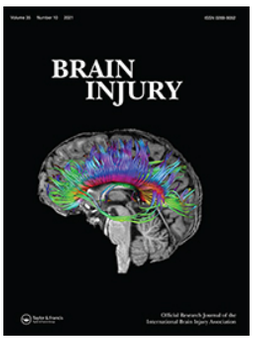

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Smooth Pursuit Eye Movements as a Biomarker for Mild Concussion within 7-Days of Injury

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ABSTRACT

Aim: Deficits in smooth-pursuit eye movements (SPEM) are often associated with mild traumatic brain injury(TBI). Eye tracking tests serve as a quick objective clinical tool to assess such predictive visual tracking. In this study, SPEM was assessed along circular, horizontal and vertical trajectories in adolescents with concussion and age-matched controls.

Methods: Ninety-one young adolescents with concussion and 140 visually healthy age-matched controls with a mean age of 14 years performed a computerized test of circular, horizontal and vertical tracking task using an eye tracker. Oculomotor tracking was assessed by computing the rate of fixation, saccades and SPEM made while performing the tasks.

Results: The predictive visual tracking task was able to differentiate the TBI group from the non-TBI group. The TBI group showed a significant difference in the fixation, saccades and SPEM percentages for circular tracking movement compared to the controls. There was a significant difference in fixation and SPEM % for horizontal and vertical tracking.

Conclusions: Predictive visual tracking, assessed using eye tracking technology, is able to differentiate deficits in oculomotor functions in individuals with and without concussion. The eye tracking technology may serve as a quick objective tool to detect and monitor neural deficits due to TBI.

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SPEM; smooth-pursuit eye movements; eye tracking; oculomotor; concussion

Introduction

Concussion is a complex pathophysiological process induced by traumatic biomechanical forces affecting the brain (1). It may result in sudden onset of neurological symptoms that may resolve spontaneously. A recent study in the US reported that 20.8% of athletes from a group of public and private high school sustained at least one diagnosed concussion during their life time (2). Another study estimated that the prevalence of concussion/head injuries ranged from 6.5% to 18.3% among adolescents (3).

Clinically, the term concussion is often interchangeably used with mild traumatic brain injury (TBI), cerebral concussion or mild head injury (4). Concussion is considered a variant form of mild TBI and occurs especially in people who engage in sports activities. Unlike mild TBI, concussion can occur without a disturbance in the state of consciousness and memory yielding a Glasgow Coma Scale score of 15 (1). Although there is no evidence of abnormality on standard neuroimaging records, concussion cause functional disturbances rather than structural changes (5).

Concussion causes a wide range of symptoms and impairments in neurological functions including cognitive dysfunctions such as impaired attention, poor memory and sensorimotor deficits that include oculomotor and vestibular dysfunctions. A significant number of studies have demonstrated deficits in oculomotor and vestibular functions in children and adolescents with concussion and mild head injury (6–9).

Most methods of diagnosis employ some combination of three tools such as neurological, oculomotor and vestibular assessment for the sideline concussion testing and in emergency departments (1,10,11). However, there exists an element of subjectivity and inadequate sensitivity. Eyetracking is a powerful tool for objective measurement of eye movements and therefore can provide one objective and sensitive measure of concussion detection (12–14).

Oculomotor assessment can be further divided into specific types of eye movements including saccades, smooth pursuits and fixations (15). Saccades are fast eye movements that bring an object of interest onto the fovea, fixation is the act of maintaining eye gaze on the object of regard to get visual inputs and it usually occurs between two saccades, and smooth pursuits use predictive tracking movements to stabilize moving targets on fovea. Smooth-pursuit eye movements (SPEM) can occur in any direction of gaze including circular smooth pursuit (CSP), horizontal smooth pursuit (HSP) and vertical smooth pursuit (VSP) (16).

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The complexity of the SPEM system means that a number of smooth pursuit metrics have been found to distinguish TBI from non-TBI groups (17–19). Synchronization is the distance between the target and the user's gaze. A perfect synchronization is a score of 1.0. This metric has close ties to attention and adaptation in the brain, and it has been found in multiple studies to be an accurate predictor of concussion. Research shows that the right anterior corona radiata (ACR) and genu of the corpus callosum, two of the brain tracts involved in synchronization, are some of the most susceptible to damage from concussion.

Variance is another relatively new metric that is related to the neurology of smooth pursuit. It refers to the average variance from the ideal pathway and is measured in millimeters. The variance is assessed from three segments of the pathway- middle, left or right and up or down. Past research also shows lower smooth pursuit percentage, higher saccade percentage and higher fixation percentage when comparing TBI to non-TBI groups (20). Velocity error is another metric that has shown differentiation between TBI and non-TBI (21). It shows how far the user's velocity was away from the target's velocity (non-directional). Eye/Target Velocity Error refers to speed represented in degrees/second off target. A lower number denotes better performance. This metric is calculated by subtracting the location of the stimuli and the user's eyes at the same sample time and is reported as degrees per second. Clinically, when pursuits fail to keep up with the tracking target, a 'catch-up' saccade is usually employed to bring the object of interest back to the fovea. Hence, an increase in saccades and fixations and a decrease in smooth pursuits are often a trifactor for neurological abnormality via SPEM assessment.

The smooth pursuit system is very complex and still not yet fully understood (22). Recent research indicates that visual information is relayed from the striate cortex to a range of extrastriate areas where information is encoded. From there, information travels down projections to the brain stem and other cortical area. The brain stem relays information to the cerebellum, which is critical in generating pursuits. Other cortical areas that make up the network that controls pursuits include the frontal eye field, the superior colliculus and the basal ganglia.

Smooth pursuits can be further understood by considering the difference between HSP, VSP and CSP pathways. In HSPs, the signal originates in the M ganglion cells in the retina (23). From there, signals are relayed to the striate cortex (V1 area) and then to the V2, V3 and mid temporal (MT) areas. From the MT areas, the signal travels to the medial superior temporal (MST) and the frontal and posterior parietal cortex's. The MT, MST and frontal eye field all share projections to the dorsolateral pontine nuclei (DLPN), which propagates the signal along a double decussation pathway before the contralateral medial rectus is innervated. Parallel to this, the nucleus of the optic tract receives projections from the MT and MST areas and sends them to the DLPN, a process which is specific to HSPs.

The VSP pathway only differs from the horizontal at three locations. Instead of the DLPN receiving signals from the MT, MST and frontal eye field, the rostral nucleus reticularis tegmenti pontis in the basal pons receives the signal. During the double decussation, the y-group is involved rather than the medial vestibular nucleus. Finally, the VSP pathway involves the dentate neuron in the cerebellum. CSPs have been found to activate the visual cortex bilaterally and caudal part of the right intraparietal sulcus (24). Signal increases have also been detected in the MT area and premotor cortex (FEF). Finally, there is a depression of activity found in the insula and anterior cingulate (11).

Intact vestibulo-ocular reflexes require a network of brain areas including the occipital and parietal lobes, FEF and brainstem, all of which are susceptible to damage from concussion. This is why variance has been shown to be a promising indicator of concussion (12).

Several studies have looked at smooth pursuits as a metric of concussion detection, and a reasonable body of research supports the conclusion that smooth pursuits are a relevant and useful diagnostic tool to concussion detection. However, no known studies consider difference between TBI and non-TBI in HSP, VSP and CSP in one study. Because these different types of movements have different pathways, it is important that all three are clinically assessed to obtain a more complete picture of neurological function. Furthermore, assessment of SPEM in cases with concussion is difficult to observe clinically. The purpose of this paper was to assess SPEM as a differentiating biomarker between mild TBI (within 7days of injury) and non-TBI age-matched controls.

Methods

Participants

Data from 231 participants from neurology and neuro-optometry practices throughout the USA were analyzed. The neuro-optometrists are eyecare professionals, who are trained for diagnosing TBI and assessing visuo-perceptual deficits associated with TBI. Practices that agreed to recruit patients were informed about the study and the pre-screening criteria. All SPEM data and IRB consent forms are captured at the location using the RightEye Vision system. The information is then transferred, stored and processed in a cloud-based repository. Ninety-one participants were clinically diagnosed as having a mild TBI within 10 days of the assessment by the board-certified neuro-optometrist or neurologists. One-hundred and forty participants were age and gender-matched controls. Participants were between the ages of 8 and 19 years (M = 14.20, SD = 2.78); 165 were males (71.4%), and 66 were females (28.6%). Of the 231 participants, 68.8% were White, 3.0% were Hispanic, 0.4% were Asians, 7.4% were Black and 20.4% opted not to report ethnicity. The groups were matched by age (see Table 1).

Acute Concussion Evaluation

Participants were included if their injury event was within 7days. They were assessed with the Acute Concussion Evaluation (ACE) questionnaire (25). The ACE is intended to

Table 1. Demographic data by age and gender.

Group (n)	Mean Age (±SD)	Female	Male
TBI (91)	14.13 (2.97)	27	64
Non-TBI (140)	14.31 (2.48)	39	101

n = number, SD = standard deviation

provide an evidence-based clinical protocol to conduct an initial evaluation and diagnosis of patients with known or suspected mild concussion. It is part of the 'Heads Up to Health Care Providers' toolkit developed by the Centers for Disease Control and Prevention in 2017. The ACE includes a 22-item symptom checklist of physical, cognitive, emotional and sleep symptoms. The total concussive scores on the ACE range from 0 to 22. The average score for the participants in this study on the ACE was 9 (range 2–18) with headaches being the primary symptom in 85% of the participants. The ACE was conducted by a board-certified neurologist with more than 20 years of clinical practice in concussion.

Apparatus

Stimuli were presented using the RightEye tests on a Tobii I15 vision 15" monitor fitted with a Tobii 90 Hz remote eye tracker and a Logitech (model Y-R0017) wireless keyboard and mouse. RightEye oculomotor tests are eye movement tasks designed to assess saccadic and pursuit eye movements. Specifically, SPEM are assessed in horizontal, vertical and circular trajectories. A detailed description of the RightEye tests and its outcome measures is reported in Murray et al. 2019,(16) study. The participants were seated in a stationary (nonwheeled) chair that could not be adjusted in height. They sat in front of a desk in a quiet, private room. Participants' heads were unconstrained. The eye traces were captured by a Tobi remote eye tracking system with a sampling rate of 90 Hz, and a nine-point calibration sequence was used to screen for eligible participants. The accuracy of the Tobii eye tracker was 0.4 degree within the desired headbox of 32 cm × 21 cm at 56 cm from the screen. For standardization of testing, participants were asked to sit in front of the eye tracking system at an exact measured distance of 56 cm (ideal positioning within the headbox range of the eye tracker).

Oculomotor tasks

Three types of pursuit tests were run: CSP, HSP and VSP. Participants were asked to 'follow the dot, on the screen, as accurately as possible with their eyes'. The dot was 0.2 degree in diameter and moved at a speed of 25.13 degree of visual angle per second. The tests were taken with a black background with white dot and lasted 20s. The diameter of movement of the CSP circle was 20 degree. The visual degrees of the HSP and VSP tests were 15 degree in every direction from the center of the screen (26). The key measures for CSP, HSP and VSP measured from the eye tracker were number of fixations, saccades and pursuits expressed in percentages and were considered as sensitive indicators to differentiate TBI from non-TBI groups. The fixation percentage was calculated based on number of fixations made while performing the tracking task in the stipulated testing time, the saccade percentages are number of saccades made during the tracking movement, and pursuit percentages are the tracking eye movements within the acceptable distance and speed of the moving target in the testing time.

Procedure

Participants were recruited through advertisements placed on the internet, social media, and bulletin boards and spread by word of mouth. The study was conducted in accordance with the tenets of the Declaration of Helsinki. The study protocols were approved by the Institutional Review Board of East Carolina University. The nature of the study was explained to the participants, and all participants provided written consent to participate. Following informed consent, participants were asked to complete a prescreening questionnaire and an acuity vision screening, where they were required to identify four shapes at 4 mm in diameter. If any of the prescreening questions were answered positively and any of the vision screening shapes were not correctly identified, then the participant was excluded from the study. Participants were excluded from the study if they reported any of the following conditions, which may have prevented successful test calibration during the prescreening process: this included vision-related issues such as extreme tropias, phorias, static visual acuity of >20/400, nystagmus, cataracts or eyelash impediments or if they had consumed drugs or alcohol within 24 hours of testing (23–27). Participants were also excluded if they were unable to pass a nine-point calibration sequence or if they were beyond 7 days post injury. Less than 1% of the participants fell into these categories.

Qualified participants who successfully passed the nine-point calibration sequence completed the eye tracking tests. The calibration sequence required participants to fixate one at a time on nine points displayed on the screen. The participants had to successfully fixate on at least eight of nine points on the screen to pass the calibration sequence. Written instructions on screen and animations were provided before each test to demonstrate appropriate behavior required in each of the tests.

Data analysis

The differences in the groups (non-TBI, TBI) were analyzed on clinically verified data using JMP PRO 14.0 (SAS Institute; Cary, NC). First, three MANOVAs were conducted for each test (CSP, HSP and VSP) and then separate one-way MANOVA were conducted to compare fixation percent, smooth pursuit percentage and saccade percentage between mTBI and non-mTBI. When significant follow-up one-way univariate ANOVAs were utilized for each measure. The alpha level was set at $p < .05$ and partial eta-squared (η_p^2) was used to determine effect size. A receiver operating characteristic (ROC), area under the curve and sensitivity and specificity were calculated to predict outcome measure that best differentiate TBI from non-TBI group. All data were examined for the assumptions of multicollinearity and normality, and in cases where these assumptions were violated, a non-parametric test was used.

The I–VDT algorithm is a velocity and dispersion threshold that is outlined in the Komogortsev and Karpov et al. paper on the automated classification and scoring of SPEMs in presence of fixations and saccades (27). Specifically, RightEye has a hierarchical process for classification of eye movements. First, the saccades are detected, following which smooth pursuits and fixations are identified.

Table 2. Mean and standard deviation for CSP variables.

Group (n)	Fixation Percentage (SD)	Smooth Pursuit Percentage (SD)	Saccade Percentage (SD)
TBI (91)	3.19 (5.97)	89.5 (7.96)	7.31 (3.64)
Non-TBI (140)	1.41 (3.38)	93.11 (5.75)	5.48 (3.94)

n = number, SD = standard deviation

Table 3. Results of ROC analysis.

Variable	AUC	S.E.	*p*	Cut-Off	Sensitivity	Specificity
Circular smooth pursuit						
Fixation percentage	0.62	0.153	.0001	2.71	75.7%	72.5%
Smooth Pursuit Percentage	0.67	2.072	.269	90.94	69.5%	71.4%
Saccade Percentage	0.67	0.210	.069	6.29	83.2%	72.6%
Horizontal smooth pursuit						
Fixation percentage	0.75	0.173	.001	3.29	80.2%	76.8%
Smooth Pursuit Percentage	0.65	1.23	.053	89.27	76.9%	72.4%
Saccade Percentage	0.43	0.17	.025	6.46	98.6%	94.7%
Vertical smooth pursuit						
Fixation percentage	0.72	0.264	.0001	18.73	85.7%	64.3%
Smooth Pursuit Percentage	0.71	0.688	.0001	70.86	90.1%	72.8%
Saccade Percentage	0.55	0.209	.018	6.79	70.3%	91.9%

ROC - receiver operating characteristics, AUC - area under curve, S.E. – standard error of mean, *p* – probability value

Table 4. Mean and standard deviation for HSP variables.

Group (n)	Fixation Percentage (SD)	Smooth Pursuit Percentage (SD)	Saccade Percentage (SD)
TBI (91)	5.33 (6.54)	88.49 (9.63)	6.19 (5.25)
Non-TBI (140)	1.61 (3.59)	91.73 (10.4)	6.66 (9.63)

n = number, SD = standard deviation

Table 5. Mean and standard deviation for VSP variables.

Group (n)	Fixation Percentage (SD)	Smooth Pursuit Percentage (SD)	Saccade Percentage (SD)
TBI (91)	27.23 (16.63)	65.94 (18.4)	7.31 (3.64)
Non-TBI (140)	15.55 (12.48)	77.92 (14.26)	5.48 (3.94)

n = number, SD = standard deviation

Saccades are identified if the velocity of eye movements exceed 30 degree/second and greater than ¼ degree radius dispersion for less than 100 millisecond duration. If the velocity of eye movements is below 30 degree/second, it could be either a fixation or a SPEM. Smooth pursuits are differentiated from fixations by dispersion and time threshold. Fixations are classified if the eye trace is located within ¼ degree radius of dispersion from the tracking target for a minimum duration of 100 ms. However, if eye trace takes less than 100 milliseconds to move beyond ¼ degree radius of target position with a velocity of less than 30 degrees/second, a smooth pursuit is identified. Once eye movements are classified, the saccades, pursuits and fixation eye movements were calculated. These numbers are converted into percentages by using total time spent within the eye movement classification divided by test time then multiplied by 100 as fixation percentage, smooth pursuit percentage and saccade percentage.

Results

Circular smooth pursuit

A one-way MANOVA for CSP was conducted to compare fixation percentage, smooth pursuit percentage and saccade percentage. Significant differences in the three outcome measures of CSP were found between groups (Wilks' Lambda = .929, F (3, 227) = 5.75, $p < .0001$). The follow-up ANOVA results demonstrated a significant main effect for fixation percentage [F (1, 229) = 8.23; $p < .01$, $\eta_p^2 = 0.035$], smooth pursuit percentage [F (1, 229) = 15.99; $p < .001$, $\eta_p^2 = 0.053$] and saccade percentage [F (1, 229) = 12.73; $p < .001$, $\eta_p^2 = .065$]. The ROC curves produced area under curve values for fixation, smooth pursuit and saccade percentage as 0.62, 0.67 and 0.67, respectively (see Tables 2 and 3). Figure 1 displays the ROC curves for fixation, SPEM and saccade percentage for CSP.

Horizontal smooth pursuit

The MANOVA for HSP demonstrated between-group differences for the dependent variables (fixation percentage, smooth pursuit percentage and saccade percentage) [Wilks' Lambda = .871, F (3, 227) = 11.214, $p < .0001$]. The follow-up ANOVA results demonstrated a significant main effect for fixation percentage [F (1, 229) = 30.89; $p < .001$, $\eta_p^2 = 0.119$] and smooth pursuit percentage [F (1, 229) = 5.68; $p < .001$, $\eta_p^2 = 0.024$]; however, saccade percentage differences between mTBI and non-TBI were non-significant [F (1, 229) = 0.181; $p = .671$, $\eta_p^2 = .001$]. The ROC curves produced area under curve values for fixation, smooth pursuit and saccade percentage as 0.75, 0.65 and 0.43, respectively (see Tables 3 and 4). Figure 2 displays the ROC curves for fixation, SPEM and saccade percentage for HSP.

Vertical smooth pursuit

The MANOVA for VSP similarly demonstrated significant differences between mTBI and non-TBI for the dependent variables (fixation percentage, smooth pursuit percentage and saccade percentage) [Wilks' Lambda = .860, F (3, 227) = 12.303, $p < .0001$]. Likewise, the follow-up ANOVA results demonstrated a significant main effect for fixation percentage [F (1, 229) = 37.01; $p < .001$, $\eta_p^2 = 0.139$] and smooth pursuit percentage [F (1, 229) = 30.88; $p < .0001$, $\eta_p^2 = 0.119$]. There was no significant difference between mTBI and non-TBI groups for saccade percentage [F (1, 229) = .163; $p = .687$, $\eta_p^2 = .001$]. The ROC curves produced area under curve values for fixation, smooth pursuit and saccade percentage as 0.72, 0.71 and 0.55, respectively (see Tables 3 and 5). Figure 3 displays the ROC curves for fixation, SPEM and saccade percentage for VSP.

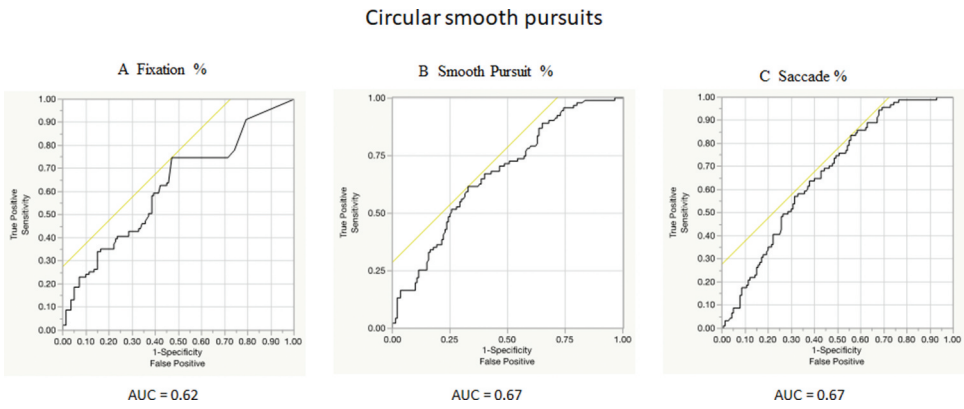

Figure 1. ROC curve and AUC values for CSPs for A. fixation %, B. smooth pursuit % and C. saccade % – TBI vs non-TBI. Abbreviations: ROC - receiver operating characteristic, AUC - area under the curve.

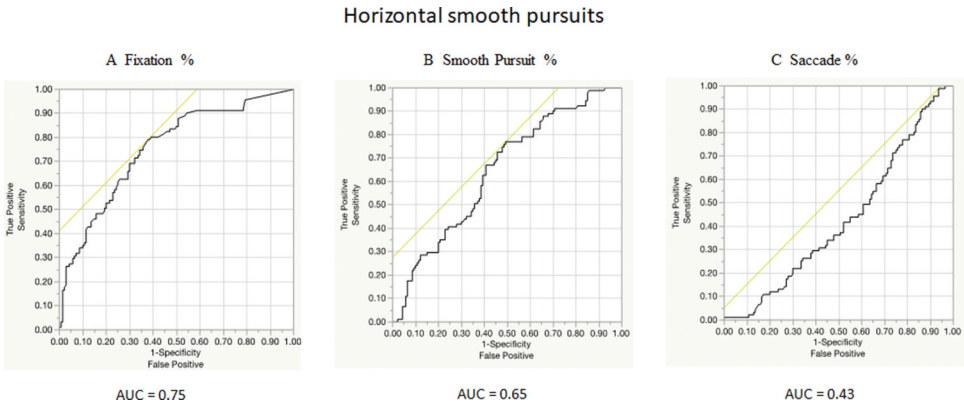

Figure 2. ROC curve and AUC values for HSP for A. fixation %, B. smooth pursuit % and C. saccade percentages – TBI vs non-TBI. Abbreviations: ROC - receiver operating characteristic, AUC - area under the curve.

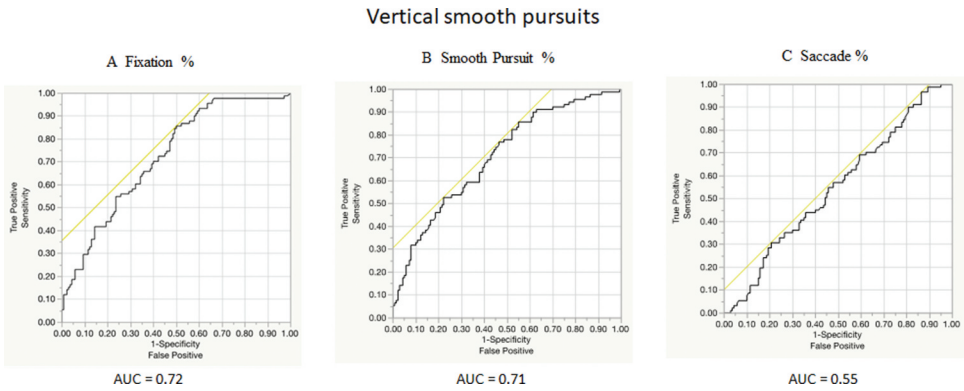

Figure 3. ROC curve and AUC values for VSP for A. fixation, B. smooth pursuit and C. saccade percentages – TBI vs non-TBI. Abbreviations: ROC - receiver operating characteristic, AUC - area under the curve.

Discussion

The aim of this study was to examine SPEM as a differentiating biomarker between the TBI (within 7 days of injury) and age-matched non-TBI group. This is the first study that quantified the fixation, saccade and SPEM percentages in circular, horizontal and vertical tracking eye movements. Our results showed that fixation percentage and percentages of circular, horizontal and vertical SPEM demonstrated distinct differences between TBI and non-TBI groups. There was no difference between groups for saccade percentage for horizontal and vertical saccades. Our results demonstrate a clear indicator of poor predictive visual tracking skills in people with mild TBI and provide further evidence of using eye movements and eye tracking technology to detect subtle (or residual) neural deficits due to mild concussion.

The SPEM is the ability to smoothly track an object traveling less than 30 degree/second and greater than ¼ degree radius dispersion for less than 100 millisecond. The significant increase in fixation and saccade percentage and decreased SPEM % for circular tracking metrics for the TBI group implies that the participants with concussion had difficulty to predict and follow a moving target smoothly. This indicates lag in SPEM, which is a consistent finding with previous literature (18,28–30).

The inability to track the moving object smoothly causes unnecessary fixations in the TBI group compared to non-TBI group for all three trajectories including the horizontal and vertical trajectories. This poor SPEM performance clearly indicates defective predictive visual tracking behavior.

The fact that there was increased saccade percentage specifically for the circular path may be because of the need to make multiple catch-up saccades to maintain the moving target on the fovea. These saccades help to reduce the retinal slip. However, there was not much need of such catch-up saccades for horizontal and vertical trajectories as the target moved in the same plane unlike the circular path. Although there was no significant difference in saccade percentage between study groups for both horizontal and vertical tracking, there was increased fixation percentage suggesting difficulty to smoothly follow a moving object in the same plane. The differences in fixation and SPEM percentage were significant even for the horizontal path, which is more commonly used in our daily activities. The largest area under the curves was produced by fixation percentage (0.75) for HSP followed by fixation percentage (0.72) and SPEM percentage (0.71) for VSP, indicating that these variables might best discriminate participants in the TBI group from non-TBI group.

Concurrently, the occurrence of oculomotor deficits in mild TBI was often associated with poor cognitive functions, which is one of the main hall marks of TBI. The cognitive processes involved in SPEM is associated with attention and visuospatial memory (31,32). The information related to target position and target velocity needs to be periodically updated in the visuospatial memory to execute precise tracking of moving object. Any delay in the update and/or mismatch of predictive target location stored in the visual memory would either cause lag or lead resulting in fixations and/or catch-up saccades in SPEM.

Our results are consistent with findings in previous SPEM studies. Maruta et al. investigated circular tracking eye movements using video-oculography in a group of 13 subjects with mild TBI and found lag shown by the decreased SPEM velocity gain and increased temporal phase and spatial positional error rates for the mTBI group (33). The lower velocity gain is analogous to the decreased SPEM percentage findings in our study, as both the measures indicate that the eye gaze positions lagged behind the target positions. In another study, they found that the performance variability of circular eye movement tracking significantly correlated with the damage to ACR and genu of corpus callosum using the diffusion tensor imaging technique in mTBI with chronic post-concussion syndrome and identified attentional and working memory deficits (19). This indicates tracking smooth pursuits as a useful Smeasure to investigate neuronal damage owing to the complex circuitry of oculomotor functions in the brain. Heitger et al. showed increased lag in random and sinusoidal tracking and slowed average peak velocity for sinusoidal tracking in people with mild TBI with a mean post-injury period of 10 days that persisted until 1 year (28,29). This finding indicates that SPEM may serve as a functional measure to monitor recovery chronic TBI.

People with TBI might have poor predictive visual tracking, which is an essential skill for many activities in daily living and in sports such as during playing tennis or cricket. The circular SPEM significantly differentiated the TBI from non-TBI group showing significant difference in fixation, saccade and SPEM percentages. This study clearly indicates that the RightEye eye tracking technology can be used to detect and quantify the defective SPEM system, which might serve as a sensitive test to detect subtle neural deficits in mild TBI (26). The RightEye utilizes the velocity and dispersion threshold algorithm and precisely detects both fast and slow eye movements.

Clinically, this study may be important to healthcare professionals in ER or in a sport injury clinic to screen for immediate neurological disruptions caused by TBI. A simple way to screen or do a sideline testing would be to do a visual tracking task and observe the recurrent number of fixations and saccadic eye movements in between the disrupted smooth tracking eye movement and help clinicians decision-make for further confirmatory testing.

The present study had a few limitations. First, the sample size was small (n = 91). However, the sample size was considered adequate for the objective of the present study. The study investigated acute mild TBI with a mean post-injury of 7 days. Hence, the result of this current study might be applied for acute mild TBI. Further research should consider exploring SPEM for various injury severities, diverse injury etiologies such as sports injury, motor vehicle accidents, whiplash injuries with severe neck pain, blast injuries and for people with chronic TBI and for various age groups. Also, tracking SPEM over a period of time after concussion might help in monitoring recovery and might be a predictor of symptom burden. In addition, further research on whether impaired smooth pursuits would affect the functional ability to track moving objects could be explored in future. Gender differences in concussion outcomes have been recently reported. However, sub-analysis for SPEM data was not performed for gender differences as there was unequal distribution between males and females in this study.

Conclusions

This study provided further evidence that participants with concussion demonstrated by impaired pursuit eyemovements, and SPEM could be used to differentiate injury status from non-injured. Computerized eye tracking technology provides a quick real-time measure of oculomotor deficits caused by mild TBI and can be used to detect and quantify the immediate impact of mTBI in a clinical setup such as in emergency rooms or as a screening tool during sideline testing and to decide on return to play in sports injuries.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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