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Screening for lifetime concussion in athletes: Importance of oculomotor measures

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Abstract

Hypothesis/objective: The purpose of the present study was to determine the utility of oculomotor-based evaluation protocols in screening for lifetime concussion incidence in elite hockey players.

Methods: Forty-two Division I collegiate male and female hockey players were evaluated using the guidelines of an overall oculomotor-based diagnostic clinical test protocol for the mTBI population. The sensitivity of the collected measures to lifetime concussion was then compared with the corresponding sensitivity of measures of neuropsychological functioning (ImPACT) often used with athletes for acute concussion diagnosis.

Results: This model showed that a hockey player with a Near Point of Fixation Disparity (NPFD) equal to or greater than 15 cm, Visagraph comprehension rate less than 85% and the total score on part A of an ADHD questionnaire equal to or greater than 11 was on average 10.72-times more likely to have previously suffered a concussion than an athlete with lower values on the NPFD and ADHD questionnaire and a higher comprehension rate on the Visagraph. None of the IMPACT baseline assessment measures were significantly predictive of the individual's concussion history.

Conclusion: The study provides a relatively sensitive screening tool to assess the probability of previous concussion(s) in an athlete. This model may allow athletic personnel to address in a timely manner the risks associated with repeat concussions and to develop individualized concussion management protocols.

Keywords

Concussion, hockey, ImPACT, NPFD, oculomotor measures, Visagraph

History

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Introduction

According to the Centers for Disease Control and Prevention (CDC), between 1.6–3.8 million sports-related concussions occur annually in the US [1] and account for 5–9% of all sports-related injuries [2, 3]. This figure may be substantially under-estimated as several studies recently reported that the true incidence of concussion is likely to be higher because many athletes fail to report concussions [4–6].

A concussion is defined as a traumatically-induced transient disturbance of brain function caused by a complex pathophysiological process. Concussions have also been referred to as mild traumatic brain injuries (mTBI) characterized by a 'neurometabolic cascade', a cellular process accompanied by a disruption of ionic balance and normal metabolism, which creates increased energy demands in the presence of decreased cerebral blood flow and ongoing mitochondrial dysfunction [7–9]. Until normal brain cellular function is restored, animal and human studies suggest increased post-concussive vulnerability, showing that a repeat brain injury before complete recovery aggravates cellular metabolic changes and results in more significant cognitive deficits [7, 9–12].

Experimental evidence further suggests the concussed brain is less responsive to physiological neural activation [8, 13]. Thus, excessive cognitive or physical activity before complete recovery may result in prolonged dysfunction. Most studies report that 80–90% of athletes have symptom resolution by 7 days following their injury [14–18], although symptom resolution may not always indicate a complete cognitive recovery, as persistent deficits may be present on neuropsychological (NP) testing [17, 19].

Even if return-to-play (RTP) is cleared in the absence of physical, cognitive, neurological and affective symptoms, the history of a previous concussion increases the likelihood of another concussion by 2–5.8 times [20–22]. There is, thus, an increasing concern that brain impact exposure and recurrent concussions contribute to long-term neurological sequelae including chronic traumatic encephalopathy (CTE) and chronic neurocognitive impairment (CNI) [23]. For example, Guskiewicz et al. [24] found that former athletes who suffered multiple concussions had a 5-fold prevalence of mild cognitive impairment (MCI) (a condition that converts at a rate of 10–20% annually into dementia) compared with retired athletes without a history of concussion. Moreover, de Beaumont et al. [25] reported significant differences among former athletes who had sustained a sports concussion

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30 years prior to testing and healthy former athletes on neuropsychological tests of episodic memory and response inhibition; event-related potentials (P3a/P3b components), cortical silent period (CSP) and movement velocity. The researchers concluded that the results provided evidence for the chronicity of cognitive and motor system deficits consecutive to sports concussion.

Such cognitive and motor changes can occur years after a symptom-free interval and CNI symptoms and behaviours can be demonstrated by NP testing. While some NP studies have identified an association between prior concussions and chronic cognitive dysfunction [26–28], others, however, have found no association [29, 30].

This disparity in the literature has prompted researchers to question the sensitivity of neurocognitive test batteries used to evaluate any long-term subtle changes in cognitive function following multiple concussions. For example, Bruce and Echemendia [29] found that self-reported concussion history was not associated with performance on traditional and computerized neuropsychological tests in a large collegiate sample of athletes from a variety of sports. Their findings were in line with previous reports of other investigators who did not find any association between self-reported concussion history and computerized neuropsychological assessment such as the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), a widely used computerized neurocognitive assessment in North America [30–32].

In view of apparent insensitivity of traditional and computerized neuropsychological tests to the potentially deleterious effects of repeated concussion, further research is, thus, warranted to develop scientifically valid screening protocols for lifetime concussion incidence, which would assist in formulation of better concussion management protocols and return-to-play decisions.

One of the promising directions in screening for the history of previous concussions in athletes has been suggested by the extant research on oculomotor deficits associated with mTBI that persist beyond the acute phase of cerebral injury. In their review of current literature on the topic of acquired brain injury and sensorimotor dysfunction, Ciuffreda and Kapoor [33] reported that individuals with mTBI may present a constellation of visual symptoms that may include oculomotor and accommodative dysfunctions, binocular vision deficits, visual field loss/reduced sensitivity, visual memory deficits, visual attentional problems, vestibular impairment, spatial localization errors, perceptual deficits, visual information processing problems and visuomotor co-ordination impairment.

In another study, Ciuffreda et al. [34] determined the frequency of occurrence of oculomotor dysfunctions including vergence, accommodation and version in 160 individuals with mTBI between 8–91 years of age. The researchers reported that vergence system abnormalities were the most common dysfunction, with 56.3% of the sample showing one or more vergence-related abnormalities. While convergence insufficiency (CI) was the main vergence dysfunction (42.5%), other vergence deficits also found with high frequency included binocular instability, convergence excess, basic exo and divergence insufficiency. In addition, 51.3% of the sample manifested one or more versional dysfunctions, with saccadic deficits (e.g. saccadic dysmetria) being the most common anomaly. Among those who were below 40 years of age (51 out of the 160 subjects), 41.1% exhibited an accommodative dysfunction, with accommodative insufficiency (AI) being the most common problem.

These results are similar to the findings of retrospective studies by Goodrich et al. [35] and Brahm et al. [36], who reported a very high frequency of civilian and military mTBI patients manifesting oculomotor problems (50–90%), with the most common symptom related to reading speed and comprehension (50–90%). Fortunately most of the above oculomotor problems can be remediated with existing optical devices and visual therapeutic techniques, which has been found to improve mTBI rehabilitation outcomes [37]. By extension, timely identification and management of concussion-related visuomotor dysfunction in athletes may improve their risk and severity of subsequent concussions as well as their recovery prognosis.

The current study followed the guidelines of an overall oculomotor-based diagnostic clinical test protocol developed for the mTBI population by Ciuffreda et al. [38] to evaluate 42 Division I collegiate male and female hockey players. This protocol broadly targets such oculomotor parameters as vergence (e.g. near point convergence, vergence facility, phoria, fixation disparity and stereoacuity), accommodation (e.g. accommodative amplitude and facility) and version (e.g. fixational stability, saccadic accuracy and pursuit accuracy), with a particular emphasis on vergence. Thiagarajan et al. [37] note that the majority of clinical case series presented in the literature report vergence system abnormalities following mTBI, with the most common finding of convergence insufficiency, typically causing symptoms related to reading.

This study then compared the sensitivity of the collected measures of visual functioning to the history of previous concussion(s) with the corresponding sensitivity of measures of neuropsychological functioning (ImPACT) to determine the former's utility in screening for lifetime concussion incidence.

Methods

Subjects

A total of 42 student athletes from NCAA Division I Men's ($n = 21$) and Women's ($n = 21$) Hockey teams, ranging in age from 18–23, with a mean age of 20.52, participated in the study. The sample consisted of four goaltenders, 14 defensemen and 24 forwards. Seventeen athletes reported to have had at least one concussion in the past, with nine players reporting a concussion for the 12-month period preceding evaluation. The Institutional Review Board (IRB) of the researchers' university reviewed and approved the study protocol and the informed consent document. Written informed consent was obtained from each participant prior to his/her examination.

Instruments

Basic visual examination

Distance acuity. Distance binocular visual acuities were assessed at 16 feet using the computerized Landolt C paradigm, which is included in the Nike SPARQ Sensory

Performance System. All of the athletes achieved a binocular acuity equal or better than 20/30 OU. Because of time constraints, a cycloplegic refraction on the athletes was not feasible. However, an automated refraction using a Z-View Aberrometer (Ophthonix) was performed on each eye with the athlete's habitual non-correction or over the athlete's habitual contact lens correction in place, whichever the case may have been. All athletes showed this habitual non-corrected refractive error or residual over-refraction contact lens error to be between +1.00 and −0.75 sphere and astigmatism between plo and −1.00 for each eye. All further vision assessments were then performed with the athlete's habitual non-correction/contact lens correction in place.

Reduced Snellen Visual Acuity at Near. A reduced Snellen acuity chart (RH Burton 'Dial a Chart' No. 2), which consists of five lines of graduated acuity letters ranging in size from 20/50 to 20/15 and with each line containing six letters, was placed in front of the seated subject at 40 cm. With the left eye covered, the subject was instructed to read aloud the smallest line of letters they could discriminate. This was repeated for the left eye and with both eyes together (OD, OS, OU) and the accuracy of the subject's responses were recorded.

Occulomotor-based vision problems: Vergence

Vergence Facility Testing. Vergence facility was assessed using the Vectograph No. 9 (Stereo Optical), which includes a 20/30 reduced Snellen letters target. This was placed on a light box at a test distance of 40 cm while the subject wore polaroid vectograph glasses. A 12Δ BO/3Δ BI split prism (Gulden Ophthalmics, Elkins Park, PA) was used for this procedure, with the base-in prism held initially in front of the subject's right eye. The subject was instructed to look at the horizontal rows of letters corresponding to the 20/30 lines and to report when the target became clear and single by saying the word 'single'. As soon as the subject responded, the opposing prism was placed in front of the eye with the subject reporting when the target again became clear and single. Each time the subject reported the target as 'single', the investigator moved the split prism to introduce the opposite prism before the right eye. This was repeated for a total of 60 seconds and timed using a hand held digital stopwatch. Fusing images created by both the 3Δ BI prism and the 12Δ BO prism once counted as one cycle. Vergence facility was recorded in cycles per minute to the closest half cycle.

Saladin horizontal and vertical static fixation disparity. Horizontal and vertical static fixation disparity was assessed using the Saladin card which was back-illuminated on a light box placed at 40 cm and parallel to the subject's face. The subjects wore polarized vectograph glasses and were instructed to keep clear the words surrounding a series of circles that contained aligned and misaligned polarized nonius lines. Subjects were asked to report which circle contained the set of nonius lines that appeared perfectly aligned, both horizontally and vertically. These results were then recorded.

Modified Thorington Phoria. This is a measure of the subjects dissociated near-point horizontal phoria. The Saladin Card was placed on the moveable slide of the ACR/21 ruler and placed at 40 cm, while the other end of the slide was gently placed against the subject's forehead. A Maddox rod was held by the subject before their right eye with the lines horizontal. The Saladin Card contains a horizontal line of numbers to the right and left of a small centre hole in the card. A penlight was held behind the hole by the examiner and illuminated, creating a percept of the vertical red line of light by the subject against the card when both eyes were open. Subjects were instructed to fixate the centre white light, while keeping the numbers on the card clear. Subjects were then instructed to report the number to the right or left of the centre white light that the vertical red line passed through. If the red line was reported as moving, subjects were asked to close their eyes and report the location of the red line when they first opened their eyes. The dissociated phoria was recorded as ortho (red line aligned with the centre hole) or in prism diopters eso or exo (uncrossed or crossed diplopia, respectively).

Distance Fixation Disparity: FFD card (Vision Assessment Corporation). This test was used to evaluate the presence or absence of a subject's horizontal or vertical fixation disparity at far. It uses polarized vernier nonius lines that are viewed separately by each eye and a central accommodative target viewed by both eyes. The subject stood with his/her head straight. The test was performed at far distance of 16 feet. Standard room illumination was used and the athlete wore polaroid vectograph glasses. The subject was asked to watch the centre E accommodative target and note whether or not the bottom arrow or the top arrow appeared to remain directly aligned with the opposite arrow or one of the arrows was misaligned. Next, the subject was asked to notice if the horizontal arrows appeared to remain aligned to each other or misaligned. Any horizontal or vertical misalignment of the nonius lines was reported and recorded.

Near-point of fixation disparity. A dynamic near-point of fixation disparity test (NPFD) was performed using a fixation disparity cross designed of polarized vernier acuity nonious lines to assess vergence misalignment as well as a central cognitive fusion lock (Letter E) to engage accommodation (Vision Assessment Corporation, Elk Grove Village, IL). The NPFD is felt by the test's designer to be a more sensitive measure of the disruption of binocular vision and near visual stamina than a standard near-point of convergence test or static near fixation disparity test. The NPFD Card was placed on the moveable rod of the Astron International (ACR/21) Accommodative Rule while the subject wore polaroid vectograph glasses. The centre of the forehead at the level of the brow was used as the zero measure point from which the NPFD was taken. With the end of the ruler placed against the forehead, the target was moved slowly toward the subject at ∼1–2 centimetres per second until the subject reported that the vertical nonius lines began to move out of alignment, at which point the distance from the zero measure point was read off the ruler.

Near stereopsis. The Vectogram No. 11 Stereo Test (Stereo Optical, Chicago, IL) was used for assessing near stereopsis. The test slides were positioned on a light box placed parallel to the subject's face at 40 cm before the seated subject who wore polarized vectograph glasses. The subject was asked to call out the number of the circle on each of the six lines that seemed to float closer than the other circles. The lowest line of accurate near stereo response was then recorded.

Occulomotor-based vision problems: Accommodation

Accommodative amplitudes. The accommodative amplitude of the right eye, left eye and both eyes was performed using the Donders push-up method, which makes use of the Astron International (ACR/21) Accommodative Rule. 20/20 letters were placed on the ACR/21 Rule rod with the other end of the rule placed gently on the subject's forehead. With the left eye occluded, the moveable target of 20/20 letters was slowly moved towards the subject at $\sim$1 to 2 cm s^{-1}. The subject was instructed to report immediately when the target first started to become blurry. At this point, the target was stopped and the subject was asked if the letters became clear or remained blurred. If the letters cleared, the target was moved closer to the subject at the same rate until blur was reported again. The point of first sustained blur was considered to be the end-point. The accommodative amplitude was recorded to the nearest half centimetre on the exam form and subsequently converted into a dioptric value. The right eye was occluded and the procedure was repeated for the left eye and again repeated with neither eye occluded. The dioptric results for each eye and both eyes were recorded.

Accommodative flipper facility (+/−2.00 lens flippers). The testing procedure uses two minus and two plus lens pairs mounted on opposing sides of a flipper frame. The lenses were held by the examiner in front of the eyes of the subject who wore polaroid vectograph glasses. The subject first focused through one pair of plus lenses while looking at a 20/30 line of acuity letters on a No. 9 Vectogram (Stereo Optical, Chicago, IL) slide, which was used as a suppression control and is backlit by a light box at near distance (40 cm). The subject was instructed to say 'clear' when and only if both lines of print were clearly in simultaneous focus. A flip was quickly performed by the examiner so that the subject was forced to focus through the other (minus) lens pair. When and if a report of 'clear' was made, a flip was then repeated for 60 seconds and the number of flips counted while using a handheld digital stopwatch. The number of cycles completed in 1 minute (cpm) was recorded as the measurement of binocular accommodative facility (the exertion and relaxation change of the accommodation at a fixed vergence distance) in cpm.

CISS questionnaire. The Convergence Insufficiency Symptom Survey (CISS) is a 15-item questionnaire assessing severity of symptoms related to reading and near-point work such as fatigue, headaches, reading performance and perceptual distortions. A score of 22 or higher on the CISS has been shown to differentiate between adults with convergence insufficiency (CI) from those with normal binocular vision [39].

Occulomotor-based vision problems: Version

Visagraph II. Objective eye movements were obtained using the Visagraph II eye movement system, which is based on the infrared limbal reflection technique in conjunction with text paragraphs of various difficulty and the Visagraph computer analysis program. These programs employ Taylor's normative values for reading eye movement behaviours of various age levels. The eye movement recording goggles were placed on the subject and adjusted per the instruction manual for the near interpupillary distance. Subjects were seated and given the Test Booklet containing paragraphs of both Level 10 and Level 5 text difficulty. These text levels were selected as a way to differentiate language-based oculomotor behaviours from those that are vision-based according to the suggested protocols of Tannen and Ciuffreda [40]. Each subject held the Test Booklet comfortably at a distance of 16–20 inches from the subject's eyes and centred along the subject's midline. They were instructed to read a paragraph silently and normally and were told that 10 questions would be asked about the story following the reading. If a 70% level of comprehension is not achieved, a third paragraph is typically given to the subject to read. However, another Level 10 paragraph was not needed as all the subjects achieved at least a 70% comprehension accuracy on the second paragraph.

Coherent motion threshold. Computer software using Random Dot Kinematograms, which is designed to measure coherent motion thresholds, was presented to each subject via a laptop computer. The screen dimensions on the computer used was 41 degrees horizontally and 31 degrees vertically. Displayed at the centre of the laptop screen appeared a white 'plus' sign fixation target subtending 1.5 degrees horizontally and vertically against a black background. Subjects were seated 50 centimetres away from the front of the laptop screen along the midline with their habitual refractive correction in place. The Coherent Threshold dot matrix was presented within the two panels on the computer screen. One panel had a variable amount of coherently moving dots imbedded amongst the random dots, moving together laterally to the right and to the left, while the other screen displayed randomly moving dots every 50 milliseconds (Brownian motion). The subject was instructed to select the panel that appears to have the dots moving laterally by pressing a key on the keyboard. After two practice trials, the percentage of dots moving together were systematically varied by the software: starting at 75%, then increasing by 3 dB and then decreasing by 1 dB, until the threshold for each subject was attained. The coherent and random-motion display panels alternated randomly between left and right sides of the computer screen. The stimuli were presented for 2.96 seconds. The subjects had an unlimited time after the stimuli were presented to indicate their response. All subjects were instructed to maintain fixation on the plus sign fixation target during the test. A 2-alternative, forced choice paradigm was used to score the Coherent Motion Threshold (CMT). A double interlaced staircase method was used, with the threshold being the geometric mean of the last eight of 10 reversals. The threshold was obtained for both trials and averaged across the two trials for each subject. The CMT score represents the minimum percentage of coherently moving dots necessary for the subject to be able to just detect the horizontally moving direction (i.e. left and right) of the dots. Each subject performed the coherent threshold test twice, with each trial lasting ~7 minutes.

Non-vision-based problems

ImPACT. ImPACT (Immediate Post-Concussion Assessment and Cognitive Testing; ImPACT Applications, Inc. Pittsburg, PA) is a widely used computerized concussion evaluation system developed to provide useful information to assist qualified practitioners in making decisions about athletes' return-to-play following concussions. ImPACT takes ~20 minutes to complete. It collects information about the severity of the athlete's most recent concussion symptoms ($n = 22$) via a 7-point Likert scale and also measures multiple aspects of the athlete's cognitive functioning including: attention span, working memory, sustained and selective attention time, response variability, non-verbal problem-solving and reaction time. Specific neurocognitive modules include Word Discrimination, Design Memory, X's and O's, Symbol Matching, Colour Match and Three Letter Memory.

There are five ImPACT test scores calculated from the neuropsychological tests administered: Verbal Memory Composite, Visual Memory Composite, Reaction Time Composite, Impulse Control Composite and Total Symptom Composite Score. The Total Symptom Composite score represents the total for all 22-symptom descriptors. A lower score indicates fewer endorsed symptoms by the athlete. Several validation studies have indicated that the verbal memory, visual memory, processing speed, reaction time and symptom scores accurately discriminate concussed from non-injured athletes [41–43].

ADHD questionnaire. The Adult ADHD Self-Report Scale version 1.1 (ASRS-v1.1) Symptom Checklist was used in the present study as a known effective measure for detecting ADHD in the general population with a sensitivity of 68.7% and a specificity of 99.5% [44]. The ASRS-v1.1 is a standardized questionnaire based on *Diagnostic and Statistical Manual of Mental Disorders* (4th ed., text rev.; *DSM-IV-TR*; APA, 2000) [45] criteria. It is composed of 18 questions, six of which are most predictive of ADHD symptoms. Its first four questions address the inattention portion of ADHD and its final two address the hyperactivity portion [46]. When taken together, this sub-set of six questions forms the ASRS-v1.1 Screener and Part A of the Symptom Checklist. In their validity study using the ASRS-V1.1, Kessler et al. [44] suggested a scoring strategy that involves summing responses from the six items and dividing them into four distinct categories. A respondent scoring 0–9 represents a 'highly unlikely' candidate for ADHD, 10–13 represents the 'unlikely' category, 14–16 represents the 'likely' category and 17–24 represents a 'highly likely' category.

The 12 remaining questions form Part B of the Symptom Checklist. A result was considered positive for those who scored 4 or more on Part A of the Symptom Checklist. Part B is not commonly used for diagnostic purposes; however, it does provide additional cues to symptom frequency and is viewed as a guideline for further probing into patient symptoms.

Procedure

Upon arrival at the testing location (a Midwestern optometric clinic), informed consent was obtained from each subject followed by administration of a Z-View Aberrometer & Autorefractor (Ophthonix, Visa, CA) over the subject's habitual playing refraction to determine what, if any, refractive error or residual error there might be for each eye under non-cyclopleged conditions. If contact lenses were worn, the test was repeated without contact lenses and the lenses were replaced on the subject's eyes after the test was completed. The refractive outcome (uncorrected refraction or contact lens over-refraction) was then recorded for each eye along with the Aberration Index.

The athletes then completed the Convergence Insufficiency Symptom Survey (CISS) and the Adult ADHD Self-Report Scale (ASRS-v1.1) Symptom Checklist. Following completion of the questionnaires, the athletes' near-point visual skills were assessed by a professional optometrist. The time to complete visual evaluation was ~30 minutes.

The ImPact Neurocognitive battery was administered to each player by their trained coaching staff before the beginning of the regular 2011–2012 season (baseline assessment) and every time brain injury was suspected. For the purposes of this study, the most recent available ImPact data was used for each player (baseline player's data was used if no concussion was suspected during the regular season).

Statistical analyses

Collected measures of visual processing and neurological status were used to predict individual player's lifetime concussion history using binary logistic regression. First the maximum allowable number of predictors was determined in this model based on the number of available data points for the dependent measure. Using G-Power 3.1 it was estimated that, for the χ^2 family of tests and a sample size of 42 participants, one would be able to assess the model's Goodness-of-fit while maintaining the minimal acceptable statistical power of 0.80 if no more than four predictor variables were included in the model and large effect sizes ($w = 0.50$) were observed.

Since this study did not follow any *a-priori* theory of what variables may be better predictors of lifetime concussion, independent-sample *t*-tests were first used to isolate those variables on which the athletes with the history of concussion significantly differed from the athletes without previous concussion history. For those measures on which mean differences between the groups were statistically significant, their Receiver Operating Characteristics (ROC) curves were then examined to assess their ability to discriminate between players with lifetime concussion vs those without any concussion history. First, 50th, 75th and 90th percentile scores were obtained for these measures and separate ROC analyses were run for each percentile to determine best cut-off scores. If ROC Area Under the Curve (AUC) for any of the three percentile scores within the variable of interest was statistically significant (identified instances of concussion significantly better than chance at $\alpha = 0.05$), it was included that a percentile score as a cut-off score for a new binary predictor variable (1 = equal to or greater than the cut-off percentile; 0 = less than the cut-off percentile).

The new binary predictor variables were then included into a logistic regression model using the backward elimination procedure to obtain the most parsimonious model capable of explaining the greatest amount of variance in the criterion. In backward elimination all predictors are entered into the model first and then at each step the predictor that produces the smallest increment in R^2 is tested to determine whether it should be removed from the equation.

Results

Lifetime concussion incidence

Five variables were found to have significant mean differences between previously concussed and non-concussed players. These measures included accommodative facility (AF), near point of fixation disparity (NPFD), mean comprehension rate averaged over grade 5 and grade 10 material on the Visagraph test (Visagraph-C), mean duration of eye fixations averaged over grade 5 and grade 10 material on the Visagraph test (Visagraph-D) and the total score for part A of the ADHD questionnaire (see Table I). Examination of ROC AUCs for the 50th, 75th and 90th percentile showed that cut-off scores for the 75th percentile had significant ROC AUCs for NPFD, total score for part A of the ADHD questionnaire and reading comprehension (see Figure 1). All percentile scores' ROC AUCs for AF were less than 0.50 (worse than chance) and none of the percentile scores' ROC AUCs for 'duration of fixations' were statistically significant. The latter two variables were, thus, excluded from logistic regression.

The results of the analysis showed that all three variables (NPFD, Visagraph-C and ADHD-A) were retained in the model at the final step. The model had an overall prediction accuracy of 83.3%, which was a statistically significant ($\chi^2 = 21.58$, $p < 0.01$) improvement compared to no variables in the model (59.5%). Overall the model accounted for 54% of variability in the dependent measure (Nagelkerke $R^2 = 0.54$) and reached an acceptable level of discrimination according to Hosmer and Lemeshow [47], as its overall ROC AUS was 0.70. Each individual predictor significantly contributed to the explanation of variance in the DV (see Table II). Based on the odds ratios for individual predictors, a hockey player with the near point of fixation disparity equal to or greater than 15 cm, Visagraph comprehension rate less than 85% and the total score on part A of the ADHD questionnaire equal to or greater than 11 was on average 10.72-times more likely to have had a concussion than an athletes with lower values on the NPFD and ADHD-A and a higher comprehension rate on Visagraph. Figure 2 shows that the model had better specificity to no concussion (100%) than sensitivity to concussion (~60%) as none of the non-concussed players were erroneously identified by the model as having had a concussion in the past, but seven individuals with concussion were missed and, thus, classified as non-concussed. The graph

Table I. Means, standard deviations and p values for mean differences on measures of oculomotor and neuropsychological functioning between hockey players with a history of a previous concussion and those without the history of concussion.

Measures	Lifetime concussion ($n = 17$)	No concussion ($n = 25$)	p Value
Visual			
Visual Acuity at Near OU (LogMAR)	−0.08 (0.06)	−0.09 (0.04)	0.46
Accommodative Amplitude (Diopters)	8.97 (1.67)	9.08 (1.47)	0.82
Accommodative Facility (cpm)	8.15 (5.51)	12.04 (5.69)	0.03*
Stereopsis at near (Seconds of Arc)	26 (0.0)	26.76 (3.8)	0.41
Vergence facility (cpm)	10.65 (8.51)	12.82 (8.20)	0.41
Fixation Disparity at near horizontal (Arc Minutes; + = exo; − = eso)	+0.48 (1.50)	+0.80 (1.82)	0.54
Fixation Disparity at near vertical (Arc Minutes; + = R. Hypo; − = R. Hyper)	+0.12(0.60)	−0.20 (0.58)	0.09
Near Point of Fixation Disparity (cm)	11.76 (9.48)	5.48 (5.58)	0.01**
Phoria at near (prism diopters; + = exo; − = eso)	2.00 (4.05)	1.08 (3.67)	0.45
Coherent motion threshold average (% of dots needed to see lateral motion)	5.33 (1.80)	4.29 (1.74)	0.07
Self-Report Measures			
Convergence Insufficiency Symptom Survey	17.76 (9.09)	13.44 (9.97)	0.16
Total Score for ADHD Part A	10.24 (2.77)	7.88 (4.01)	0.04*
Total Score for ADHD Part B	16.35 (5.41)	13.40 (7.47)	0.17
ImPACT			
Total Symptom Score	3.29 (6.68)	2.79 (4.31)	0.77
Memory Composite Verbal	90.18 (8.88)	89.04 (8.44)	0.68
Memory Composite Visual	76.29 (11.75)	78.13 (11.14)	0.62
Visual Motor Speed Composite	44.62 (5.63)	41.42 (7.02)	0.13
Reaction Time Composite	0.51 (0.07)	0.54 (0.07)	0.17
Impulse Control Composite	11.12 (10.63)	11.29 (14.61)	0.97
Visagraph (averaged over grades 5 and 10 material)			
Fixations (100 words)	113.21 (31.32)	109.88 (22.02)	0.68
Regressions (100 words)	17.06 (12.95)	15.28 (9.25)	0.61
Duration of Fixations (sec)	0.25 (0.02)	0.23 (0.02)	0.02*
Reading rate with comprehension (words/min)	223.82 (56.44)	239.06 (54.00)	0.38
Grade level efficiency (Relative Efficiency = Rate (wpm)/Fixations per 100 words + Regressions per 100 words)	9.13 (3.69)	9.68 (2.94)	0.60
Comprehension (%)	0.77 (0.07)	0.84 (0.06)	0.01**

*Significant at $\alpha = 0.05$; **significant at $\alpha = 0.01$.

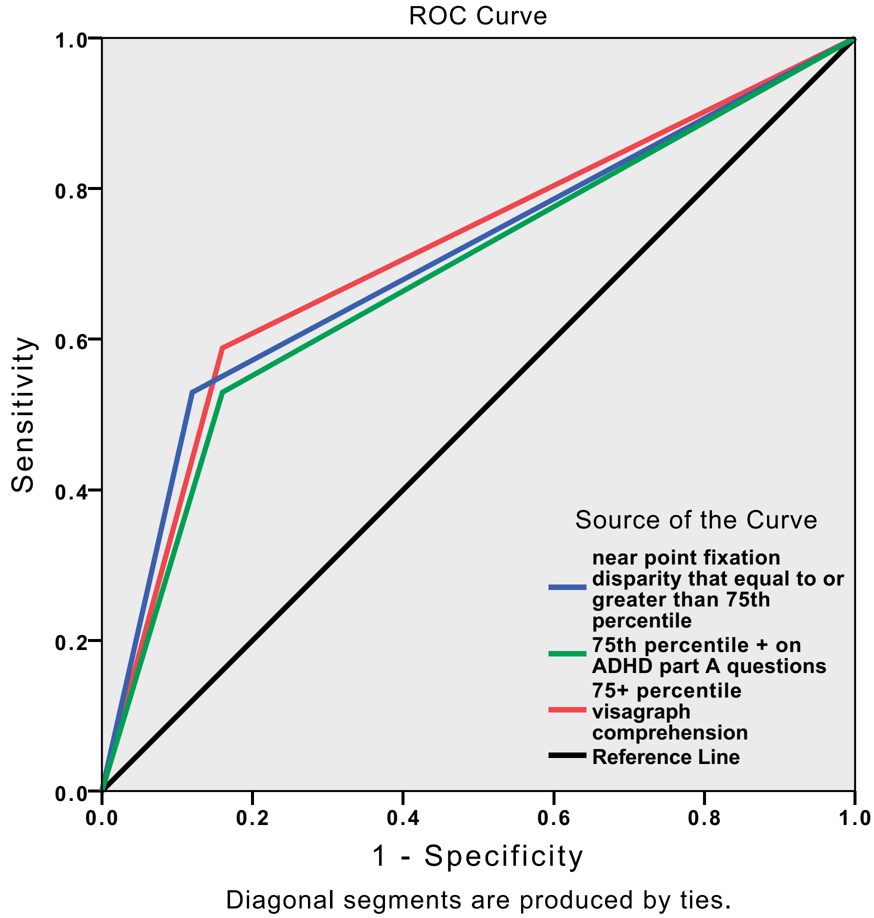

Figure 1. Receiver operator characteristic (ROC) curves for predictors, whose threshold cut-off values (≥75th percentile) showed ROC AUC values that indicated discrimination of lifetime concussion significantly better than chance at alpha = 0.05.

Table II. Logistic regression analyses summary predicting concussion in the past 12 months and lifetime concussion incidence.

Criterion	Predictors	B	SEB	Odds ratio	ROC[a] (AUC)
Had a lifetime concussion	Visagraph: Comprehension (≥0.85%)	−2.11*	0.96	8.31	0.71*
	Near Point of Fixation Disparity (≥15.0)	2.36*	1.02	10.56	0.71*
	ADHD: Total Score Part A (≥11.0)	2.59*	1.02	13.28	0.69*

*$p < 0.05$; Nagelkerke $R^2 = 0.54$.
[a]Null hypothesis: true area = 0.50.

also shows that three of the missed seven individuals were at the border of being placed in the 'concussed' category as their probability values were ~0.50.

Discussion

Overall the results of the study demonstrated that greater near-point fixation disparity, higher ADHD symptomatology and poorer reading comprehension are important in identifying individuals with a history of previous concussion(s). On the other hand none of the IMPACT baseline assessment measures were significantly predictive of the individual's concussion history.

The null findings on the ImPACT measures were expected. As previously mentioned several research groups did not find any association between athletes' performance on ImPACT and previously sustained concussions [29–32].

While ImPACT continues to be an important instrument in immediate evaluation of a suspected concussion and in making return-to-play decisions, its utility in screening for a history of previous concussions (that the athlete may not be aware of) and associated risks of repeat concussions, longer recovery and permanent neurocognitive decline is rather limited. On the other hand several visual and self-report measures used in the present study showed high sensitivity to previously sustained concussions.

In the visual domain problems of vergence (accommodative facility and near point of fixation disparity) and version (eye fixations during reading) were associated with the previous history of concussion. Coherent motion threshold was also greater in the previously concussed players and this difference was almost statistically significant ($p = 0.07$, see Table I). Near-point of fixation disparity, however, was one of the strongest predictors of concussion in the hockey players. Athletes with NPFD values equal to or greater than 15 cm were 10.56-times more likely to have sustained a concussion in the past than those with lower scores on this measures. The NPFD is a fairly new test of convergence insufficiency (CI) that combines features of traditional static fixation disparity tests and a dynamic test of near-point of converge.

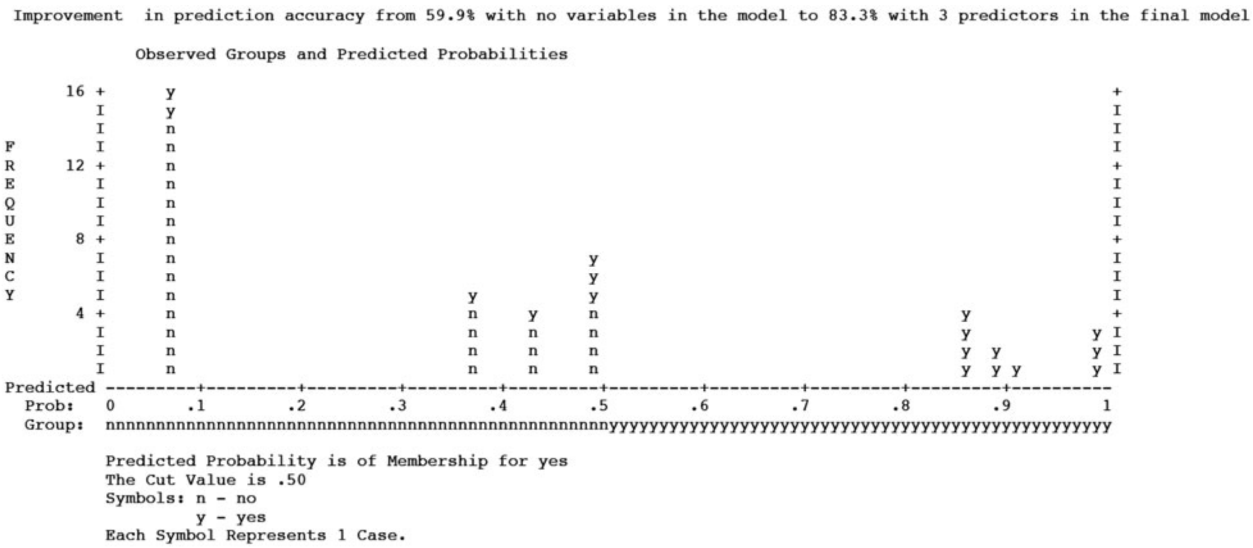

Figure 2. Observed groups and predicted probabilities of having had a concussion based on a model with three categorical predictors (75th percentile scores for near-point of fixation disparity, total score for part A on the ADHD questionnaire and comprehension on the Visagraph test).

Convergence Insufficiency (CI) is a binocular vision disorder, often associated with symptoms such as double vision, eyestrain, headaches, blurred vision and loss of place while reading or performing near work [48]. Significant CI has been observed in several studies of mTBI patients (see Thiagarajan et al. [37] for a review). Traditionally it is measured with the test of the near point of convergence (NPC), which has recently been supplemented with the self-report measure of CI, the Convergence Insufficiency Symptom Survey (CISS). The near point of convergence is the point to which the lines of sight are directed when convergence is at its maximum. Typically in NPC an accommodative target (e.g. a letter) is advanced towards the nose along the ruler pressed against the bridge of the nose. The NPC break point is the patient's report of diplopia. A receded NPC is the most commonly observed clinical sign in persons with CI [47]. Various investigators have reported different pass/fail criteria including 13.1 cm [5] and 7.5 cm [49].

Krohel et al. [50] accessed NPC in 23 patients with mTBI who reported reading difficulty (26%) and/or diplopia at near (52%) as their main symptoms. CI manifested as a receded near point of convergence (NPC) in 74% of these patients. This result is consistent with findings of Cohen et al. [51], who found CI in two different mTBI populations tested based on the time elapsed after their head trauma. That is, while 42% of the patients tested 3 years after trauma suffered from long-standing CI, it was similarly found in 38% of the patients tested only 3 months after their injury, suggesting that time after insult does not appear to influence the frequency of CI.

The Near Point of Fixation Disparity (NPFD) is administered in the same way as the Near Point of Convergence (NPC); however, while the break point of the NPC is double vision, the break point of the Near Point of Fixation Disparity (NPFD) is the distance at which a Fixation Disparity is present and which cannot be resolved within a 1–2 second time period. The NPFD target includes a central circle fusion lock, which is seen by both eyes inside of which is a small letter E (20/100 Snellen Equivalent), which is also seen by both eyes and is used to stimulate accommodation. Vertical and horizontal nonius lines surround this central target to form a fixation disparity cross which is seen dichoptically. As the target is moved slowly inward toward the subject, there is a gradual increase in the vergence and accommodative demand placed upon the visual system as the subject fixates the central target. If the subject's vergence and/or accommodative response is unable to keep up with the increasing demand, the result will be a breakdown in the exact alignment of the vertical nonius lines, observed by the subject as a fixation disparity 'break point'. The reason for the observed vertical misalignment to the incoming target may be due to a lag in the vergence component alone or due to a lag in the accommodative component, which influences the vergence response via the synkinetic accommodative-vergence relationship. The designer of the test reports that, while a normal response can be found for a subject with convergence insufficiency on traditional NPC testing, such a subject can often be found to have an abnormally receded NPFD, making the test more sensitive [52]. This is because the traditional NPC break point measures the loss of binocularity that occurs outside of Panum's area while the NPFC break point represents a disruption of binocularity within Panum's area that is occurring much sooner than the NPC break point as one approaches the edge of one's fusion limit [52].

The NPFD findings were supported by the CI symptom scores for the concussed vs the non-concussed group. Athletes with a previous history of concussion had a mean CISS score of 17.76 compared to 13.44 for the athletes with no history of previous concussions. Although this difference was not statistically significant, in combination with significant NPFD findings it supports greater convergence insufficiency in the concussed group. To the author's knowledge this is the first study to demonstrate the NPFD's excellent sensitivity to lifetime concussion, a finding that warrants further larger-scale investigations.

The results of Visagraph testing are consistent with previous findings looking at eye movements during reading and reading behaviours. Several studies have previously shown that patients with mTBI are afflicted with an array of oculomotor-based problems that may negatively impact upon their reading ability [53–56]. These include inaccurate saccades, inaccurate and highly variable fixation and vergence dysfunction [34]. These signs are consistent with one of the most frequently-reported symptoms, namely 'ocular motility difficulty when reading', which is often associated with reading discomfort, poor reading comprehension, attentional focus and global reading strategy and slower reading rate [56]. In this study, concussed athletes had significantly longer eye-fixation durations during reading, which in combination with their greater CI may have adversely affected their comprehension rate. The latter was a robust predictor of lifetime concussions showing good discrimination ability (ROC AUC = 0.71) and increasing the likelihood of a lifetime concussion by 8.31-times for someone with comprehension scores below 85%.

Athletes' scores on the Adult ADHD Self-Report Scale (ASRS-v1.1) Symptom Checklist were also highly predictive of their concussion history, with scores of 11 or greater for part A of the questionnaire increasing the likelihood of a lifetime concussion by 13.3-times. While in this study both groups of athletes were unlikely to have ADHD according to the ASRS-v1.1 criteria (see Methods for details), the lifetime concussion group had mean scores in the 'unlikely' category ($M = 10.24$) while the non-concussed players fell into the 'highly unlikely group'. Apparently one probabilistic category difference between the two groups on this questionnaire was enough to discriminate between athletes with a previous concussion history and those without such history.

Oftentimes diagnosis and management of a concussion is encumbered by the presence of a learning disability or Attention Deficit Hyperactivity Disorder (ADHD) since both conditions share a number of common symptoms/features including deficits in memory, attention and concentration [23, 57]. Nevertheless, in non-ADHD athletes, problems of inattention following concussion seem to persist long after their injury. For example, Terry et al. [58] recently reported significantly lower Attention index scores of the Repeated Battery for the Assessment of Neuropsychological Status (RBANS) in a group of formerly concussed athletes (at least 6 months post-mTBI) compared to their age-matched healthy controls in the absence of any haemodynamic (fMRI) or other behavioural index differences such as reaction time and accuracy. Nolin et al. [59] also showed subtle differences in attention and inhibition in adolescents with a previous history of sports-related concussions (SRC) compared to age-matched control when a virtual-reality based version of a continuous performance test was used, but not with traditional testing. Continuous performance tests are often used in conjunction with clinical measures to diagnose ADHD. The present study showed that the ASRS-v1.1 Symptom Checklist may be a sensitive measure of the subtle neurocognitive changes related to inattention and hyperactivity that may persist following SRC.

Study limitations

One of the natural limitations of studying elite athletes is a highly circumscribed participant pool. Although this study was able to test 87.5% of the target population (hockey players who appeared on the roster for the NCAA 2011–2012 season ($n = 42$)), the number of participants was still relatively small to allow regression modelling with more than four predictors and was barely adequate to detect only large effect sizes. Thus, some of the other potentially important relationships may have been overlooked due to the lack of statistical power.

Another obvious limitation of the current study design is the correlational nature of the observed relationships. Additionally, only the NPFD break point was recorded and it was only measured once. This study did not measure the recovery point, which the designer feels may be even more sensitive to binocular instability than the break point [52]. It is also recommended that the NPFD is repeated three times and that the break and recovery points are averaged. The test has not yet been standardized or normed. Investigations into test–re-test reliability, intra-observer reliability of the NPFD and development of age norms for the test are currently under way.

Nevertheless, this is one of the first steps in the direction of designing better screening protocols for previously sustained concussion. Although the described model still overlooked several individuals with lifetime concussion history, it did not misclassify any of the healthy individuals and can, thus, significantly improve efforts to better identify athletes more vulnerable to brain injury and neuropsychological, physical and perceptual deficits associated with it. Timely institution of rehabilitative procedures including vision therapy and sports vision training may improve the athlete's overall neuropsychological status and improve not only sports-specific performance but possibly his/her academic performance associated with near-point visual skills such as reading.

Conclusion

Overall this model showed that a hockey player with the near-point of fixation disparity equal to or greater than 15 cm, Visagraph comprehension rate less than 85% and the total score on part A of the ADHD questionnaire equal to or greater than 11 was on average 10.72-times more likely to have previously suffered a concussion than an athlete with lower values on the NPFD and ADHD questionnaire and a higher comprehension rate on the Visagraph. While these findings need to be replicated in a larger athletic sample, they offer a relatively sensitive screening tool to assess the probability of previous concussion(s) in an athlete who does not report any history of previous mTBI. This will allow athletic personnel to address in a timely manner the risks associated with repeat concussions and to develop individualized concussion management protocols. This type of screening (if replicated in future research) would be inexpensive and relatively easy to administer, even by non-medical professionals such as coaching staff.

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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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