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Frequency of oculomotor disorders in adolescents 11 to 17 years of age with concussion, 4 to 12 weeks post injury

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ABSTRACT

The purpose of the study was to determine the frequency of vision diagnoses after concussion in adolescents and evaluate the sensitivity and specificity of physician-administered screening for detecting convergence and accommodative disorders post-concussion. We enrolled participants 11 to 17 years old, assessed 4 to 12 weeks following a diagnosed concussion. During the initial concussion examination, a sports medicine physician measured the near point of convergence (NPC), monocular accommodative amplitude (AA), and symptoms using the Convergence Insufficiency Symptom Survey (CISS). A comprehensive oculomotor evaluation was performed by an optometrist. One hundred and thirteen adolescents were enrolled, with a mean age of 15.2 years. Seventy-nine of the 113 (70%) participants had at least one oculomotor diagnosis after concussion, with the most common problems being vergence disorders (60%) and accommodative disorders (57%). The most common vergence disorder was convergence insufficiency (35%). Among accommodative disorders, the most common problem was accommodative insufficiency (35%). In all, 47% of the participants had more than one oculomotor diagnosis following concussion. The sensitivity of physician screening using measures of NPC, AA, and CISS for detecting convergence and accommodative insufficiency was 63%, 43%, 48%, respectively. The results of this study provide additional evidence that vision problems are common in adolescents with persistent concussion symptoms in the sub-acute phase 4 to 12 weeks post-concussion, and current physician screening methods using the NPC, AA, or the CISS underperform. Thus, it is prudent that adolescents with post-concussion symptoms lasting more than 4 weeks post injury receive a comprehensive oculomotor examination.

1. Introduction

Studies have found that vision problems are common after concussion (a form of mild traumatic brain injury) (Master et al., 2016; Howell et al., 2018; Storey et al., 2017), and may interfere with return to school, work, and sports (Swanson et al., 2017; Master et al., 2018; Pearce et al., 2015). Many of the visual symptoms experienced by patients post-concussion have also been reported by those with vergence and accommodative problems (Gallaway et al., 2017). Some researchers have even identified an oculomotor sub-type of concussion in which vision problems are the primary factor causing persistent symptoms (Collins et al., 2014; Ellis et al., 2015). Others have suggested the importance of incorporating oculomotor testing into the physician medical assessment of concussive brain injury (Master et al., 2018a, 2018b; Zasler et al., 2019; Ventura et al., 2015; Galetta et al., 2015; Mucha et al., 2014; Poltavski and Biberdorf, 2014; Raghuram et al., 2019). Given these multiple reports (Swanson et al., 2017; Master et al., 2018; Pearce et al., 2015) suggesting that vision problems play a role in concussion recovery, it is surprising that there are relatively few prospective studies investigating the frequency of post-concussion vision disorders, particularly in the pediatric population.

Most of the literature reporting the frequency of vision problems after traumatic brain injury pertains to the adult population (Brahm et al., 2009; Goodrich et al., 2013, 2007; Stelmack et al., 2009; Capo-

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Aponte et al., 2012; Ciuffreda et al., 2007; Alvarez et al., 2012), and in many cases consists of participants with both mild and moderate traumatic brain injury that have not been distinguished from those with concussion (Goodrich et al., 2013; Stelmack et al., 2009; Capo-Aponte et al., 2012; Ciuffreda et al., 2007; Alvarez et al., 2012; Suchoff et al., 2008). These studies are generally retrospective chart reviews (Ciuffreda et al., 2007; Alvarez et al., 2012; Goodrich et al., 2013, 2007; Stelmack et al., 2009) in which investigators only administered one or several vision tests, but did not include assessments of binocular vision, accommodation, and eye movement function (Goodrich et al., 2013, 2007). Typically, only the cover test, near point of convergence, and amplitude of accommodation have been performed (Goodrich et al., 2013, 2007). In addition, well-defined diagnostic criteria were not included for determining how diagnostic decisions were reached. Thus, these studies likely underestimated the frequency of post-concussion vision disorders such as vergence, accommodative, and saccadic eye movement problems. We were only able to identify one existing prospective study documenting the frequency of oculomotor problems among adolescents with concussion (Master et al., 2016). In this cross sectional, prospective study of adolescents 11 to 17 years old with a concussion diagnosis, Master et al. found that 69% of the participants had at least one vision diagnosis. A limitation of this study, however, was the lack of an eligibility requirement specifying the time frame from injury to assessment. Twenty-nine percent of their participants were seen within 1 month of injury, 26% between 1 and 3 months, and 45% >3 months post injury. Participants seen within 1 month of injury were more likely to have a vision diagnosis than those evaluated more than 3 months post injury. This finding is consistent with the observation of some authors suggesting frequent resolution of vision problems within the first month of a concussion (Storey et al., 2017). Raghuram et al. (Raghuram et al., 2019) performed a retrospective, cross-sectional study of 83 patients (mean age 15.3 years) > 28 days post-concussion with chronic concussion-related symptoms. They found that 89% of the participants had a receded near point of convergence. Of these participants 84% had accommodative deficits, and 36% had convergence insufficiency. However, they used different diagnostic criteria than Master et al. (Master et al., 2016) making comparison of the two sets of data challenging. Thus, there is a need for additional prospective data on the frequency of post-concussion vision disorders in adolescents with persistent symptoms.

The primary purpose of this study was to determine the frequency of post-concussion vision disorders, in adolescents with persistent post concussive symptoms 4 to 12 weeks post-injury. A second objective was to determine the sensitivity and specificity of a screening performed by non-eyecare professionals for detecting convergence and accommodative insufficiency post-concussion compared with a diagnosis reached by an optometrist after a comprehensive oculomotor examination.

2. Participants and methods

We conducted a cross-sectional study of patients who presented to the Minds Matter Concussion Program at The Children's Hospital of Philadelphia. All patients who presented for clinical care between March 2, 2018 and May 31, 2019, when an optometrist was available to perform vision testing, were eligible for the study. The Children's Hospital of Philadelphia institutional review board approved this study prior to the commencement of subject enrollment and data collection. The parent or guardian (hereafter parent) of each study participant gave written informed consent and each participant gave written assent to participate.

2.1. Participant selection

The study included patients 11 to 17 years old with the medical diagnosis of concussion (based on the criteria outlined in the 5th Consensus Statement (McCrory et al., 2016)), who were experiencing persistent concussion symptoms and were 4 to 12 weeks post-injury at the time of enrollment. The decision about whether the patient had persistent concussive symptoms was based on the physician's analysis of three factors; the clinical case history, the results of the Post-Concussion Symptom Inventory (PSCI), and symptom provocation during the visio-vestibular examination (described below). We selected 4 to 12 weeks post injury as an eligibility criterion because most children with concussion recover spontaneously within 2 to 4 weeks (McCrory et al., 2008), and our goal was to study the 15–20% that suffer from a persistent concussive signs and symptoms (Belanger and Vanderploeg, 2005; McCrea et al., 2003; Collins et al., 2006; McClincy et al., 2006; Eisenberg et al., 2013; Corwin et al., 2014; Iverson et al., 2006).

We excluded those who were unable to participate in vision testing for any reason, did not have corrected 20/30 visual acuity with their current eyeglasses, had significant uncorrected refractive error, or required a change in their current eyeglasses. The criteria used to determine if there was significant uncorrected refractive error or a need for a change were: myopia > –0.75 D spherical equivalent in either eye, hyperopia > +1.00 D spherical equivalent in either eye, anisometropia > 0.75 D spherical equivalent, or astigmatism > 0.75 D in either eye. In addition, we excluded participants with pre-existing history of strabismus or amblyopia; eye surgery; patching for amblyopia; binocular vision problem treated with vision therapy, lenses or prism; or medical diagnosis of multiple sclerosis, myasthenia gravis, or Graves' disease.

2.2. Concussion Examination/Testing

A standardized visio-vestibular physical examination for concussion, which has been previously published (Master et al., 2018; Corwin et al., 2019a, 2019b), and recently validated (Corwin et al., 2020) was performed by sports medicine pediatricians at the Minds Matter Concussion Program of the Sports Medicine and Performance Center of The Children's Hospital of Philadelphia. In brief, symptom provocation and physical signs with the standardized visio-vestibular assessment of smooth pursuits, saccades, and gaze stability vestibulo-ocular reflex testing were determined. In this protocol, after a test procedure is performed, the patient is asked to verbally report if any symptoms were provoked by the procedure (binary response of yes or no) compared with their immediate pre-assessment symptom level. The visio-vestibular examination also included a standardized assessment of a complex tandem gait task where the patient takes five steps forwards and backwards under both eyes open and eyes closed conditions (Master et al., 2018; Corwin et al., 2019a, 2019b). In addition, the Post-concussion Symptom Inventory (PAR, Lutz, FL) was administered to each participant. The Post-concussion Symptom Inventory (Schneider and Gioia, 2007) is self-report survey for children and adolescents and is used to measure symptoms in the cognitive, emotional, sleep, and physical domains.

As part of the comprehensive concussion examination protocol, physicians performed the near point of convergence test using the Near Point Rule (Gulden Ophthalmics, Elkins Park, PA) with a moveable card containing a vertical column of 20/30 letters as the visual target. The edge of rule was placed at the center of the patient's forehead just above the level of the brow. The target was moved at a consistent rate of 1–2 cm/sec toward the patient. When diplopia was reported, movement was stopped, and the patient was asked "Does the target stay two or does it come back into one?" If the patient recovered single vision within 1–2 s, the target was again moved toward the patient until the patient was unable to regain fusion. This measurement was recorded as the NPC "break". Following this assessment, one eye was occluded, and the monocular accommodative amplitude was measured with each eye using the same instrument and target. The target was slowly (1–2 cm/sec) moved toward the patient. When blurred vision was reported, movement was stopped, and the patient was asked "Does the target stay blurry or does it become clear again?" If the patient recovered clear vision within 1–2 s, the target was again moved toward the patient until the patient was unable to regain clarity. This measurement was recorded as the amplitude of accommodation in centimeters. These two procedures (near point of convergence and accommodative amplitude) were performed by the optometrist in this study using the identical instrumentation, instructional sets, and targets in the comprehensive oculomotor examination. The CISS (Rouse et al., 2009; Borsting et al., 2003) was administered at the beginning of the concussion evaluation to assess visual symptoms. The investigator did not ask the CISS questions verbally, rather, the participants completed the CISS using an iPad. After the concussion examination the physician reached a diagnosis of concussion or no concussion. In addition, the physician made a clinical decision about whether the participant had persistent post-concussion symptoms based on the history, the Post-Concussion Symptom Inventory, and symptom provocation experienced after each test of the visio-vestibular examination.

2.3. Comprehensive oculomotor evaluation

Baseline tests were performed by an optometrist, directly following the concussion examination. This comprehensive oculomotor evaluation included best-corrected visual acuity at distance (Snellen Chart), non-cycloplegic auto-refraction, and a sensorimotor examination including cover testing at distance and near, near point of convergence, positive and negative fusional vergence at near using a prism bar (step vergence), vergence facility at distance and near (near vergence facility was performed first), monocular accommodative amplitude, and monocular accommodative facility, the Developmental Eye Movement Test (DEM). Details of the purpose, administration details, and criteria for identifying a problem for each test are listed in Table 1. This test battery (except for the DEM and vergence facility performed at distance) has been used in previous studies to identify binocular vision, accommodative and eye movement disorders (Master et al., 2016; Scheiman et al., 2005; CITT-ART Investigator Group, 2019; Convergence Insufficiency Treatment Trial Investigator Group, 2008), and the clinical protocol is available at https://optometry.osu.edu/CITT-manual-procedures. Vergence facility testing at distance (4 m) was added to the test battery based on recent literature suggesting that it is a more sensitive test for detecting vergence facility problems than vergence facility performed at near for patients with convergence insufficiency (Scheiman and Wick, 2019; Trieu et al., 2016).

2.4. Diagnostic criteria

After completion of the comprehensive oculomotor evaluation, the optometrist who performed the examination, used the diagnostic criteria listed in Table 2 to identify whether the participant had normal oculomotor function or an oculomotor disorder. These criteria are similar to those used in a previous publication (Master et al., 2016), with some modification based on a study by Raghuram et al. (Raghuram et al., 2019). In a number of previous studies the severity of the convergence insufficiency has been categorized based on the numbers of signs that are present (3-sign convergence insufficiency, 2-sign convergence insufficiency) (Rouse et al., 1998a, 1997b, 1997c). To be considered a 3-sign convergence insufficiency an individual must have at least $\geq 4\Delta$ more exophoria at near than at distance, a receded near point of convergence, and reduced positive fusional vergence. A 2-sign convergence insufficiency would still require at least $\geq 4\ \Delta$ more exophoria at near than at distance, but only one of the other two signs. In this study, participants with either 2- or 3-sign convergence insufficiency were included in the convergence insufficiency diagnostic category. The major change from our previous study (Master et al., 2016) was to add a new diagnostic category to allow us to identify a condition in which participants have a receded near point of convergence but do not meet the exophoria criterion (described above) required to be classified as having convergence insufficiency. This change in our classification system was based on recent research (Raghuram et al., 2019) that showed this is a common finding post-concussion, and in that study the authors named this condition “convergence deficit”. We used the same terminology in this study (Table 2).

Table 1
Vision Examination Tests.

Name of Test	Administration Details	Failure Criteria
Cover/Uncover Test	• Performed at 4 m and 40 cm • Fixation target: vertical column of 20/30 letters	• Any strabismus
Prism and Alternate Cover Test	• Performed at 4 m and 40 cm • Fixation target: vertical column of 20/30 letters	• Esophoria $\geq 3\ \Delta$ at distance or near • Exophoria 4 Δ greater at near than at distance • Exophoria $\geq 10\ \Delta$ at distance
Near Point of Convergence	• Gulden Near Point Rod • Fixation target: vertical column of 20/30 letters	• ≥6cm
Positive Fusional Vergence	• Horizontal prism bar • Testing distance 40 cm • Fixation target: vertical column of 20/30 letters	• $\leq 15\ \Delta$ break or Sheard’s criterion not met
Negative Fusional Vergence	• Horizontal prism bar • Testing distance 40 cm • Fixation target: vertical column of 20/30 letters	• $< 8\ \Delta$ break or Sheard’s criterion not met
Vergence Facility (12 base-out/3 base-in)	• 12 base-out/3 base-in • Testing distance 40 cm and 4 m • Fixation target: vertical column of 20/30 letters	• ≤9cpm
Accommodative Amplitude	• Testing distance 40 cm • Fixation target: vertical column of 20/30 letters	• <15–1/4 age-2D
Accommodative Facility (+2/−2 lenses)	• Testing distance 40 cm • Fixation target: vertical column of 20/30 letters	• ≤ 6 cpm
Developmental Eye Movement Test (DEM)	• DEM Test Plates A-C	• Ratio Score: 1 SD or more below the mean Accuracy Score: 1 SD or more below the mean

2.5. Statistical analysis

All analyses were performed using SPSS Version 24.0. The frequency of vergence, accommodative, and saccadic disorders was assessed based on the diagnostic criteria in Table 2. Means, standard deviations, and ranges were calculated for age and days since injury. We divided the sample into 3 subgroups based on the time since the concussion injury and when they were examined: 4 to 6 weeks, 7 to 9 weeks, and 10 to 12 weeks post-injury. We only included diagnostic conditions with a sample size of 20 or more participants. Using Chi Square analysis, we compared the frequency of the various oculomotor disorders in these 3 time periods. To assess the accuracy of the physician-administered screening to identify convergence or accommodative insufficiency compared with the clinical diagnosis reached by the optometrist based on a comprehensive oculomotor examination, we calculated sensitivity and specificity for the following with the established cutoff values: the near point

Table 2
Diagnostic Criteria for Vergence, Accommodation, and Eye Movement Disorders.

Clinical Diagnosis & Findings	Diagnostic Criteria
Convergence Insufficiency	**First criterion and one other must be met**
Exophoria at near	4 Δ greater exophoria than at distance
Near point of convergence (NPC)	≥ 6 cm break
Positive fusional convergence	≤ 15 Δ break or Sheard's[a] criterion not met
Vergence facility (D or N) (3 Δ BI/12 Δ BO)	≤ 9 cpm with difficulty fusing BO
Convergence Deficit[b]	**First criterion and one other must be met**
Near point of convergence (NPC)	≥ 6 cm break
Positive fusional vergence	≤ 15 Δ break or Sheard's[a] criterion not met
Vergence facility (D or N) (3 Δ BI/12 Δ BO)	≤ 9 cpm with difficulty fusing BO
Convergence Excess	**First criterion and one other must be met**
Esophoria at near	≥3 Δ
Negative fusional vergence	< 8 Δ break or fails Sheard's[a] criterion
Vergence facility (D or N) (3 Δ BI/12 Δ BO)	≤ 9 cpm; difficulty fusing BI prism
Fusional Vergence Dysfunction	**Either criterion is met**
Vergence amplitudes	Positive fusional vergence ≤ 15 Δ break or "Sheard's criterion[a] not met, and negative fusional vergence < 8 Δ break or fails Sheard's[a] criterion
Vergence facility (D or N) ((3 Δ BI/12 Δ BO)	≤ 9 cpm with difficulty fusing BO AND BI
Accommodative Insufficiency	**First criterion or second criterion met with right eye**
Accommodative amplitude	>2D less than < 15–1/4 age
Accommodative facility	≤ 6 cpm (difficulty with minus lenses)
Accommodative Infacility	**Monocular Criteria: Met with right eye**
Accommodative facility	≤ 6 cpm (difficulty with both + 2D and −2 D lenses)
Accommodative Excess	**Monocular Criteria: Met with right eye**
Accommodative facility	≤ 6 cpm (difficulty with + 2D)
Saccadic Dysfunction	**First criterion or second criterion must be met**
Developmental Eye Movement (ratio score)	>1 SD or more below the mean
Developmental Eye Movement (accuracy score)	>1 SD or more below the mean

[a]Compensating vergence amplitudes (positive or negative fusional vergence) of at least twice the magnitude of the near phoria; [b]Participants did not have exophoria greater at near than at far; Δ = prism diopter; BI = base-in; BO = base-out; cpm = cycles per minute; D = diopters

of convergence (≤6 cm) for detecting convergence insufficiency, accommodative amplitude (<15–1/4 age −2D) for detecting accommodative insufficiency, and the CISS (≥16) for detecting saccadic disorders. Sensitivity refers to how well a test correctly identifies people who have the disease, and specificity refers to how well the test identifies people who do not have the condition. We used a one-way ANOVA to determine if there were any differences between the mean CISS score for those with no oculomotor disorders, compared to those with either convergence insufficiency alone or accommodative insufficiency alone.

3. Results

One hundred and twenty-seven participants were examined and 113 were enrolled during the study period. Fourteen potential participants were excluded at baseline. Nine participants were excluded because they had worse than 20/30 visual acuity in one or both eyes, did not bring their glasses, the eyeglass prescription required a change, or there was significant uncorrected refractive error. The mean spherical equivalent and standard deviation of the 113 participants was −1.10D +/- 2.00D for the right eye and −0.94D +/- 1.80D for the left eye. Three participants had amblyopia, and two had a pre-existing history of strabismus. The mean age was 15.2 years (SD = 1.8, age range 11.3 to 17.9 years). Of the study participants, 65% (74/113) were female, and 50% (57/113) sustained their concussion as the result of sports participation. Seventy of the 113 (62%) participants were found to have vestibular problems for which vestibular therapy was recommended. The most common sports injury for females was soccer-related, and for males it was, football-, lacrosse-, and soccer–related. The most frequent cause of injury was being struck by an object for females and struck by a person or by an object for males (Table 3).

Participants were seen between 4 weeks (28 days) and 12 weeks (84 days) of their injury with a mean of 52 days (SD = 15.8 days). All participants had persistent concussion symptoms based on the physician's analyses of symptoms elicited during the clinical case history, scores on the Post-Concussion Symptom Inventory, and any increase in symptoms elicited during the physician's visio-vestibular examination. The three most common symptoms elicited during the visio-vestibular examination were headache, difficulty concentrating, and fatigue. In regard to the participant's visual symptoms, the mean CISS score was 22.5 (SD = 13.9). Based on previous research (Rouse et al., 2009; Borsting et al., 2003) a CISS score of 16 or higher is considered a significant level of visual symptoms.

For those participants with persistent concussion symptoms and normal oculomotor function (n = 34), the mean CISS score was 18.1 (SD = 14.6), compared with to those who had a diagnosis of convergence insufficiency or convergence deficit without accommodative insufficiency [n = 21, CISS score 26.1 (SD = 12.9)], or accommodative insufficiency alone [17.0 (SD = 14.9)]. The results of an ANOVA revealed no statistically significant differences among the groups (normal oculomotor function, convergence insufficiency, convergence deficit, accommodative insufficiency) [$F(2,61) = 2.36$, $P = .10$]. Each question of the CISS can be scored on a 0 to 4 Likert scale. The three symptoms on the CISS that had the highest median and sum values were; lose concentration (median = 2.00, sum = 237, 47 participants scored

Table 3
Cause of Injury.

Cause of Injury	N (Males)	%	N (Females)	%	N Total	Total %
Sport-Related						
Soccer	5	4	12	11	17	15
Lacrosse	5	4	3	3	8	6
Football	6	5	0	0	6	5
Cheerleading	0	0	4	4	4	4
Basketball	2	2	1	1	3	3
Rugby	0	0	3	3	3	3
Crew	1	1	1	1	2	2
Field hockey	0	0	2	2	2	2
Softball	0	0	2	2	2	2
Wrestling	2	2	0	0	2	2
Dodgeball	0	0	1	1	1	1
Free Play	1	1	0	0	1	1
Gymnastics	0	0	1	1	1	1
Horseback Riding	0	0	1	1	1	1
Kickball	0	0	1	1	1	1
Snowboarding	0	0	1	1	1	1
cccccccc	0	0	1	1	1	1
Volleyball	0	0	1	2	1	1
Baseball	0	0	0	0	0	0
Ice hockey	0	0	0	0	0	0
Swimming	0	0	0	0	0	0
Tennis	0	0	0	0	0	0
Track/field	0	0	0	0	0	0
TOTAL	22	18	35	31	57	50
Non-Sports-Related/Cause of injury						
Struck by object or against object	13	12	34	30	47	43
Struck by person	15	13	13	12	28	25
Fall	4	4	15	13	19	17
Struck as Pedestrian	2	2	2	2	4	4
Assault	2	2	1	1	3	2
Passenger in car	1	1	2	2	3	2
Bicycle –related	1	1	0	0	1	1
Other	0	0	8	7	8	7
TOTAL	38	34	76	67	113	100

above 2), headaches (median = 2.00, sum = 228, 46 participants scored above 2), and eyes feel tired (median = 2.00, sum = 216, 34 participants scored above 2), all related to reading or when doing close work.

Table 4 lists the percentage of participants identified as failing any individual tests based on the established criteria. The 3 tests most frequently failed were vergence facility performed at distance (61%), the CISS (61%), and the near point of convergence (60%).

3.1. Frequency data

Seventy-nine of the 113 (70%) of enrolled participants had at least one oculomotor diagnosis after concussion, with the most common problems being vergence disorders 60%, accommodative disorders 56%, accommodative insufficiency 35%, and convergence insufficiency 34% (Table 5). Of note, 53% of the participants had more than one vision diagnosis following concussion, and 86% of participants with convergence insufficiency also had accommodation deficits including accommodative insufficiency, excess, and infacility.

3.2. Frequency data related to time of enrollment post-injury

We subdivided the span of 4 to 12 weeks into three categories (4 to 6 weeks, 7 to 9 weeks, 10 to 12 weeks post-concussion) to test the hypothesis that the frequency would decrease over time as the enrollment time frame moved further away from the time of injury. There were no statistically significant differences for any of the diagnostic conditions (Table 6)

3.3. Physician-administered screening tests

The two screening tests performed by the physicians were the near point of convergence and accommodative amplitude. Although the physicians and optometrists used the identical equipment and test protocols, there were statistically significant differences in the mean values when we compared the physician to the optometrist results. For the near point of convergence, the means/standard deviations were 5.02 cm/2.89, and 7.6 cm/4.3 for the physician and optometrist assessment, respectively ($P < .0001$). For the accommodative amplitude we found 7.94 cm/3.49 and 11.32 cm/3.78 for the physician and optometrist assessment, respectively ($P < .0001$).

We determined the sensitivity and specificity of physician-administered measurement of the near point of convergence break for detecting convergence insufficiency or convergence deficit compared to the reference standard of the oculomotor diagnosis determined by an optometrist based on a comprehensive oculomotor evaluation. The results are listed in Table 7 and show low sensitivity for the near point of convergence alone, or the CISS as a stand-alone test with reasonably good specificity. Thus, the use of the near point of convergence break or the CISS score alone would potentially result in under referral of these

Table 4
Percentage of participants identified as failing criteria for each test (N = 113).

Name of Test	Criteria used to determine problem	N (%)
Convergence Insufficiency Symptom Survey	Score of ≥ 16	69 (61)
Prism and Alternate Cover Test (near)	Esophoria ≥ 3 Δ	10 (11)
Prism and Alternate Cover Test (distance)	Exophoria 4 Δ greater than at distance	39 (35)
Near Point of Convergence	≥6cm	68 (60)
Positive Fusional Vergence (near)	≤ 15 Δ break or Sheard's criterion not met	34 (30)
Negative Fusional Vergence (near)	< 8 Δ break or Sheard's criterion not met	4 (4)
Vergence Facility (12 BO/3 BI) (distance)	≤9cpm	69 (61)
Vergence Facility (12 BO/3 BI) (near)	≤9cpm	47 (42)
Accommodative Amplitude (right eye)	>2 D<15–0.25 (age in years)	40 (35)
Accommodative Facility (+2/-2 lenses) (right eye)	≤ 6 cpm	11 (10)
Accommodative Facility (failed + side of test right eye)	Can easily clear minus, but not plus lenses	13 (12)
Developmental Eye Movement Test (DEM- Accuracy)	Error score > 1 SD	6 (5)
Developmental Eye Movement Test (DEM- Speed)	Ratio score > 1 SD	18 (16)

Δ = prism diopter; cm = centimeters; cpm = cycles per minute; D = diopters; DEM = Developmental Eye Movement Test; BO = base-out; BI = base-in

Table 5
Frequency of Vision Problems (N = 113).

Diagnosis	N	%
No vision disorder	34	30
Convergence insufficiency	39	35
Convergence deficit	11	10
Convergence excess	10	9
Fusional vergence dysfunction	8	7
Vergence disorders combined	68	60
Accommodative insufficiency	40	35
Accommodative excess	13	12
Accommodative infacility	11	10
Accommodative disorders combined	64	57
Saccadic dysfunction	20	18

Table 6
Time post-injury and its effect on frequency of oculomotor disorders.

	4–6 weeks	7–9 weeks	10–12 weeks	Total	Pearson Chi-Square
# of subjects	38	47	28	113	
Diagnosis(N)	**% with dx (N)**	**% with dx (N)**	**% with dx (N)**		
Vergence disorder combined	53% (20)	70% (31)	61% (17)	68	$P = .44$
Convergence insufficiency	26% (10)	36% (17)	43% (12)	39	$P = .20$
Accommodative disorder combined	66% (25)	55% (26)	46%(13)	64	$P = .34$
Accommodative insufficiency	40% (15)	32% (15)	36% (10)	40	$P = .71$
Saccadic dysfunction	21%(8)	17%(8)	14%(4)	20	$P = .76$
Normal	37% (14)	21% (10)	36%(10)	34	$P = .23$

Table 7
Sensitivity and specificity of screening tests for the detection of oculomotor disorders.

Comparison Physician Administered screening test/compared to reference standard	Sensitivity (%) True Positive	Specificity (%) True negative
Detection of Convergence Disorder		
NPC/diagnosis of convergence disorder	63	88
CISS/diagnosis of convergence disorder	47	80
NPC + CISS/diagnosis of convergence disorder	94	49
Detection of Accommodative Insufficiency		
AA/diagnosis of accommodative insufficiency	43	80
CISS/diagnosis of accommodative insufficiency	42	70
AA + CISS/diagnosis of accommodative insufficiency	75	38
Detection of any concussion-related vision disorder		
CISS/diagnosis of any concussion-related vision disorder	48	97
NPC + AA + CISS/diagnosis of any concussion-related vision disorder	76	61

NPC = near point of convergence; AA = accommodative amplitude, AI = accommodative insufficiency; CISS = Convergence Insufficiency Symptom Survey conditions. When the near point of convergence and the CISS test are combined, the sensitivity is excellent, but the specificity drops to less than 50% which would lead to over-referral. We also compared the physician-administered accommodative amplitude alone, the CISS alone, or a combination of the accommodative amplitude plus CISS to the reference standard. The results indicate poor sensitivity with the accommodative amplitude or CISS alone, with better specificity. The combination of accommodation amplitude and the CISS yielded the highest sensitivity, but with very poor specificity.

Table 7 also provides the results for the sensitivity and specificity of the physician-administered measurement of the CISS alone or CISS plus the near point of convergence, and accommodative amplitude for detecting any oculomotor problem (vergence, accommodation, eye movement). The CISS alone has poor sensitivity, but excellent specificity, while the combination of all three measures yields better sensitivity and borderline specificity.

4. Discussion

4.1. Overview

In this study of 11 to 17-year-old adolescents evaluated 4 to 12 weeks post concussion, 70% were found to have one or more oculomotor deficiencies, with vergence disorders present in 60%, accommodative disorders in 57%, and saccadic dysfunction in 18%. The most common diagnoses were accommodative insufficiency (35%) and convergence insufficiency (35%). These frequency findings are lower than a previous study published by our investigator group in which 49% had convergence insufficiency and 51% had accommodative insufficiency. These differences may be due to the more restricted eligibility criterion used in this study in which we only enrolled participants 4 to 12 weeks post-injury. In the previous study, 29% of the sample were less than 4 weeks post-injury, 26% were evaluated between 1 and 3 months after their injury, and 45% were seen > 3 months after their injury. The participants seen before 4 weeks post-concussion were more likely to have a vision diagnosis than those evaluated more than 1 month after injury (Master et al., 2016). In addition, in the previous study the criteria for convergence insufficiency were different and did not consider the diagnosis of convergence deficit. If we combine those two categories here (as was done in the previous study), the frequency of convergence insufficiency in the present study is 44%.

4.2. Comparison to non-concussed adolescents

Although we did not have an age-matched control group of neurologically-normal, non-concussed adolescents in this study, there is one recent study of 295 neurologically-normal, non-concussed children, 6 to 18 years old in which the near point of convergence was assessed (Corwin et al., 2018). The authors found that only 2.4% of the participants failed the near point of convergence test using the ≥ 6 cm criterion.

While frequency data are available for non-strabismic vergence and accommodative problems in adolescents with no history of concussion (Rouse et al., 1999; Hussaindeen et al., 2017; Wajuihian and Hansraj, 2016; Davis et al., 2016), comparison to these previous studies is challenging because different diagnostic criteria were used. However, the exception is the 3- or 2-sign convergence insufficiency definition (Rouse et al., 1999; Hussaindeen et al., 2017; Wajuihian and Hansraj, 2016; Davis et al., 2016). The frequency of 3- or 2-sign convergence insufficiency in the four studies of non-concussed children ranged from 6.2% to 19.6% compared with 39.8% found in this study and 49% in a previous study of adolescents after concussion (Master et al., 2016). The frequency of accommodative insufficiency ranged from 8% to 18.2% in the two studies of non-concussed children (Hussaindeen et al., 2017; Davis et al., 2016) compared with 35.4% in this study, and 51% in a previous study of adolescents after concussion (Master et al., 2016).

4.3. Comparison of frequency of the conditions related to time since injury

We did not find any statistically significant differences in the frequency of the diagnostic conditions between 4 and 12 weeks post-concussion. This result is not surprising since this was a cross-sectional rather than a longitudinal study.

4.4. Physician screening compared to a comprehensive examination

In clinical practice, non-eye care professionals are likely to screen for convergence, accommodative, and eye movement problems first before recommending a comprehensive eye examination. A number of authors have suggested that the near point of convergence could be used to screen for post-concussion vision disorders, particularly convergence insufficiency (Storey et al., 2017; Pearce et al., 2015; Mucha et al., 2014; DuPrey et al., 2017). However, in a recent study, investigators found that a receded near point of convergence is not synonymous with a diagnosis of convergence insufficiency, suggesting that using the near point of convergence test alone for a screening is insufficient (Raghuram et al., 2019). In this study, we had the opportunity to compare the physician-administered screening to detect convergence and accommodative insufficiency to a diagnosis of these conditions by an optometrist based on a comprehensive oculomotor examination. Physicians used the same standard equipment (near point rod) and administration protocol as the optometrist. The results show that using a cutoff value of ≥ 6 cm for the near point of convergence test alone misses one of every three children with convergence insufficiency compared to an evaluation by an optometrist. The monocular amplitude of accommodation test correctly identifies only four of 10 children with accommodative insufficiency. These data suggest that as a stand-alone tests the near point of convergence and accommodative amplitude tests are somewhat useful but could result in an unacceptable false negative rate. Other combinations of screening tests were also evaluated (near point of convergence + CISS, accommodative amplitude + CISS), but none yielded a satisfactory combination of sensitivity and specificity (Table 7). Thus, while it certainly is advisable for non-eyecare professionals to screen for vision problems for patients with persistent post-concussive symptoms, there needs to be an awareness of the potential for these tests to under-detect these problems. If such a screening reveals negative results, but the patient continues to struggle with recovery, a more extensive oculomotor examination performed by an eye care professional is warranted.

4.5. Value of the CISS as a screening tool

The Convergence Insufficiency Symptom Survey (CISS) was designed to quantify the severity of symptoms associated with convergence insufficiency and primarily to be used as an outcome measure to assess changes in symptoms after treatment. Studies have established its construct validity and reliability (Rouse et al., 2009; Borsting et al., 2003). The CISS has since been used as the primary outcome measure for multiple randomized trials evaluating the effectiveness of active treatments for symptomatic convergence insufficiency in populations other than concussed adolescents (Scheiman et al., 2005a, 2005b, 2005c, 2016d; CITT-ART Investigator Group, 2019; Convergence Insufficiency Treatment Trial Investigator Group, 2008; Momeni-Moghaddam et al., 2015; Aletaha et al., 2018). Some researchers have attempted to use it as a screening test for convergence insufficiency and other binocular vision and accommodative problems with varying results (Horwood et al., 2014; Clark and Clark, 2017; Horan et al., 2015). In most cases the CISS was not found to be useful as a stand-alone screening test to identify patients with convergence insufficiency. This is not surprising since the CISS was not designed to do this. In this study we evaluated the potential value of using the CISS in the concussion examination as a way to identify an adolescent who may benefit from a vision assessment. The sensitivity and specificity analysis using the recommended cutoff value of ≥ 16 suggests that the CISS alone is not an effective tool in isolation to diagnose vision disorders following concussion. In addition, it is interesting that in participants considered to have normal oculomotor function, the mean CISS score was 18.1, which is higher than the suggested cutoff of ≥ 16. This finding suggests that perhaps these patients have other co-morbid, non-visual conditions causing the elevated symptoms. The CISS has not been validated or designed to be used with the population of patients with persistent post-concussion symptoms. It would need to be modified to include additional questions that are appropriate for this population and re-validated.

4.6. Strengths and limitations

Strengths of this study include its prospective design, the use of eye care professionals to perform the vision testing, and pre-defined diagnostic criteria. Limitations include the lack of an age-matched control group with no history of concussion. The inclusion of a control group with no history of concussion would have strengthened the significance of the outcome data. It should also be noted that we deviated from the traditional administrative protocol for the CISS. We allowed participants to complete the survey on their own using an iPad instead of reading each symptom out loud to the participant.

5. Conclusions

These results indicate a high frequency of convergence, accommodative, and saccadic disorders in adolescents with persistent post-concussion symptoms that persist 1-month post-injury. The symptoms associated with these vision disorders may contribute to the challenges of returning to school and sports. Unfortunately, simply screening these adolescents by performing a near point of convergence or accommodative amplitude test, as is often done, fails to detect one-third of those with a convergence disorder and more than 50% of those with accommodative insufficiency, respectively. Our data suggest that it is prudent for adolescents with persistent post concussion symptoms more than 1-month post-injury to undergo a comprehensive evaluation for vergence, accommodative, and saccadic dysfunctions.

CRediT authorship contribution statement

Mitchell Scheiman: Conceptualization, Methodology, Investigation, Writing - original draft. **Matthew F. Grady:** Investigation, Writing - review & editing. **Erin Jenewein:** Investigation, Writing - review & editing. **Ruth Shoge:** Investigation. **Olivia E. Podolak:** Investigation, Writing - review & editing. **David H. Howell:** Conceptualization, Methodology, Writing - review & editing. **Christina L. Master:** Conceptualization, Methodology, Investigation, Writing - original draft.

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