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Assessment of oculomotor control and balance post-concussion: A preliminary study for a novel approach to concussion management

Nicholas G. Murray[1], V. N. Pradeep Ambati[1], Monica M. Contreras[2], Anthony P. Salvatore[3], & Rebecca J. Reed-Jones[2,4]

[1]Interdisciplinary Health Sciences PhD Program, [2]Department of Kinesiology, [3]Speech Language Pathology Program, and [4]Physical Therapy Program, College of Health Sciences, The University of Texas at El Paso, El Paso, TX, USA

Abstract

Primary objective: Balance disturbances occur in ~30% of concussion injuries, with vestibular dysfunction reported as the main contributor. However, few have studied oculomotor control post-concussion to assess vestibular dysfunction.
Research design: The current research measured the differences in oculomotor control between athletes post-concussion (PC) and athletes without concussion (NC) during an active balance control task.
Methods: Nine PC and nine NC athletes wore a monocular eye tracking device, while balance tests were performed using the Nintendo WiiFit® soccer heading game. Average game scores, eye deviations from centre (Gaze Deviations) and gaze fixation (Percentage Time on Centre) were measured.
Results: PC made significantly greater Gaze Deviations from centre compared to NC ($p < 0.001$), however Percentage Time on Centre and game scores were not significantly different between groups. Correlations between gaze and balance within groups revealed a significant positive correlation in NC, while a significant negative correlation in PC.
Conclusions: Results from this exploratory examination of oculomotor behaviour post-concussion revealed significant differences in gaze stability between athletes with a concussion and those without, suggesting vestibular involvement post-concussion. Assessment of oculomotor control during balance activities may provide further insight into dysfunction of the vestibular system following a concussion injury.

Keywords

Assessment, balance, concussion, eye tracking, post-concussion syndrome, vestibular, vision

History

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Introduction

An estimated 3.2 million concussion injuries occur in the US per year, with over 300 000 of those being related to sport [1]. Concussion accounts for approximately one third of all injuries in high school and collegiate athletics, with 16% of these injuries resulting from secondary concussion [2–4]. Secondary concussions are serious injuries as they place athletes at an increased risk for brain haemorrhage or death [5]. In addition, secondary concussions can amplify the potentially lifelong neurological deficits associated with a concussion; as such a strong need exists for the development of evidence-based Return-To-Play (TRP) policies [5, 6]. A critical step in the development of better RTP policies is research aimed at investigating recovery of concussion injuries [1].

Concussion has been defined by the 4th International Conference on Concussion in Sport as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces [5]. Potential concussion symptoms may include confusion, amnesia, loss of consciousness, loss of spatial and temporal awareness, headaches, migraines, speech impairment, dizziness, nausea, balance disturbances, oculomotor control reduction, vision impairment, speech reduction, gait unsteadiness and poor co-ordination [5]. Due to the variability of the symptoms experienced and the multiple mechanisms of injury that can contribute to a concussion injury, no two concussions are similar [5, 7]. This has created difficulty in the assessment and management of sport-related concussion.

Balance disturbances occur in ~30% of sport-related concussion injuries, with dizziness occurring in 75.6% of injuries [2, 6]. Balance disturbance is the inability to stand with an upright posture without deviating outside the limits of the base of support and are a considerable deterrent to activities of daily living (ADLs). During athletics, balance disturbances could place the athlete at a greater risk for falling and/or collisions leading to additional injury.

Vestibular dysfunction is a proposed source of balance dysfunction after a concussion injury [6]. Due to the sensitivity of the vestibular organ, impacts in the cranial area can disturb the hair cells or dislodge otoliths that

Correspondence: R. J. Reed-Jones, PhD, Kinesiology Program, Department of Applied Human Sciences, Faculty of Science, University of Prince Edward Island, 550 University Ave, Charlottetown, PE, Canada C1A 4P3. Tel: (902) 628-4358. Email: rreedjones@upei.ca

can interfere with spatial position information [8]. Incorrect spatial information could result in the dizziness and balance loss symptoms following concussion injury. The physical damage sustained by the vestibular system from concussion injury is still largely unknown. However, two major mechanisms for potential damage have been proposed. First, acute or long lasting damage of the peripheral receptors, specifically the hair cells, could provide the brain with inaccurate acceleration senses and, thus, reduce the brain's ability to orient itself properly in space [8]. Second, damage could occur centrally and affect the central nervous system's (CNS) integration of sensory information. A reduced ability to filter or weight incoming afferent sensory information would alter the CNS's ability to maintain balance equilibrium during locomotion or quiet stance [9, 10].

The consensus among concussion experts is that postural stability or balance issues resolve within 72 hours of initial injury [11]. However, using a visually driven postural response task with motion capture and force plates, abnormal postural responses to visual field motion have been observed up to 30 days after initial concussion injury [3]. This evidence supports that balance disturbances could extend past the 72-hour mark and suggest that current clinical balance tests used are not sensitive to long-term balance disturbances.

The most commonly used tests in concussion research and management are the modified Clinical Test of Sensory Organization and Balance (CTSIB) [12], Sensory Organization Test (SOT) [13], the Balance Error Scoring System (BESS) [6] and the Romberg Scale [14]. However, these tests have many limitations. Experts consider the CTSIB to be a lower standard of balance assessment [6]. The lower standard is due to the heavy weighting of somatosensory information with the use of a foam platform during the testing conditions. Furthermore, results are rated subjectively, thus inducing error into the measure. The SOT is the most commonly used in concussion research; however, the inability to induce medial-lateral perturbations in addition to anterior-posterior platform perturbations severely limits the functionality of the balance assessment. The BESS and the Romberg Scale examinations are excellent clinical sideline tests to ascertain balance disturbances in suspected concussion incidence [6, 15], however; due to an athlete's ability to overcome task-oriented goals along with the subjectivity of the assessments, the BESS and Romberg may not be sensitive enough to determine balance changes during recovery after the seventh day of concussion recovery [6]. Overall, there is a lack of sensitive balance measures to evaluate concussion recovery after the seventh day of injury. More research is necessary to ascertain the progression of balance recovery post-concussion. Furthermore, novel methods are needed to assess balance function and to ascertain the mechanism(s) responsible for balance dysfunction.

Among the three sensory systems, the visual and the vestibular system are directly linked [16]. The vestibular ocular reflex (VOR) allows the eyes to maintain a steady focused image in relation to head movement, referred to as gaze, as registered by the vestibular system [12, 16]. This complex relationship may provide researchers with a window into vestibular function during balance control that is more sensitive than overall gross motor control of the body as measured by standard clinical balance tests. To date, the role of the vestibular system in oculomotor control for stabilization and tracking post-concussion (PC) is absent in research literature.

The purpose of the current research was to measure the differences in oculomotor control between athletes post-concussion and athletes without concussion during an active balance control task. It was hypothesized that vestibular dysfunction post-concussion would present as reduced stabilization and oculomotor control during a visually driven dynamic balance task. The goal of this exploratory study was to provide evidence to support the use of gaze assessment in conjunction with balance assessment post-concussion and support the notion of the need to develop visually driven tests to evaluate post-concussion recovery.

Methods

Participants

Nine athletes with concussions (PC: seven female, two male, mean age 16 ± 3.03 years) and nine athletes with no concussion history (NC: six female, three male, mean age 24.3 ± 7.5 years) participated in the study. Participants were recruited from the Concussion Management Clinic (CMC), a service conducted by the Speech Language Pathology Program. Athletes with concussions were diagnosed with a concussion and referred to the clinic by their physician or athletic trainers. PC athletes were assessed by the CMC and the researchers within 48–72 hours post-injury. At this time, participants were asked if they would like to participate in the study. Participants were excluded if any of the following were observed by a medical doctor: abnormal behaviour (expressed by an extreme emotional state), excessive neurological symptoms (indication of a traumatic brain injury) or the inability to safely conduct the experiment due to major bodily injury such as lacerations, bone fractures or the like. All participants were assessed using the ImPACT test. The ImPACT test aids in determining if cognitive dysfunction is present post-injury. Cognitive dysfunction is considered present if one of the composite scores on the ImPACT test falls outside the range of normal score variation using the Reliable Change Index [17]. While the presence of a cognitive dysfunction as determined by the ImPACT test cannot diagnose a concussion alone, it aids in confirming clinical concussion judgements [17]. Each participant of the current study had at least one composite score that fell outside the range of normal score variation on the post-concussion ImPACT test, using the Reliable Change Index. A full description of the ImPACT test is reported in another publication [18]. In addition to the use of the ImPACT test to aid in determining the presence of a concussion, self-reported symptoms were also measured. Self-reported symptoms were graded on a scale of 0–6 and the total percentages of each symptom present in the participant pool were calculated (Table I). These percentages were used later in the data analysis.

Prior to data collection, all participants signed an informed consent approved by the institutional review board of the University. The study was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki.

Table I. Percentage of concussed participants self-reported symptoms on weeks 1 and 2.

Symptoms	Week 1 percentage	Week 2 percentage
Headache	73	30
Trouble Sleeping	55	10
Balance	*45*	*10*
Dizzy	*45*	*20*
Sleep Less	45	10
Drowsy	45	10
Slowed Down	45	20
Concentration	45	20
Remembering	45	10
Nausea	36	20
Fatigue	36	10
Sensitivity to Light	36	30
Irritability	36	10
Sensitivity to Noise	27	10
Nervousness	27	10
Vomiting	18	0
Foggy	18	10
Sadness	9	10
Emotional	9	10
Numbness	9	10
Visual Problems	9	10
Sleep More	0	10

Italic text indicates relevance symptomology related to balance, percentage calculated based upon the presence of the symptom, not the strength of the symptom. All symptoms were recorded using the ImPACT test self-reported symptoms 24 hours prior to actual testing date.

Procedure

Balance tests were performed using the Nintendo WiiFit® soccer heading game. The term soccer is used in place of the universal term football to accurately report the title of the videogame. The game uses the Wii Balance Board to measure centre of pressure (COP) and allows the participant to direct an on-screen avatar via lower body COP postural adjustments (Figure 1). Participants were awarded points by successfully intercepting and heading a soccer ball while dodging distraction objects (Figure 2).

The WiiFit was used to assess balance as it was recently adopted by the NCAA to assess balance recovery during a concussion episode in athletes [19]. Furthermore, WiiFit games (basic balance test and the soccer heading game) have been reported to relate to functional measures of health [20] and the balance board has been determined as a comparable measure of static COP [21, 22] and is currently used in the CMC as a rehabilitation and measurement tool. Although the video game has its measurement limitations (limited reliability and validity evidence for use in concussion assessment), it does represent a comprehensive balance activity involving directing centre of pressure in response to visual stimuli.

Instructions to all participants included fixating vision on the centre of the screen and adjusting posture via the lower body instead of the head during the game. Participants performed a practice trial followed by three scored experimental trials. Each trial lasted on average 3 minutes of continuous play with a 5 minute rest period between trials.

Eye movements during the soccer game were captured at 120 Hz using a monocular ASL Eye Tracking system (model H6, Applied Science Laboratories, Bedford, MA). The system captures the position of the left eye as well as

Figure 1. Full body experimental set-up: both feet are centred on the force plate sensors of the WiiFit platform.

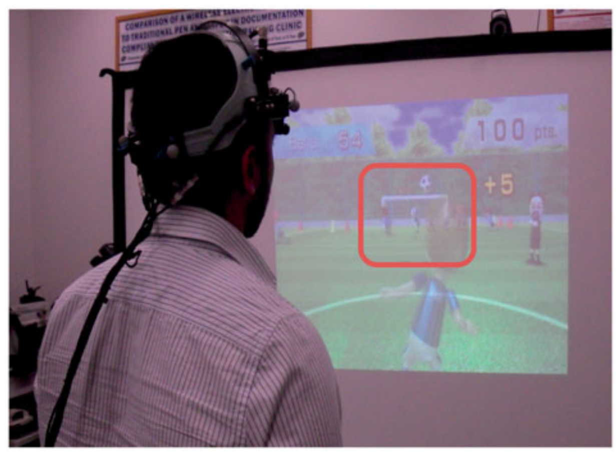

Figure 2. Experimental set-up: the participant wore a head mounted eye tracking system. In front, the Wii Soccer game was displayed. The participant stood on the Wii Balance Board to direct the Mii (avatar) to head soccer balls while dodging distracter items. The defined centre of screen for gaze analysis is indicated by the square on the screen.

a head-oriented view of the environment (scene-out). Calibration of eye position with respect to the scene camera involved a 9-point calibration matrix. Following calibration, the scene-out video included superimposed cross hairs denoting the position of the eye (gaze point of interest). This was recorded with Pinnacle software (30 Hz; Pinnacle Systems, Mountain View, CA) and exported for coding. The WiiFit® balance board and eye tracking system were calibrated for each participant prior to data collection.

Data reduction

Eye data was coded for point of interest (POI) using an in-house designed macro in Microsoft Excel (Microsoft, Redmond, WA). POIs included the centre, left and right of the screen (Figure 2). Gaze stabilization was measured using two variables: the percentage of time that gaze was fixed on the centre of the game screen (*Percentage Time on Centre*) and the number of gaze deviations (eye movements) made away from the centre of the screen during play (*Gaze Deviations*).

The Wii console calculated the Soccer Game Score based on correct interaction (heading of soccer ball) with the soccer balls. Single interactions rewarded a single point. Multipliers were given as the number of correct interactions continued unabated, rewarding up to 10 points per positive interaction. Contact with distracter objects (shoes and/or panda heads) reduced the overall score by minus three points per object. Overall score had a maximum of 600 points.

Statistical analysis

Measures were averaged for the three experimental trials for further analysis. Spearman Rho correlations were performed between the measures; Gaze Deviations, Percentage Time on Centre and Soccer Game Score with self-reported prevalence of balance and dizziness symptoms. A between-subjects ANOVA assessed the difference of group (NC and PC; independent variable) on Percentage Time on Centre, Gaze Deviations and Soccer Game Score (dependent variables). Pearson Product correlations between Percentage Time on Centre and Soccer Game Score were also performed.

Motor learning data sub-set

Due to the exploratory nature of this study, an additional experiment was conducted to investigate potential differences between NC and PC groups with repeated play of the WiiFit soccer heading game. It was hypothesized that the WiiFit soccer heading game would have a learning effect present in both NC and PC groups; however, the strength of the effect was unknown. Repeated measures ANOVA assessed differences in Soccer Game Scores over a multi-week learning period. Fourteen healthy asymptomatic individuals (six females, eight males, mean age 23.5 ± 2.56 years) participated in the NC group. NC evaluations occurred 1 week apart from one another (7 days) for 3 weeks, resulting in three data collection periods. Five PC individuals (five females, mean age $= 18.6 \pm 2.86$ years) participated in this data sub-set. PC athletes were a sub-set of the athletes involved in the main experiment of the study who returned for a second concussion assessment (7 days between measurements), thus resulting in two data collection periods. The lack of matching the number of weeks between PC and NC groups was due to attrition of the PC individuals between testing.

Results

PC participants self-reported dizziness and balance symptoms as 45% of total symptoms present in the 24 hours prior to testing (Table I). The percentage is the total prevalence of the symptom in the sample population, not the strength of the symptom. No significant correlations were observed between oculomotor behaviour and balance measures (Gaze Deviations, Percentage Time on Centre or Soccer Game Score) and prevalence of self-reported balance and dizzy symptoms.

Table II. Mean and standard deviation of dependent variables: Gaze Deviations; Percentage Time on Centre; and Soccer Game Score.

Observation	Group	Mean (SD)	*p* Value
Gaze Deviations	NC	24.1 (8.82)	<0.001*
	PC	46.5 (13.58)	
Percentage Time on Centre	NC	59.5 (25.5)	0.516
	PC	64.2 (25)	
Soccer Game Score	NC	120.78 (85.04)	0.344
	PC	88.56 (50.8)	

All *p* values are from between-subjects ANOVA comparing groups (NC and PC), *indicates significance at the 0.05 α-level.

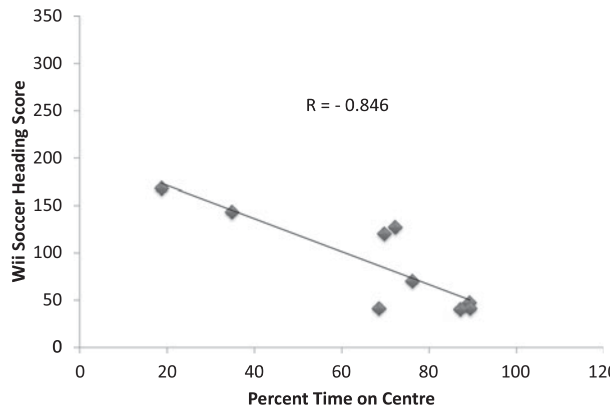

Figure 3. Athletes with concussion (PC) demonstrated a significant ($p = 0.004$) negative correlation between the time spent fixating the center of the screen (Percentage Time on Centre) and their overall soccer score (Wii Soccer Heading Score).

A significant main effect was observed for Gaze Deviations from centre between the participant groups ($F_{(1,18)} = 18.57$, $p < 0.001$, $\eta^2 = 0.522$). PC individuals had a significantly greater number of Gaze Deviations from centre when compared to NC individuals (95% CI $= -37.80$–102.24). No significant between-group differences were observed for Percentage Time on Centre ($F_{(1,16)} = 0.441$, $p = 0.516$) or Soccer Game Score ($F_{(1,17)} = 0.952$, $p = 0.344$, $\eta^2 = 0.056$) (Table II).

A significant negative correlation was observed between Percentage Time on Centre and Soccer Game Score in PC individuals ($r = -0.846$, $p = 0.004$). Interestingly, a significant positive correlation was observed for NC between Percentage Time on Centre and Soccer Game Score ($r = 0.792$, $p = 0.011$). Therefore, an inverse relationship was observed between PC and NC groups. PC individuals decreased Soccer Game Score as the Percentage Time on Centre increased (Figure 3), while NC individuals increased Soccer Game Score as the Percentage Time on Centre increased (Figure 4).

Motor learning data sub-set

The results from the additional motor learning data sub-set revealed that PC participants did not improve game play across a 2-week period (Table III). In contrast, significant differences in Soccer Game Scores between repeated visits in NC participants were observed (Table III).

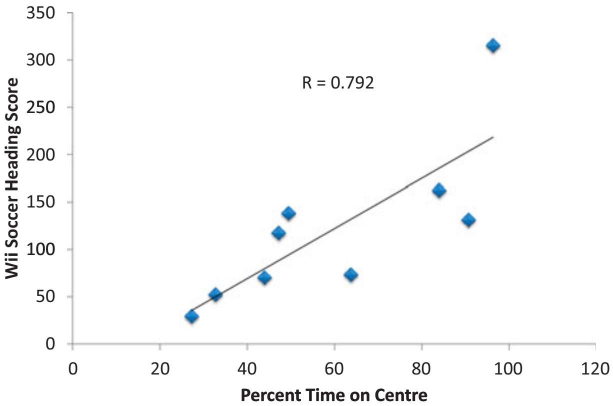

Figure 4. Athletes without concussion (NC) demonstrated a significant ($p = 0.011$) positive correlation between the time spent fixating the centre of the screen (Percentage Time on Centre) and their overall soccer score (Wii Soccer Heading Score).

Table III. Means and standard deviations of the Soccer Game Scores for NC and PC at Week 1, Week 2, and Week 3, respectively.

Group	Week 1	Week 2	Week 3	*p* value
NC	150.31 (98.39)	208.02 (103.6)	249.24 (99.31)	<0.001*
PC	93.00 (61.41)	109.20 (73.67)	N/A	0.061

*$p < 0.001$ for multivariate across time period (week 1, week 2, week 3).

Discussion

The purpose of the current study was to measure differences in oculomotor control between athletes post-concussion (PC) and those without concussion (NC) during an active balance control task. Using the Nintendo WiiFit soccer heading game, PC and NC athletes actively directed their COP in response to visual stimuli. This paradigm allowed gaze characteristics to be measured simultaneously with balance score.

The results of the current study indicate that PC athletes have significantly greater eye movements when performing a visually driven balance assessment in comparison to NC athletes. Furthermore, PC athletes demonstrated a significant linear relationship where an increase in the time spent fixating on the centre of the screen resulted in a decrease in game score (Figure 3), while NC athletes demonstrated the opposite relationship (Figure 4). Interestingly, this relationship occurred while there were no significant differences in mean group Soccer Game Score or mean Percentage Time on Centre (gaze) between PC and NC athletes (Table II).

The vestibular system is highly sensitive to acceleration of the head in linear or angular directions. When the head is displaced during motion yet the visual point is fixed, the Vestibular Ocular Reflex (VOR) allows the visual image to remain stable during motion [8, 12, 16]. As afferent information from the vestibular system is given to the ocular system, the ocular musculature proceeds to make fine adjustments to maintain a focused image [23, 24]. This reflex was demonstrated by the healthy NC athletes who were able to direct their COP in response to the visual stimuli while maintaining a fixed position of reference in the centre of the screen with minimal eye deviations from centre. In contrast, PC athletes demonstrated a significant negative correlation with Percentage Time on Centre and Soccer Game Score. Furthermore, PC athletes recorded nearly twice as many eye deviations from the centre of the screen when compared to NC athletes (Table II). These observations suggest a disruption in the normal VOR response during this activity. A reduced ability to stabilize a fixed eye position could be directly related to two major problems [16, 25, 26]. First, if vestibular afferent information was damaged then one would expect a decrease in the ability to fixate during motion via the VOR. Second, if an afferent signal weighting dysfunction was present, then sensory conflict could occur and the ability to sort the correct afferent cues could be reduced.

Disruption to vestibular afferent flow could be caused by a number of issues: peripheral damage of the vestibular system, otoliths that are present in the semicircular canals and a labyrinth concussion [8]. Peripheral damage to the vestibular organ could result in physical abnormalities in the ability of the hair cells within the semicircular canals to register angular movement. Without MRI scans to confirm peripheral vestibular damage, the current study cannot confirm or deny the presence of peripheral damage, however; peripheral damage is unlikely due to the absence of specific symptoms in the study's sample. First, if otoliths were present within the semicircular canals, vertigo would be persistent until the otoliths were absorbed back into the canal system [8]. In the current study, dizziness resolved following the first testing session in a majority of PC athletes (Table III), therefore limiting the applicability of this possible explanation. A labyrinth concussion is a concussion episode where the site of injury is located in or around the inner ear. A typical sign of a labyrinth concussion is tinnitus or ringing in the ears that continues for many days after the concussion [8]. These PC athletes did not report the presence of tinnitus, thus this type of damage was unlikely to have occurred in this population. Additionally, lateral or medial concussions are rare in contact and non-contact sports [27, 28]. A lateral or medial concussion could result in direct vestibular organ damage when compared to other anterior or posterior cranial collisions.

Efferent weighting dysfunction or sensory conflict theory has been determined to be a viable option to explain balance dysfunction and dizziness [29, 30]. The ability to use or process vestibular information in the cortical areas of the brain or the motor cortex along with other afferent signals from the visual and somatosensory system may be affected in athletes with concussion [29, 30]. If the afferent flow of information regarding postural position and body orientation is unable to be processed effectively or efficiently, balance dysfunction can occur. The rationale for this statement is based on the fact that a concussion potentially impacts the entire brain given the metabolic cascade that characterizes a concussion [31–33]. The cellular and vascular changes that occur following a concussion results in ionic shifts, abnormal energy demands, diminished cerebral blood flow and impaired neurotransmission [31]. Thus, one hypothesis for the observed balance dysfunction is that the sensory and motor cortices may be affected following a sport-related concussion. This is due to a high percentage of concussion injuries that result from an impact to the front and top of the skull, thus effecting anterior and posterior brain areas [27, 28]. Secondly, at the macroscopic level, phenomena such as lingering oedema [34] may cause abnormal pressure on one or more of the basal ganglia loops [35, 36]. Albeit this observation is highly speculative, a potential disruption of the direct and indirect pathways of the basal ganglia could exist during lingering brain swelling.

The direct and indirect pathways of the basal ganglia loops serve to either excite or inhibit cortical brain structures, including pre-motor, motor and visual areas [35, 36]. If lingering brain swelling is present from the concussion injury, the ability of the basal ganglia loops to further excite or inhibit cortical brain structures involved in the modulation of postural control could be diminished. Both the motor cortex and basal ganglia loops (including the hypothalamus) have been demonstrated as areas of the brain that sort afferent signals and properly weight efferent responses [24]. If afferent flow of sensory information is not interrupted, then a potential source of dysfunction could be due to efferent effecter signals that are not distributed, weighted or sent properly. The result of such efferent signal disruptions would be insufficient or inappropriate muscular activity when maintaining centre of mass (COM) control [24].

An interesting finding of the current study was the increased eye deviations in PC athletes when compared to NC athletes. This observation could be indicative of how the vestibular system is weighted during sensory integration for postural control. For example, if vestibular information was under-weighted, then the ability to register angular or linear acceleration would be diminished and could result in reduced oculomotor control [24]. If vestibular information was over-weighted, then additional information from the visual system or the somatosensory system would have little influence on determining body location in space. The result of greater vestibular weight could be over-correction in ocuolomotor control [24]. In both of these weighing scenarios, greater eye deviations from the centre of the screen would be indicative of improper corrections for head movement.

While the theory of under- and over-weighting vestibular cues during motion has not been thoroughly examined in humans, animal studies have been conducted examining sensory information weighting and self-motion perception. Fetsch et al. [37] used humans and animals to determine the optimal threshold levels for re-weighting of visual and vestibular information during a self-motion task. They determined that, if vestibular afferent information is under-weighted, then increased visual cues are used to determine self-perception of motion [37]. This suggests that reduced reliance on angular or linear acceleration afferent information to provide accurate personal positional data affects the body's ability to modulate postural control. Lastly, Fetsch et al. [37] determined that vestibular over-weighting would result in an imbalance in the certainty of causation between the visual and vestibular systems. This could lead to increased eye scanning due to the VOR, receiving additionally unusable or interpretable information. Therefore, the data from the current study presents an avenue of research that may lead to the development of novel approaches for evaluating central sensory integration post-concussion.

In addition to between-group comparisons, correlations were performed within the PC groups. Self-reported symptoms of balance and dizziness were compared with the measures of Gaze Deviations, Percentage Time on Centre, and Soccer Game Score to determine if poor performance on these measures were related to balance dysfunction symptoms. No significant correlations were found; however; this could have been due to a lack of power for the subjective nature of the self-report. As the sample size increases with future research, potential relationships could develop.

The results from the motor learning data sub-set revealed that NC individuals had a strong learning effect on the game over repeated play, while PC individuals did not. NC individuals improved on the soccer game each week of testing over the 3-week period (Table III). Conversely, PC athletes did not improve on the soccer game over a 2-week testing period (Table III). One potential explanation for these results is that the PC group continued to experience disruption to balance control resulting in the absence of improvement on the balance task (the soccer game). Balance dysfunction is reported to resolve 72 hours following initial injury [6]; however; the data suggest a residual dysfunction in the balance control system up to 2 weeks post-injury. A potential reason for this discrepancy is that the 72-hour observation occurs when using clinical tests such as the Romberg Test and the Balance Error Scoring Test (BESS) [6, 29]. It is possible that athletes are able to overcome and reach the ceiling on these assessments shortly after a concussion episode, thus leaving clinicians with the inability to accurately measure balance dysfunction. This study examined PC athletes for a full 7 days between testing sessions and no improvement was determined on the soccer game. These lower scores remained while balance-associated symptoms decreased from 45% to 10% of participants between the two sessions. These results suggest that balance dysfunction could be present well after the pre-determined 72-hour initial assessment (Table I). Thus, this research supports the need to test PC athletes with functional balance assessments to examine active postural control.

Several limitations of the current study should be addressed in future research. First, both PC and NC athlete groups were comprised mainly of females. Therefore, a gender bias could be present when generalizing the findings to athletic populations. Secondly, PC athletes were referred to the clinic for examination and testing, but did not all come within the same time period for their initial evaluation (ranging from 24–72 hours post-injury). Thus, some athletes could have been further into the recovery process on the first date of testing when compared to others. Third, some athletes could have increased performance on the soccer game due to prior experience with the assessment or a more sport-specific movement. Fourth, the NC individuals that participated in the learning effect of the soccer heading game were not all athletes. Thus, a difference in NC athletes learning effect needs to be examined further. Fifth and lastly, the small sample size of this study limits the generalizability of the study results.

Conclusions

Measuring oculomotor control, with an eye tracking system, during an active balance task, differences were observed between athletes with a concussion and athletes without concussion that point to a number of interesting implications for vestibular or sensory integration dysfunction post-concussion. This study suggests a link between concussion injuries and oculomotor control during postural control that now requires further research to support the hypothesis of the authors that cortical brain sensory integration is the main contributor to the oculomotor control deficits observed.

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Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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