N. P., Mani, R., & Carrick, F. R. (2021). Smooth pursuit eye movements as a biomarker for mild concussion within 7-days of injury. *Brain Injury*, *35*(14), 1682–1689. https://doi.org/10.1080/02699052.2021.2012825

Hunfalvay, M., Murray, N. P., Roberts, C. M., Tyagi, A., Barclay, K. W., & Carrick, F. R. (2020). Oculomotor behavior as a biomarker for differentiating pediatric patients with mild traumatic brain injury and age matched controls. *Frontiers in Behavioral Neuroscience*, *14*, 581819. https://doi.org/10.3389/fnbeh.2020.581819

Hunfalvay, M., Roberts, C. M., Murray, N., Tyagi, A., Kelly, H., & Bolte, T. (2019). Horizontal and vertical self-paced saccades as a diagnostic marker of traumatic brain injury. *Concussion*, *4*(1), CNC60. https://doi.org/10.2217/cnc-2019-0001

Hunt, A. W., Mah, K., Reed, N., Engel, L., & Keightley, M. (2016). Oculomotor-based vision assessment in mild traumatic brain injury: A systematic review. *The Journal of Head Trauma Rehabilitation*, *31*(4), 252–261. https://doi.org/10.1097/HTR.0000000000000174

Johnson, B., Zhang, K., Hallett, M., & Slobounov, S. (2015). Functional neuroimaging of acute oculomotor deficits in concussed athletes. *Brain Imaging and Behavior*, *9*(3), 564–573. https://doi.org/10.1007/s11682-014-9316-x

Kiefer, A. W., DiCesare, C., Nalepka, P., Foss, K. B., Thomas, S., & Myer, G. D. (2018). Less efficient oculomotor performance is associated with increased incidence of head impacts in high school ice hockey. *Journal of Science and Medicine in Sport*, *21*(1), 4–9. https://doi.org/10.1016/j.jsams.2017.06.016

Komogortsev, O. V., & Karpov, A. (2013). Automated classification and scoring of smooth pursuit eye movements in the presence of fixations and saccades. *Behavior Research Methods*, *45*(1), 203–215. https://doi.org/10.3758/s13428-012-0234-9

Land, M., & Tatler, B. (2009). *Looking and acting: Vision and eye movements in natural behaviour*. Oxford University Press.

Lange, B., Hunfalvay, M., Murray, N., Roberts, C.-M., & Bolte, T. (2018). *Reliability of computerized eye-tracking reaction time tests in non-athletes, athletes, and individuals with traumatic brain injury*. (Vol. 6, pp.165–180). Optometry & Visual Performance.

Langlois, J. A., Rutland-Brown, W., & Wald, M. M. (2006). The epidemiology and impact of traumatic brain injury: A brief overview. *The Journal of Head Trauma Rehabilitation*, *21*(5), 375–378. https://doi.org/10.1097/00001199-200609000-00001

Lemme, N. J., Johnston, B., DeFroda, S. F., Owens, B. D., & Kriz, P. K. (2020). Incidence of combat sport-related mild traumatic brain injuries presenting to the emergency department from 2012 to 2016. *Clinical Journal of Sport Medicine*, *30*(6), 585–590. https://doi.org/10.1097/JSM.0000000000000633

Maruta, J., Suh, M., Niogi, S. N., Mukherjee, P., & Ghajar, J. (2010). Visual tracking synchronization as a metric for concussion screening. *The Journal of Head Trauma Rehabilitation*, *25*(4), 293–305. https://doi.org/10.1097/HTR.0b013e3181e67936

McCrory, P., Meeuwisse, W., Johnston, K., Dvorak, J., Aubry, M., Molloy, M., & Cantu, R. (2009). Consensus statement on concussion in sport: The 3rd International Conference on Concussion in Sport held in Zurich, November 2008. *British Journal of Sports Medicine*, *43*(Suppl_1), i76–90. https://doi.org/10.1136/bjsm.2009.058248

Møllenbach, E., Hansen, J. P., & Lillholm, M. (2013). Eye movements in gaze interaction. *Journal of Eye Movement Research*, *6*(2), 1. https://doi.org/10.16910/jemr.6.2.1

Murray, N., Kubitz, K., Roberts, C.-M., Hunfalvay, M., Bolte, T., & Tyagi, A. (2019). An examination of the oculomotor behavior metrics within a suite of digitized eye tracking tests. *Vision Development & Rehabilitation*, *5*, 269–284. https://doi.org/10.31707/VDR2019.5.4.p269

Murray, N. G., D'Amico, N. R., Powell, D., Mormile, M. E., Grimes, K. E., Munkasy, B. A., Gore, R. K., & Reed-Jones, R. J. (2017). ASB clinical biomechanics award winner 2016: Assessment of gaze stability within 24-48hours post-concussion. *Clinical Biomechanics*, *44*, 21–27. https://doi.org/10.1016/j.clinbiomech.2017.03.002

Rice, S. G, Fitness, A. A. o. P. C. o. S. M. a. (2008). Medical conditions affecting sports participation. *Pediatrics*, *121*(4), 841–848. https://doi.org/10.1542/peds.2008-0080

Snegireva, N., Derman, W., Patricios, J., & Welman, K. E. (2018). Eye tracking technology in sports-related concussion: A systematic review and meta-analysis. *Physiological Measurement*, *39*(12), 12TR01. https://doi.org/10.1088/1361-6579/aaef44

Sussman, E. S., Ho, A. L., Pendharkar, A. V., & Ghajar, J. (2016). Clinical evaluation of concussion: The evolving role of oculomotor assessments. *Neurosurgical Focus*, *40*(4), E7. https://doi.org/10.3171/2016.1.FOCUS15610

Thompson, H. J., McCormick, W. C., & Kagan, S. H. (2006). Traumatic brain injury in older adults: Epidemiology, outcomes, and future implications. *Journal of the American*

Geriatrics Society, *54*(10), 1590–1595. https://doi.org/10.1111/j.1532-5415.2006.00894.x

Wallace, J., Covassin, T., Nogle, S., Gould, D., & Kovan, J. (2017). *Knowledge of concussion and reporting behaviors in high school athletes with or without access to an athletic impact of previous concussion on SCAT Memory Score and Eye Tracking Performance*, *52*(3), 228–235. https://doi.org/10.4085/1062-6050-52.1.07

Ventura, R. E., Jancuska, J. M., Balcer, L. J., & Galetta, S. L. (2015). Diagnostic tests for concussion: Is vision part of the puzzle? *Journal of Neuro-Ophthalmology*, *35*(1), 73–81. https://doi.org/10.1097/WNO.0000000000000223

Zazryn, T., Cameron, P., & McCrory, P. (2006). A prospective cohort study of injury in amateur and professional boxing. *British Journal of Sports Medicine*, *40*(8), 670–674. https://doi.org/10.1136/bjsm.2006.025924

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