Effect of Repetitive Sub-concussive Head Impacts on Ocular Near Point of Convergence

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Introduction

Concussion management and awareness have improved but the potential danger of sub-concussive head impact is often neglected. Sub-concussion occurs from head impact that is considered mild (i.e., inducing a linear head acceleration below 29g) and has no clinical signs of concussion [5]. However, emerging evidence suggests sub-concussive head impacts may result in subtle neurological deficits [1, 17, 39]. Given the concern regarding Traumatic Brain Injury (TBI), understanding the effects of sub-concussive head insult may be just as critical, considering that mild head impact may occur far more frequently and repetitively, consistent with current emphasis on early detection of concussion and its treatment [31].

Current findings on the effects of sub-concussive head impact are sparse and use measures that may not be sensitive enough to characterize the relationship between sub-concussive neuronal insult and behavioral response. For example, Kaminski et al. [24] demonstrated no association of repetitive sub-concussive impact from soccer heading on neurocognitive assessments or balance error scoring system (BESS) [32]. However, a recent study which used a tablet device intending to measure eye movement, reported that sub-concussive head impacts induced by regular boxing sparring significantly decreased voluntary control of eye movement [38], suggesting eye movement metrics may be highly sensitive to deficits following a mild head impact. Dysfunctional eye movement has persisted for as long as 140 days after concussion, illustrated by an inverse correlation between oculomotor function and severity of post-concussion symptoms [20]. However, the limited knowledge base regarding the consequences of sub-concussive head impacts on the oculomotor system may hinder appropriate discrimination of dysfunction between concussive and sub-concussive head impacts. The oculomotor system orchestrates accommodation and vergence, and their concomitant adjustments enable individuals to visualize an object at various distances and directions [23]. Accommodation changes the shape of the lens by the contraction of the ciliary body, which enables accurate focus on an object, whereas vergence...
refers to complex movement of both eyes, which is important for binocular vision. For example, to view an object moving back and forth directly in front of the left eye, only the right eye has to move. More precisely, convergence involves adduction of the eyes by contracting the medial rectus muscles, which are controlled by cranial nerve III (oculomotor). The near point of convergence (NPC) measures the closest point to which one can maintain convergence while focusing on an object before diplopia occurs [22]. Similarly, convergence insufficiency, defined as a receded NPC, is a binocular coordination problem where simultaneous inward eye rotation is weakened. Ultimately, it can result in blurred vision, diplopia, problems reading and headache [12]. Poor oculomotor function has been reported as one of the most robust discriminators of the identification of mTBI [6,9,19]. The King-Devick test is designed to measure the performance of sagittal eye movements [34] and has been shown to be a reliable tool to screen concussed athletes. Emerging evidence indicates that a concussive head blow often mitigates sagittal eye movements assessed by the King-Devick test [13,14,25]. Furthermore, Capo-Aponte et al. reported that soldiers with blast-induced mTBIs presented 3-fold increase in NPC distance during subacute phase, 15–45 post-mTBI, compared to non-mTBI controls, suggesting that brain injury might blunt medial rectus muscle contractility [7]. These results were corroborated in the sport-related concussion cohort, such that NPC was measured in 64 concussed athletes in approximately 5.5 ± 4.0 days post-concussion and revealed 3-fold elevation in NPC score compared to 78 healthy controls [33]. While studies suggest that sub-concussive head impact causes physiological [11,29,37] and neuromechanical changes [17], effects of sub-concussive head impact on the oculomotor system, particularly NPC, have not been investigated previously.

To investigate our hypothesis that sub-concussive head impact may result in a decline in NPC, we incorporated a safe and reproducible sub-concussive intervention using an established soccer heading model [17,21], which induces mild head acceleration. Our result indicates that sub-concussive head impacts from repetitive soccer heading compromised ocular NPC up to a minimum of 24h.

Material and Methods

Participants

20 healthy adults volunteered to participate in the study. The soccer heading group consisted of 8 males and 2 females with average age of 20.7 ± 1.2 years old, and the control group consisted of 7 males and 3 females with average age of 18.9 ± 1.1 years old. Demographic information is provided in Table 1. Demographic data consist of gender, age, height, and mass, as well as self-reported years of soccer experience and number of previous mTBIs. Inclusion criteria included being a current soccer team member with at least 5 years of heading experience to ensure 1) participants possessed a basic frontal heading skill and 2) no fear of heading a soccer ball. Exclusion criteria included any history of head, neck or face injury in the 6 months prior to testing, and any neurological or ocular disorders. Corrective eye-wear (i.e., glasses) was not permitted due to safety purpose to perform soccer heading and accurate convergence measurement; instead contact lenses were allowed (contact lenses users: heading, n = 2; control, n = 3). Subjects were told to refrain from sports activities and substances that could affect their nervous systems (e.g., stimulants and/or depressants) while measuring NPC, 3 days prior to and 24-h post-testing period. Subjects also self-reported no head impact or injuries during the testing period. An Institutional Review Board approved the procedures and all subjects signed informed consent and Health Insurance Portability and Accountability Act (HIPAA) forms. We have read and understood the International Journal of Sports Medicine ethical standards document [18].

Soccer heading model

A standardized and reliable soccer heading protocol was used to induce mild head impacts [17,21]. A triaxial accelerometer (Gforce Tracker, Gforcetracker Inc., Markham, ON) was positioned directly below the external occipital protuberance (inion) and secured with pre-wrap and tape to measure linear head acceleration (g-force; Table 1). A JUGS soccer machine (JPS Sports, Tualatin, Oregon) was used to simulate a soccer throw-in with standardized ball speed across subjects. The size 5 soccer ball was inflated to 8 psi and launched from the JUGS machine at speeds of 11.2 m/s. This ball speed is similar to when soccer players make a long throw-in from the sideline to mid-field [26]. Participants stood approximately 12 m away from the machine to perform the headers. Along with a tester’s demonstration, participants were instructed to head the ball in the air and pass to a tester standing approximately 5 m in front of the participants. In the soccer heading group, subjects performed 10 standing headers with one minute interval between each header (Fig. 1); whereas, the control group remained standing with no activity for 10 min.

Near point of convergence assessment

An accommodative ruler (Fig. 2a; Bernell Incorp. Mishawaka, IN) was used to assess NPC. The near point of convergence measures the closest point to which one can maintain convergence while focusing on an object before diplopia occurs [22]. The participant was seated with the head in anatomical position. Participants wore contact lenses if needed. The accommodative ruler was placed to rest on the participant’s upper lip, and an accommodative target (reduced-size Snellen chart) was adjusted horizontally to participant’s eye level. Although letter target font size does not influence NPC score [35], participants were always instructed to maintain their gaze on a 14-point font size letter “T”. The target was moved down the length of the ruler, towards the participant’s eyes, at a rate of approximately 1–2 cm/s (Fig. 2b). The near point of convergence measurement was taken when eye mal-alignment was observed by the tester or when the participant verbally signaled once he/she experienced

| Table 1 Heading vs. Control — Group Characteristics. |
|--------------------------|--------------------------|--------------------------|
|                          | Control (n = 10)          | Heading (n = 10)          |
| Gender                   | M 3 F                     | M 2 F                     |
| Age                      | 18.9 ± 1.1                | 20.7 ± 1.16               |
| Height (cm)              | 175.8 ± 5.3               | 178.3 ± 9.18              |
| Mass (kg)                | 74.12 ± 5.65              | 74.57 ± 9.47              |
| # of previous mTBIs      | 0.5 ± 0.97                | 0.5 ± 0.71                |
| Years of soccer experience | 11.3 ± 4.37              | 14.9 ± 2.18               |
| Head Acceleration (g-force) |                           |                           |
| Avg. (g)                 | 14.49 ± 5.40              |
| Max. (g)                 | 23.14                     |
| Min. (g)                 | 9.9                       |

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diplopia and no longer perceived a single target. Upon the verbal signal, the examiner stopped moving the target and recorded the distance between the participant and object [40]. Assessment was repeated twice and average NPC scores were used for statistical analyses. The test took approximately one minute to complete. The inter-rater reliability of this test was assessed through a pilot study in our laboratory where 2 testers performed convergence assessments in 8 young, healthy, active subjects, and resulted in a strong association between 2 testers (Pearson r = 0.90, P < 0.01). Additionally, NPC measurement was repeated twice for both heading and control groups at each time point, and intra-rater reliability for those time points resulted in high to very high association between trials (pre, r = 0.88; 0-h post, r = 0.95; 24-h post, r = 0.94; P < 0.001 for all time points).

Data analysis
Student’s independent t-tests were used to compare subjects’ characteristics (age, mass, height, number of previous mTBIs, and years of heading experience) in heading and control groups. Normality of the baseline data for both groups was assessed with the Shapiro-Wilk test (P = 0.081), and ensured that the baseline data is normally distributed. A 2-way repeated measures ANOVA was used to compare outcome measurements on groups (heading vs. control) and time (Pre vs. 0h post- vs. 24h post-heading). If a significant interaction was present, then a Student-Newman-Keul’s (SNK) multiple comparison test was used to determine where effects of mild head impact occurred, and the effect size (Partial Eta Squared) was reported. Due to significant demographic difference between groups (Table 1), a conservative approach using multivariate analysis of covariance (MANCOVA) was applied to determine group differences in NPC measurement, with age and years of heading experience as covariates to count for any potential attribution. If a significant difference between groups was found, the effect size (Partial Eta Squared) was reported. As needed, follow-up one-way repeated measure ANOVAs were used to assess main effect within each group over time. All the data were analyzed using SPSS Statistics Version 20, and the level of statistical significance was set to P < 0.05. Data are presented as means ± SD.

Results

Demographic and head acceleration
Demographic and head acceleration data are summarized in Table 1. Student’s independent t-test indicated that mean age, t(18) = 3.56; P = 0.002, and years of heading experience, t(18) = 2.33; P = 0.036, in the heading group were significantly higher than those of the control group. Average head acceleration (g-force) in the heading group was 14.49±5.40g, and the range was from 9.9 to 23.14g. This document was downloaded for personal use only. Unauthorized distribution is strictly prohibited.
Near point of convergence

Mild head impacts led to an increased distance of NPC, as shown in \( \text{** Fig. 3a.} \) There was a significant main effect for Group, with a small to medium effect size, \( F(1,18) = 8.68; P = 0.009, \eta^2_p = 0.328 \) and Group X Time interaction for NPC with a medium effect size, \( F(2,36) = 5.93; P = 0.006, \eta^2_p = 0.407 \). There was no difference in NPC scores between groups at pre-test, \( t(18) = 0.613; P = 0.547 \). One-way repeated measures ANOVAs indicated a significant difference over time for the heading group, \( F(2,27) = 6.24; P = 0.006 \), but not for the control group, \( F(2,27) = 0.125; P = 0.883 \). Furthermore, the heading group showed that NPC scores for 0-h post-heading (10.50 ± 1.46 cm; \( P = 0.005 \)) and 24-h post-heading (11.45 ± 2.40 cm; \( P = 0.002 \)) were significantly worse compared to the pre-test (8.18 ± 2.45 cm; \( \text{** Fig. 3a, b.} \). There were no differences for the control group in NPC between pre-test (7.85 ± 1.96 cm), 0-h post-heading (7.45 ± 1.86 cm) and 24-h post-heading (7.80 ± 2.03 cm; \( \text{** Fig. 3a, c.} \. A MANCOVA analysis, with age and years of heading experience as covariates, revealed a significant group main effect with medium effect size, \( F(3,14) = 3.87; P = 0.033, \eta^2_p = 0.453 \). Between-group differences in NPC were found at 0-h post (\( P = 0.007 \)) and 24-h post-heading (\( P = 0.015 \)), suggesting that group differences in NPC were predominately attributed to head impacts, rather than age or years of heading experience (\( \text{** Fig. 3a.} \).

Discussion

Although extensive research has been conducted on concussion assessments in relation to sideline diagnosis and injury follow-up, the consequence of sub-concussive head impacts on nervous system function remains largely unknown. Thus, we incorporated a controlled mild head impact to assess the effects on ocular NPC. The prominent findings are that repetitive sub-concussive head impacts: 1) increased NPC distance at 0-h post-heading up to 24-h; and 2) mean NPC distances in the heading group at 0-h and 24-h post-heading were significantly reduced compared to those in the control group. The control group showed no changes in NPC distance over the same time points. This is the first report, to our knowledge, indicating that repetitive head impact with mild head acceleration negatively affected ocular NPC up to 24h.

Average NPC scores for healthy college aged population ranges from 6 to 8 cm [2, 16, 35, 40]. The present study demonstrated similar pre-test values in the heading (8.18 ± 2.45 cm) and control (7.85 ± 1.96 cm) groups. Within the heading group, compared to pre-test values, 9 of 10 heading subjects at 0-h post- and 8 of 10 heading subjects at 24-h post-heading increased NPC distance by at least 0.75 and 2 cm, respectively (\( \text{** Fig. 3b.} \). When NPC scores were compared between groups at each time point, repetitive mild head impacts increased NPC score by 3 cm at 0-h post-heading and by 3.65 cm at 24-h post-heading compared to those respective time points of the control group (\( \text{** Fig. 3a).} \)

Comparatively, Mucha et al. [33] assessed NPC in athletes (mean age 13.9 years old) with approximately 5.5 days post-concussion and found that the mean NPC score in concussed group was 4 cm greater than that of the control group.

It is well established that convergence insufficiency is a hallmark of severe TBI [6, 9, 10]; furthermore, recent studies reported that even mild head trauma, such as patients with blast-induced mTBI [7] and athletes with concussion [33], exhibited significantly worse NPC scores compared to controls. In the current study, average head acceleration induced by soccer ball heading was 14.5g. These impacts are considered sub-concussive compared to typical concussive head acceleration of 102.5g (ranging from 29.3 to 205.3g) [5]. Although comparison of NPC scores...
from studies using different levels of head impact severity is challenging, our experimental evidence suggests that NPC may be affected by even a low magnitude of head impact.

The mechanisms of visual tracking and convergence require orchestration of multiple sensory inputs, as well as one’s own motor efforts [28], meaning that cognitive processes such as sustenance of attention, spatiotemporal memory and expectation play important factors [4, 8]. Using diffusion tensor imaging to detect microstructural changes in white matter and its severity, Lipton et al. illustrated that diffuse axonal injury was observed in the dorsolateral prefrontal cortex, often associated with visuospatial function [36], in a very mild form of TBI patients within 2–14 days after trauma incidence [27]. Moreover, Maruta et al. [30] tested continuous visual tracking eye movements in 17 patients with chronic post-concussive syndrome using video-oculography and found a correlation between reduced performance and the degree of diffuse axonal injury in the right anterior corona radiata and the left superior cerebellar peduncle, which are important regions for sustenance of attention and spatial processing. Additionally, a recent animal study investigating optic nerve integrity following repetitive mTBI reported that severity of axonal injury and optic nerve degeneration are positively associated with head impact frequency and magnitude [41]. Collectively, such finding suggests that the visuomotor system may provide a sensitive measure of the functional consequences in response to head insults. While clinical significance of receded near point of convergence remains unclear, our study is in line with concussion and mTBI studies suggesting that the oculomotor system, particularly NPC, may be vulnerable to low magnitude head impact.

Future Directions

Athletes in many sports including American football and soccer incur hundreds to thousands of sub-concussive blows annually. Sub-concussive head impacts often do not elicit readily measurable acute signs and symptoms [32], with athletes continuing with sports participation and daily life activities without any expectation of serious consequences. Studies suggest that although college football players sustain an average of 1,100 sub-concussive head impacts during a football season, there is no clinically meaningful changes from preseason to postseason on neurologic functions [15]. Conversely, growing evidence indicates that chronic exposure to repetitive head blows can lead to long-term neurological alterations such as axonal injury, blood-brain barrier disruption, and neuroinflammation [3]. It is therefore important for future investigations in the area of sub-concussion to evaluate the extent to which the brain can endure regular mild head impacts without serious consequence and to identify the differences in oculomotor response from one another. Our study demonstrates that there was variation in individual NPC response to the head impacts, although this variation was not statistically significant (Fig. 3b). Individual response to concussion illustrates that some subjects sustained a concussion with a linear head acceleration as low as 29.3g, while others were diagnosed with concussion at levels of 205.3g [5]. Future longitudinal studies may investigate whether NPC can detect a participant’s susceptibility to concussions. It remains an open question as to whether there is an upper limit on what is considered a “safe” level of head impact.

Limitations

Increased NPC scores were persistent up to 24h post head impact. However, our repeated measures design with 3 time points was not able to demonstrate whether and when increased NPC returns to the pre-heading level (baseline). Future study is warranted to identify if and when NPC scores return to pre-heading value (i.e., 48 and 72h). In addition, the reduced-sized Snellen eye chart contains various sizes of letters. Although participants were instructed to focus on a single 14-point font letter, surrounding letters may disturb attentional processes. Future studies will use a single dot target, rather than Snellen eye chart to reduce a chance of dispersed attention while measuring NPC. Despite the difference in mean age and years of heading experience between groups, MANCOVA analysis ensured that the increase in NPC score between groups at 0-h post- and 24-h post-heading was attributed to mild-head impact, rather than age and years of heading experience. Lastly, it is important to note that there was no intention to make claims regarding the effects of heading in soccer; instead, we incorporated the laboratory soccer heading as a means to apply a safe and reliable head impact. In turn, with more studies, NPC has the potential to establish a threshold for concussion diagnosis and players’ safety.

Conclusion

Average linear head acceleration in our soccer heading intervention was 14.5g, which is considered a very mild head impact compared to concussive head impact. Here we provide experimental evidence for the first time, to our knowledge, that the oculomotor system may be impaired from repetitive sub-concussive head impacts up to a minimum of 24h post-heading. The NPC may serve as a potential diagnostic tool to aid clinicians identifying dysfunction from concussive and sub-concussive head impacts. Further research to determine the clinical significance of changes in NPC is warranted.

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Conflict of interest: The authors have no conflict of interest to declare.

References
