BMJ Open Sport & Exercise Medicine

Evaluation of the vestibular and ocular motor screening (VOMS) as a prognostic tool for protracted recovery following paediatric sports-related concussion

Gregory Knell ,[1,2,3] Todd Caze,[3,4] Scott O Burkhart[3]

To cite: Knell G, Caze T, Burkhart SO. Evaluation of the vestibular and ocular motor screening (VOMS) as a prognostic tool for protracted recovery following paediatric sports-related concussion. *BMJ Open Sport & Exercise Medicine* 2021;**7**:e000970. doi:10.1136/bmjsem-2020-000970

Accepted 15 March 2021

[1]Center for Pedatric Population Health, Children's Health System of Texas and University of Texas Health Science Center at Houston, Dallas, TX, USA
[2]Epidemiology, Human Genetics, and Environmental Sciences, University of Texas Health Science Center at Houston, Dallas, TX, USA
[3]Andrews Institute for Orthopaedics and Sports Medicine, Children's Health System of Texas, Plano, TX, USA
[4]Department of Psychiatry, University of Texas Southwestern Medical School, Dallas, Texas, USA

Correspondence to
Dr Gregory Knell;
gregory.knell@uth.tmc.edu

ABSTRACT

Objective To understand the relationship between initial vestibular and ocular motor screening (VOMS) and recovery time, and the utility of VOMS to screen for protracted recovery in youth/adolescent patients with sport-related concussion (SRC).

Methods Participants (8–18 years) who were diagnosed with an SRC within 7 days of the injury were administered the VOMS test by certified medical personnel. Recovery time (days) and protracted recovery (>30 days) were the primary outcomes. Multivariable regression models were used to evaluate the association between VOMS symptom provocation and (1) recovery time (days) and (2) protracted recovery. Measures of VOMS validity, predictive ability and receiver operator curves were used to assess VOMS as a prognostic tool to accurately classify a normal/protracted recovery.

Results After adjustment, any symptom provocation across all VOMS domains was associated ($p<0.05$) with greater recovery time, except the convergence test ($p=0.08$) in females. All VOMS test thresholds (≥1 to ≥10) in males and (≥1 to ≥5) in females were associated ($p<0.05$) with recovery time. However, the VOMS test performed poorly among males (receiver operating characteristic (ROC) area=0.66) and failed among females (ROC area=0.56) as a prognostic tool to identify those that will have a normal/protracted recovery.

Conclusion In this sample, overall, the VOMS test was associated with recovery time (days); however, the VOMS was not a valid stand-alone prognostic tool to identify a delayed recovery, but may be useful in combination with other concussion symptomology assessments. Future studies should confirm these findings in larger samples while taking into consideration other comorbid factors that may influence recovery time.

What are the new findings

The vestibular and ocular motor screening (VOMS) is not a valid prognostic tool to identify patients with sport-related concussion who will take longer than 30 days to recover in a paediatric sample.

How might it impact on clinical practice in the near future

These results demonstrate that elements of the VOMS test are significantly related to recovery time, and therefore future clinical practice may include VOMS as a necessary element of a larger prognostic evaluation for protracted recovery.

INTRODUCTION

Sport-related concussions (SRCs) during childhood and adolescence are a significant public health problem.[1] Recent reports suggest that up to 1.9 million youth athletes suffer an SRC each year,[2] and despite efforts to mitigate concussion risk,[3–6] there is evidence of increasing trends in SRC risk in some notable sports.[7] Although SRCs are generally a short-term injury, with most recovering within 1 month, a proportion of children and adolescents experience delayed or protracted recovery from an SRC.[8] A protracted SRC recovery may progress to long-term health complications, such as declines in academic performance, social engagement, and quality of life ratings, elevated mood dysfunction, higher healthcare utilisation and disability.[9 10]

Given the potential for several deleterious long-term health effects associated with a protracted SRC recovery, there have been several recent studies aimed at identifying risk factors for SRC recovery time and protracted recovery. Evidence suggests greater severity and volume of symptoms are the strongest predictors of slower recovery.[11] Demographic and preinjury factors of sex,[12 13] younger age,[13–15] personal history of migraine,[10] preinjury mental health problems[16] and concussion history[17] have also been found to be related to recovery time. There is some evidence on the potential effect of postacute

injury factors on recovery time, such as loss of consciousness, retrograde amnesia and anterograde amnesia; however, findings have been inconsistent.[11 18] Despite the seemingly wide array of factors associated with SRC recovery time, the evidence clearly demonstrates that the onset and development of postinjury SRC-related symptoms (headaches or migraines,[19] dizziness,[20] ocular motor problems,[20] visual motor speed[21]) are markedly related to SRC recovery time. Unfortunately, no clinic-based tools or measures exist to identify those patients with SRC who are at risk of a protracted recovery. However, one such tool, the vestibular and ocular motor screening (VOMS), has been found to be related to SRC recovery time in samples of children and adolescents,[22–24] and young adults.[25]

The VOMS is a symptom provocation measure developed to differentiate athletes with concussion from non-concussion controls.[26 27] VOMS assesses several domains within ocular motor and vestibular function. Although previous research has found VOMS to be related to recovery time in varied populations, the VOMS has not been evaluated as a prognostic tool to identify those who may take longer to recover from an SRC. This can aid clinicians in determining the likelihood of a patient taking longer than expected to recover, thereby allowing for more personalised follow-up procedures to improve clinical management and long-term patient outcomes. Therefore, the current aims of this paper are: (1) to determine the association between recovery time and (A) symptom provocation across the various VOMS domains and (B) a positive test using various VOMS thresholds, and (2) to determine the utility of VOMS as a prognostic tool to identify those adolescents who will have a normal/protracted recovery from SRC.

METHODS

Study design, setting and participants

Data for this prospective case series study were collected between October 2017 and January 2020 at a paediatric sports concussion clinic in Plano, Texas. Data for all measures were collected at the time of initial clinical examination apart from clinical recovery time which was collected at the date of medical clearance. Study inclusion criteria were patients aged 8–18 years, participating in a sport at the time of injury, diagnosed with an SRC and evaluated within 7 days from the initial date of injury. Exclusion criteria included any of the following: previous diagnosis of developmental delay, diagnosis of comorbid neck or spine injuries, previous diagnosis of congenital or acquired neurological defect or injury (moderate to severe traumatic brain injury) not related to the current concussion injury and inability to understand the premise of the study due to language barriers. Prior to the collection of any study-related data, all participants and their parents (if the participant was a minor) were given written informed consent and provided signatures of consent/assent.

Data collection

Study participants were administered the VOMS by one of six licensed medical professionals (physician, neuropsychologists, nurse practitioner, certified athletic trainer) trained in the administration of the VOMS.[26] Only one individual administered the VOMS test per participant; however, the individual administering the VOMS differed across patients. All those administering the VOMS were trained by a single neuropsychologist to ensure standardised administration of VOMS. All participant data were collected on a study-designed data sheet and later entered into database software by the study coordinator. The data collection procedure occurred as part of the standard clinical examination for which the participant was a patient in the clinic. The standardised clinical evaluation includes a clinical interview to ascertain details of the injury including mechanism, loss of consciousness, post-traumatic amnesia, history of concussion, current symptoms and what settings elicit symptom provocation. The clinical interview was conducted first, followed by the VOMS or cognitive testing. Analysis of the data occurred after all data were collected using Stata/MP V.15.1 (StataCorp, College Station, Texas, USA).

Variables

Sport-related concussion

Participants with suspected concussions, defined as a 'complex pathophysiological process affecting the brain, induced by biomechanical forces',[28] were diagnosed by a licensed medical professional trained in the assessment and treatment of concussion with the following criteria required for diagnosis: clear mechanism of injury, presence of symptoms at time of injury, current symptoms and one or more areas of cognitive impairment. All concussions were required to have occurred during sports participation.

Vestibular and ocular motor screening

The VOMS is a symptom provocation measure using smooth eye pursuit movements, saccadic eye movements, near point of convergence, vestibular ocular reflex and visual motion sensitivity to differentiate athletes with concussion from non-concussion controls.[27] The VOMS integrates the interaction of the vestibular and ocular motor systems and includes both patient and clinician reporting.[22] For aim 1A, to determine the association between recovery time and symptom provocation across the various VOMS domains, a symptom provocation was calculated by taking the sum of the differences in symptom provocation scores (scale of 0–10) from baseline for each VOMS test. The sum of differences in symptom provocation scores (from baseline to post-VOMS domain test) was modelled as discrete estimates. For aim 1B, to determine the association between recovery time and a positive test using various VOMS test thresholds, a positive VOMS test using a *k*-unit threshold was defined as a symptom provocation increase of at least *k*-units from baseline. For instance, a positive VOMS test using a 1-unit threshold

was defined as a symptom provocation increase of at least 1 unit from baseline on any VOMS test. Positive VOMS test thresholds 1–10 were modelled to determine the association between a positive VOMS test and recovery time in days (aim 1B) and to determine the utility of VOMS as a prognostic tool in correctly identifying those adolescents who will have a normal/protracted recovery from SRC (aim 2).

Recovery time

For aim 1, recovery time (days) was the primary outcome of interest. Recovery was defined as the date of medical clearance and included athletes being completely returned to both academics and sports participation. Consistent with current consensus guidelines,[1] medical clearance for a full return to play was defined as a return to preinjury levels of symptoms and preinjury levels of cognitive, vestibular and ocular performance along with no symptom provocation during exertion.[29] Patients were evaluated at each follow-up clinical visit for potential medical clearance. Typically, a follow-up visit was scheduled 7–14 days after the initial clinical visit. Additionally, participants were instructed to adjust the scheduling of follow-up visits based on their own self-reported recovery. If the patient was not medically cleared at the first follow-up visit, a second follow-up visit was scheduled 7–14 days after the initial follow-up visit. This pattern repeated itself until the patient was medically cleared. Recovery time in days was estimated as the date of medical clearance subtracted by the date of injury.

Protracted recovery

For aim 2, protracted recovery was the primary outcome of interest. Protracted recovery was defined as a recovery time taking greater than or equal to 30 days from the date of injury to the date of medical clearance.[23 29–31]

Other variables

Variables entered as potential confounders based on their known associations with VOMS and recovery time were collected as part of the standard patient intake form. These included age, sport played when injured, history of concussion(s) and the time since injury (days). The sport played when injured was reported by the participant and included 31 unique sports. Each sport was then classified as a non-contact, contact or collision sport based on previously defined criteria.[32]

Data analysis

The variables of interest used in the subsequent models to estimate the association between VOMS test scores and SRC recovery time were assessed for missing data and normality when appropriate. Participant characteristics were evaluated with t-tests, Hosmer-Lemeshow and χ^2 tests for heterogeneity to determine if there were statistical differences in the mean, median and proportion estimates, respectively.

For aim 1, the outcome of interest was a count of the number of days to recover, which was inherently absent of zeros. To account for this data structure, zero-truncated negative binomial regression models were built to estimate the relation between recovery time (days) and symptom provocation across the various VOMS domains (aim 1A) and a positive VOMS test across thresholds (aim 1B). Models were built in sex stratum to account for potential modifying effects. The models included a crude (unadjusted) model, age-adjusted model and a fully adjusted model. Covariate selection for the multivariable model was based off bivariable tests for associations between protracted recovery and the covariate of interest. Those statistical tests reaching a threshold level of 0.05 were included in the multivariable model. Age was locked in the model given the possibility of a certain level of cognitive development required to understand or answer the questions accurately. Tests for collinearity between variables were performed along with post hoc analyses of model fit and tests for the appropriateness of the zero-truncated negative binomial model selection. Observations producing outlying days to recover (males, >60 days (n=5); females, >70 days (n=8)) were deleted to improve the overall model fit.

The prognostic ability of the VOMS tool for identifying participants as having a normal or protracted recovery (aim 2) was tested using receiver operating characteristics (ROC), and estimates of sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) for each of the VOMS positive test thresholds (1–10). The area under the ROC curve was qualitatively evaluated based on the following criteria: ≥0.90, excellent; 0.89–0.80, good; 0.79–0.70, fair; 0.69–0.60, poor; ≤0.60, fail.

Sensitivity analysis

Sensitivity analyses were conducted to (1) examine the effect of including those aged 8–9 years in the analytical sample and (2) to examine the potential for bias when excluding those observations which took longer than 60 days (males) and 70 days (females) to recover from the SRC. Tests for differences by sex, sport type, concussion history and days since injury by those included and those excluded, as well as comparisons of the estimated effect sizes and measures of association were used to detect the presence of a bias.

Patient and public involvement

Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

RESULTS

Table 1 details the participants' characteristics by protracted recovery (>30 days) classification. No variable used in the analysis contained greater than 10% missing data (see table 1), therefore a complete case analysis was used in analyses. A total of 407 (74.1%) participants recovered in a median (IQR) 18.0 (13.0–23.0) days, which was significantly less (p<0.001) than the 142 protracted

Table 1 Descriptive statistics by recovery status in patients undergoing concussion recovery treatments in a paediatric clinic setting, 2017–2020

	Recovery time*, n (%)			
	Total (n=549)	Normal recovery (n=407)	Protracted recovery (n=142)	P value
Recovery time (days), median (IQR)	21.0 (15.0–31.0)	18.0 (13.0–23.0)	43.0 (35.0–52.0)	<0.001
Age				
8–12 years	152 (27.7)	121 (29.7)	31 (21.8)	0.07
13–18 years	397 (72.3)	286 (70.3)	111 (78.2)	
Missing	0 (0.0)	0 (0.0)	0 (0.0)	
Sex				
Male	312 (56.8)	246 (60.3)	66 (46.5)	0.01
Female	237 (43.2)	162 (39.7)	76 (53.5)	
Missing	0 (0.0)	0 (0.0)	0 (0.0)	
Sport				
Non-contact	68 (12.4)	42 (10.3)	26 (18.3)	0.02
Contact	220 (40.1)	159 (39.1)	61 (43.0)	
Collision	216 (39.3)	173 (42.5)	43 (30.3)	
Missing	45 (8.2)	33 (8.1)	12 (8.5)	
History of concussions				
No	405 (73.8)	307 (75.4)	98 (69.0)	0.14
Yes	144 (26.2)	100 (24.6)	44 (31.0)	
Missing	0 (0.0)	0 (0.0)	0 (0.0	
Time since injury (days), median (IQR)	3.0 (2.0–4.0)	2.0 (1.0–4.0)	3.0 (2.0–5.0)	<0.001

*Normal recovery was defined as less than 30 days from date of injury. Recovery was defined as medical clearance to return to normal activity (return to play, return to learn).

recovery participants who recovered in a median (IQR) 43.0 (35.0–52.0) days. There were significant differences by participant sex (p=0.01), and in the proportions of participants engaging in non-contact, contact and collision sports (p=0.02). There were no significant differences in the proportions of participant age groups (children, 8–12 years; adolescents, 13–18 years) (p=0.07) and history of concussion (p=0.14) by protracted recovery groups. Among those with a normal recovery time, the median (IQR) time since injury was 2.0 (1.0–4.0) days, compared with a median (IQR) 3.0 (2.0–5.0) days among those with a protracted recovery (p<0.001).

Figure 1 depicts the distribution and descriptive statistics for aim 1 outcome of interest, number of days to recover. There was a statistically different (p<0.001) median time to recover from a sports-related concussion between males (19 days) and females (23 days). The distribution of time to recover for both sexes was positively skewed, with ranges of 1–120 days for males and 0–113 days for females.

Table 2 presents the descriptive statistics of the VOMS symptom provocation test difference scores by domain and sex.

The results from table 2 indicate that the summed VOMS symptom provocation test difference scores across all symptom tests are positively skewed for both males and females. Further, for both males and females, the smooth pursuit test in the ocular motor domain had the lowest median (males, 0.0 (IQR=0.0–1.0); females, 0.0 (IQR=0.0–2.0)) summed test difference scores, while the motor sensitivity test in the vestibular domain had the highest median (males, 3.0 (IQR=1.0–6.0); females, 4.0 (IQR=2.0–6.0)) summed test difference scores.

The results from the bivariable and multivariable zero-truncated negative binomial regression models to determine the association between recovery time and any symptom provocation across the various VOMS domains (aim 1A) are shown in table 3.

Results indicate that, after adjustment, any symptom provocation across all vestibular and ocular motor domains of the VOMS test is associated (p<0.05) with recovery time in males. Among females, in the fully adjusted models, only the convergence test in the ocular motor domain was not associated (p=0.08) with recovery time, while all other tests were significantly associated (p<0.05) with a recovery time.

The results from the bivariable and multivariable regression models to determine the association between various thresholds of a positive VOMS test and recovery time (aim 1B) are shown in table 4.

The associations of the VOMS test thresholds with recovery time differed among males and females. Among

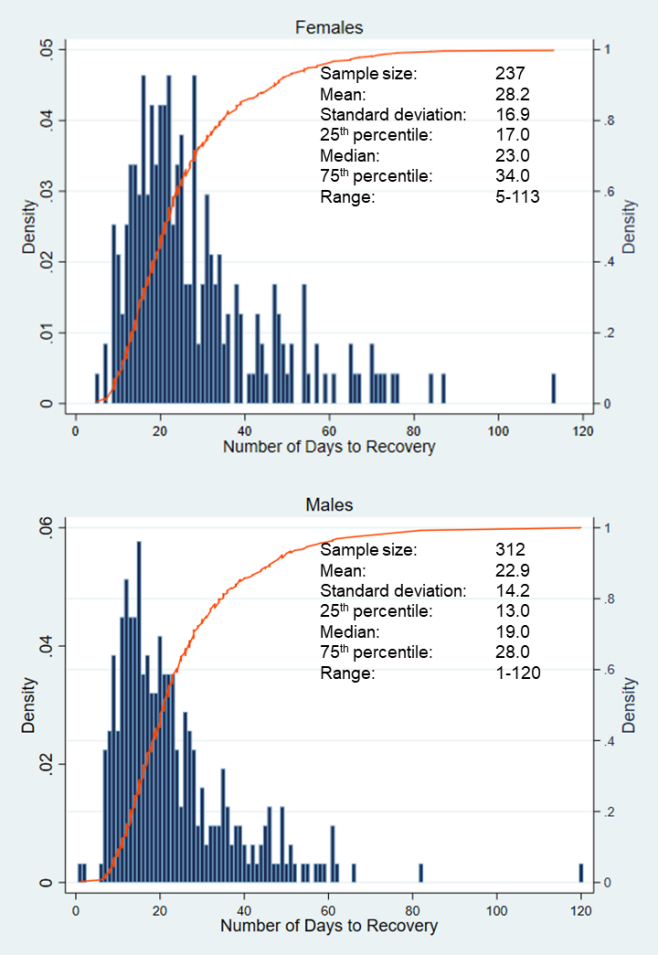

Figure 1 Distribution and descriptive statistics for SRC recovery time (days) by sex among paediatric patients in a clinic setting, 2017–2020.

Table 2 Descriptive statistics of the summed VOMS symptom provocation test difference scores by domain and sex in a clinic-based sample of paediatric patients, 2017–2020

VOMS domain*	Mean (SD)	Median (IQR)	Range
Males			
Ocular motor			
Smooth pursuits	0.89 (1.58)	0.0 (0.0–1.0)	0–12
Saccades—horizontal	1.65 (2.43)	1.0 (0.0–2.0)	0–13
Saccades—vertical	2.02 (2.75)	1.0 (0.0–3.0)	0–13
Convergence	2.27 (4.34)	1.0 (0.0–3.0)	0–56
Vestibular			
Ocular reflex—horizontal	2.96 (3.56)	2.0 (0.0–4.0)	0–19
Ocular reflex—vertical	3.01 (3.78)	2.0 (0.0–4.0)	0–24
Motor sensitivity	4.05 (4.44)	3.0 (1.0–6.0)	0–27
Females			
Ocular motor			
Smooth pursuits	1.37 (2.01)	1.0 (0.0–2.0)	0–12
Saccades—horizontal	2.20 (2.91)	1.0 (0.0–3.0)	0–23
Saccades—vertical	2.62 (3.14)	2.0 (0.0–4.0)	0–15
Convergence	3.02 (4.49)	2.0 (0.0–4.0)	0–49
Vestibular			
Ocular reflex—horizontal	3.57 (3.54)	2.0 (1.0–5.0)	0–16
Ocular reflex—vertical	3.82 (3.70)	3.0 (1.0–5.0)	0–21
Motor sensitivity	4.62 (3.99)	4.0 (2.0–6.0)	0–18

*Each of these estimates represents the summed values of symptom provocation (0–10) test differences (from baseline) across all symptom tests (headache, fogginess, dizziness, nausea), except near point of convergence (convergence) which measured in centimetres.
VOMS, vestibular and ocular motor screening.

males, all VOMS test threshold scores of 1 or greater were significantly related to longer recovery time. However, among females, only VOMS test threshold scores ranging from 1 or more to 5 or more were found to be statistically related to greater recovery time. Specifically, if a male participant were to experience at least a 1-unit increase in symptom provocation following any of the VOMS tests, the expected recovery time would increase by a factor of exp(0.3223846)=1.38 days ($p<0.001$), while holding all other factors (age, sex, days since injury and sport type) constant. Among females, those who experienced at least a 1-unit increase in symptom provocation following any of the VOMS tests, the expected recovery time would increase by a factor of exp(0.548789)=1.73 days ($p<0.001$), while holding all other factors (age, sex, days since injury and sport type) constant.

Table 5 provides the results on the assessment of the validity and predictive values of the VOMS test (aim 2).

Among males and excluding a zero test result on the VOMS, the sensitivity of the VOMS tool ranged from 44.1% (95% CI 31.2% to 57.6%) to 93.2% (95% CI 83.5% to 98.1%) and the specificity ranged from 16.7% (95% CI 12.2% to 21.9%) to 73.2% (95% CI 67.2% to 78.6%), depending on the threshold selected. Among females, the sensitivity of the VOMS tool ranged from 41.2% (95% CI 29.4% to 53.8%) to 97.1% (95% CI 89.8% to 99.6%) and the specificity ranged from 9.9% (95% CI 12.2% to 21.9%) to 60.3% (95% CI 52.3% to 67.9%), depending on the threshold selected. For example, using the two-point symptom provocation threshold (≥2 symptom provocation difference from baseline) would indicate that among those who had a protracted recovery time, 86.4% of males and 92.7% of females correctly tested positive for a protracted recovery using the VOMS. Alternatively, among those who had a normal recovery time, 28.5% of males and 23.0% of females test negative on the VOMS using the two-point symptom provocation threshold. Overall, using the two-point symptom provocation threshold, the VOMS test's ability to identify patients with a protracted recovery is acceptable, but it misidentifies a number of patients who are normal as abnormal (false positives).

Table 3 Bivariable and multivariable negative binomial regression models for the association between VOMS test symptom provocation and recovery time (days) from a sport-related concussion in a clinic-based sample of paediatric patients, 2017–2020

	Crude		Age adjusted		Fully adjusted	
VOMS domain	**β (SE)**	**P value**	**β (SE)**	**P value**	**β (SE)**	**P value**
Males						
Ocular motor						
Smooth pursuits	0.09 (0.02)	<0.001	0.09 (0.02)	<0.001	0.08 (0.02)	<0.001
Saccades—horizontal	0.06 (0.01)	<0.001	0.06 (0.01)	<0.001	0.06 (0.01)	<0.001
Saccades—vertical	0.06 (0.01)	<0.001	0.06 (0.01)	<0.001	0.05 (0.01)	<0.001
Convergence	0.03 (0.01)	<0.001	0.03 (0.01)	<0.001	0.02 (0.01)	<0.001
Vestibular						
Ocular reflex—horizontal	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001
Ocular reflex—vertical	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001
Motor sensitivity	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001
Females						
Ocular motor						
Smooth pursuits	0.05 (0.02)	0.006	0.05 (0.02)	0.006	0.05 (0.02)	0.01
Saccades—horizontal	0.04 (0.01)	0.003	0.04 (0.01)	0.002	0.04 (0.01)	0.003
Saccades—vertical	0.04 (0.01)	0.002	0.04 (0.01)	0.001	0.04 (0.01)	0.005
Convergence	0.02 (0.01)	0.02	0.02 (0.01)	0.03	0.02 (0.01)	0.08
Vestibular						
Ocular reflex—horizontal	0.04 (0.01)	<0.001	0.04 (0.01)	0.001	0.04 (0.01)	0.001
Ocular reflex—vertical	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001
Motor sensitivity	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001	0.04 (0.01)	<0.001

VOMS, vestibular and ocular motor screening.

Figure 2 presents the ROC curves for VOMS as a prognostic tool to identify those with/without protracted recovery from SRC (aim 2). The threshold values used in the ROC curve analysis were the VOMS test threshold values. For males and females, the area under the ROC curve was 0.66 and 0.56, respectively. Overall, the VOMS test performed poorly and failed as a prognostic tool to screen for protracted recovery among males and females, respectively.

Results from the sensitivity analyses used to determine the potential for bias when including those aged 8–9 years and those who took longer than 60 days (males) and 70 days (females) to recover from the SRC indicate no bias exists. Tests for differences by sex, sport type, concussion history and days since injury were evaluated. Results indicate those excluded did not differ (p>0.05) from those included in the analysis on the basis of these factors (results not shown). Additionally, the effect sizes of the parameter estimates estimating the association between domains of the VOMS tests and a positive VOMS test did not differ by greater than 10%, nor did any estimate change in statistical significance (results not shown).

DISCUSSION

Main findings

This study found that the VOMS test domains and VOMS test thresholds were significantly associated with a recovery time (days) from an SRC among a relatively large sample of male and female children and adolescents. The observed effect sizes were differentially associated across sexes, indicating a potential modifying effect by sex. Results were similar after controlling for age, days since injury and sport type (collision, contact, non-contact). Despite the VOMS associations with SRC recovery time, the VOMS test performed poorly when used as a prognostic tool to identify those that will have a protracted SRC recovery (>30 days).

From a clinical perspective, the VOMS test may be best evaluated on the basis of its predictive ability. In clinical settings, the ability of any test to accurately predict those who will have a normal or protracted recovery can be useful for developing personalised recovery protocols that align with the expected recovery time classification. In reviewing the results of the predictive value of the VOMS test (see table 4), the VOMS test generally performs adequately to correctly identify those who will have a normal recovery (NPV >70%). In particular, at the

Table 4 Bivariable and multivariable zero-truncated negative binomial regression models for recovery time from a sport-related concussion among those that test positive on VOMS in a clinic-based sample of paediatric patients, 2017–2020

	Crude		Age adjusted		Fully adjusted	
VOMS positive test threshold	**β (SE)**	**P value**	**β (SE)**	**P value**	**β (SE)**	**P value**
Males						
0	−0.35 (0.09)	<0.001	−0.35 (0.09)	<0.001	−0.34 (0.09)	<0.001
≥1	0.32 (0.08)	<0.001	0.32 (0.08)	<0.001	0.32 (0.08)	<0.001
≥2	0.30 (0.07)	<0.001	0.30 (0.07)	<0.001	0.28 (0.07)	<0.001
≥3	0.29 (0.06)	<0.001	0.30 (0.06)	<0.001	0.27 (0.06)	<0.001
≥4	0.27 (0.06)	<0.001	0.28 (0.06)	<0.001	0.27 (0.06)	<0.001
≥5	0.25 (0.06)	<0.001	0.26 (0.06)	<0.001	0.26 (0.06)	<0.001
≥6	0.25 (0.06)	<0.001	0.23 (0.06)	<0.001	0.22 (0.06)	<0.001
≥7	0.22 (0.06)	<0.001	0.20 (0.06)	0.001	0.17 (0.06)	0.004
≥8	0.19 (0.06)	0.002	0.19 (0.06)	0.002	0.17 (0.06)	0.005
≥9	0.20 (0.06)	0.002	0.20 (0.06)	0.001	0.18 (0.06)	0.004
≥10	0.21 (0.06)	0.001	0.21 (0.06)	0.001	0.18 (0.06)	0.003
Females						
0	−0.46 (0.13)	<0.001	−0.41 (0.13)	0.002	−0.52 (0.14)	<0.001
≥1	0.48 (0.12)	<0.001	0.43 (0.13)	<0.001	0.55 (0.14)	<0.001
≥2	0.45 (0.08)	<0.001	0.42 (0.08)	<0.001	0.46 (0.09)	<0.001
≥3	0.19 (0.07)	0.005	0.17 (0.07)	0.01	0.19 (0.07)	0.01
≥4	0.21 (0.06)	0.001	0.20 (0.06)	0.002	0.24 (0.07)	<0.001
≥5	0.14 (0.06)	0.03	0.13 (0.06)	0.04	0.15 (0.07)	0.02
≥6	0.12 (0.06)	0.07	0.11 (0.06)	0.09	0.13 (0.07)	0.05
≥7	0.09 (0.06)	0.16	0.08 (0.06)	0.20	0.10 (0.07)	0.13
≥8	0.09 (0.07)	0.18	0.08 (0.06)	0.22	0.10 (0.07)	0.14
≥9	0.05 (0.06)	0.41	0.05 (0.07)	0.47	0.06 (0.07)	0.40
≥10	0.05 (0.07)	0.48	0.05 (0.07)	0.53	0.05 (0.07)	0.43

VOMS, vestibular and ocular motor screening.

≥1 threshold, the test was able to correctly predict 91% of males and 89% of females who would go on to have a normal recovery time. Despite the low positive predictive values at this threshold (males, 21%; females, 31%), within this sample, clinicians can have some confidence that if a patient does not exhibit at least a 1-unit increase in symptom provocation on any VOMS test, then the patient has approximately a 90% probability of recovering within 30 days.

Overall, however, based on the poor results from the ROC analysis, the VOMS cannot be used as a stand-alone prognostic tool to identify those that will have a delayed recovery. This finding is consistent with previous research highlighting that persistent symptoms are not the function of a single pathophysiological mechanism, but rather are the result of multiple complex symptoms and/or confounding pathologies.[33] However, a positive test on the VOMS may be a reliable indication to the clinician to conduct other assessments including concussion symptomology (eg, PCSS (Post Concussion Symptom Scale)), ocular motor speed (eg, King-Devick), mood (eg, Patient Health Questionnaire-9, Generalized Anxiety Disorder Scale-7), interpretation tendency (eg, Anxiety Sensitivity) and cognitive functioning (eg, ImPACT, C3 Logix) to more accurately identify those at risk of persistent symptoms and delayed recovery. Predicting protracted recovery is important when planning for the care of athletes following an SRC to provide anticipatory education and guidance regarding the recovery trajectory as well as to consider an earlier introduction of clinical interventions for patients with longer predicted recoveries.

The findings from this study align with previous research studying the association between the VOMS and recovery time. Ellis *et al* found vestibular ocular dysfunction was significantly associated with postconcussion syndrome (three or more symptoms for at least 1 month after injury) in a sample of 101 paediatric patients.[34] Similarly, Anzalone *et al* found in a sample of 167 patients that VOMS was significantly associated with recovery time, with the strongest findings within the ocular motor category.[22] Sufrinko and colleagues also found components

Table 5 Validity and predictive value of the VOMS test for protracted recovery (>30 days) from a sport-related concussion in a clinic-based sample of paediatric patients, 2017–2020

	Validity of test		Predictive value of test	
VOMS positive test threshold	Sensitivity (95% CI)	Specificity (95% CI)	PPV (95% CI)	NPV (95% CI)
Males				
0	5.1 (1.1 to 14.2)	85.0 (79.9 to 89.2)	7.5 (2.5 to 20.2)	78.9 (77.6 to 80.2)
≥1	93.2 (83.5 to 98.1)	16.7 (12.2 to 21.9)	21.1 (19.7 to 22.6)	91.1 (79.3 to 96.5)
≥2	86.4 (75.0 to 94.0)	28.5 (22.9 to 34.5)	22.4 (20.3 to 24.7)	89.8 (81.7 to 94.5)
≥3	81.4 (69.1 to 90.3)	43.9 (37.6 to 50.4)	25.8 (22.7 to 29.0)	90.8 (45.4 to 56.9)
≥4	72.9 (59.7 to 83.6)	55.3 (48.8 to 61.6)	28.1 (24.0 to 32.4)	89.5 (84.7 to 92.9)
≥5	64.4 (50.9 to 76.5)	62.6 (56.2 to 68.7)	29.2 (24.3 to 34.6)	88.0 (83.7 to 91.3)
≥6	52.5 (39.1 to 65.7)	68.3 (62.1 to 74.1)	28.4 (22.6 to 34.9)	85.8 (82.0 to 88.9)
≥7	47.5 (34.3 to 60.9)	70.7 (64.6 to 76.3)	27.9 (21.8 to 35.1)	84.9 (81.3 to 87.9)
≥8	44.1 (31.2 to 57.6)	72.4 (66.3 to 77.9)	27.6 (21.2 to 35.1)	84.4 (81.0 to 87.3)
≥9	44.1 (31.2 to 57.6)	73.2 (67.2 to 78.6)	28.2 (21.6 to 35.9)	84.5 (81.2 to 87.4)
≥10	44.1 (31.2 to 57.6)	73.2 (67.6 to 79.0)	28.5 (21.9 to 36.3)	84.6 (81.3 to 87.5)
Females				
0	2.9 (0.4 to 10.2)	90.7 (85.1 to 94.7)	11.8 (3.0 to 36.2)	68.9 (67.5 to 70.2)
≥1	97.1 (89.8 to 99.6)	9.9 (5.8 to 15.6)	31.3 (29.9 to 32.7)	88.9 (65.4 to 97.1)
≥2	92.7 (83.7 to 97.6)	23.0 (16.7 to 30.3)	33.7 (31.3 to 36.1)	88.1 (75.2 to 94.7)
≥3	72.1 (59.9 to 82.3)	34.2 (26.9 to 42.0)	31.6 (27.8 to 35.8)	74.3 (65.1 to 81.8)
≥4	64.7 (52.2 to 75.9)	46.6 (38.7 to 54.6)	33.9 (29.0 to 39.1)	75.8 (68.5 to 81.8)
≥5	55.9 (43.3 to 67.9)	49.7 (41.7 to 57.7)	31.9 (26.6 to 37.9)	72.7 (66.2 to 78.4)
≥6	52.9 (40.5 to 65.2)	54.0 (46.0 to 61.9)	32.7 (26.9 to 39.2)	73.1 (67.1 to 78.4)
≥7	48.5 (36.2 to 61.0)	58.4 (50.4 to 66.1)	33.0 (26.6 to 40.1)	72.9 (67.3 to 77.8)
≥8	47.1 (34.8 to 59.6)	59.6 (51.6 to 67.3)	33.0 (26.5 to 40.3)	72.7 (67.3 to 77.5)
≥9	42.0 (30.2 to 54.5)	59.9 (51.9 to 67.5)	30.7 (24.1 to 38.2)	71.0 (65.9 to 75.6)
≥10	41.2 (29.4 to 53.8)	60.3 (52.3 to 67.9)	30.4 (23.7 to 38.1)	70.8 (65.7 to 75.4)

NPV, negative predictive value; PPV, positive predictive value; VOMS, vestibular and ocular motor screening.

of the VOMS to be related to SRC recovery time (n=69), but lacked the ability to predict recovery time.[24] Most recently, Whitney *et al* found that abnormal scores (≥2 point symptom provocation) on tests within the ocular motor domain were significantly associated with recovery time, but tests in the vestibular domain were not associated with recovery time.[25] This study was conducted in a sample of 79 college age athletes, the majority of which being male. The differences in age and sex make-up between the current study and Whitney *et al*'s sample, in addition to the current study's additional power with the larger sample, may explain some of the observed differences in the results. Despite the current study's results generally aligning with previous results on the association between the VOMS and recovery time, to our knowledge, no other studies have evaluated the VOMS as a prognostic tool to screen for protracted recovery. The current study's findings, along with those others, demonstrate consistent findings, across varied sites/samples, that positive symptom provocation with VOMS is significantly associated with recovery time across both sexes in children and adolescents.

Limitations

Findings from this study should be considered in light of its limitations. First, despite data collection occurring within 7 days of the injury, the lack of a true baseline estimate of VOMS does not allow one to definitively conclude that the observed symptomology is the result of the concussion alone. We found that even with restricting the analytical sample to those patients seen within the first 7 days of injury, the time from injury to examination was still a statistically significant factor that was included in the multivariable analyses. Therefore, true baseline measures of VOMS would allow for a better understanding of the causal relations between SRC and VOMS estimates. Second, the administration of the VOMS and diagnoses of concussions differed among a group of licensed medical professionals with no evaluation of inter-rater reliability, thereby introducing the

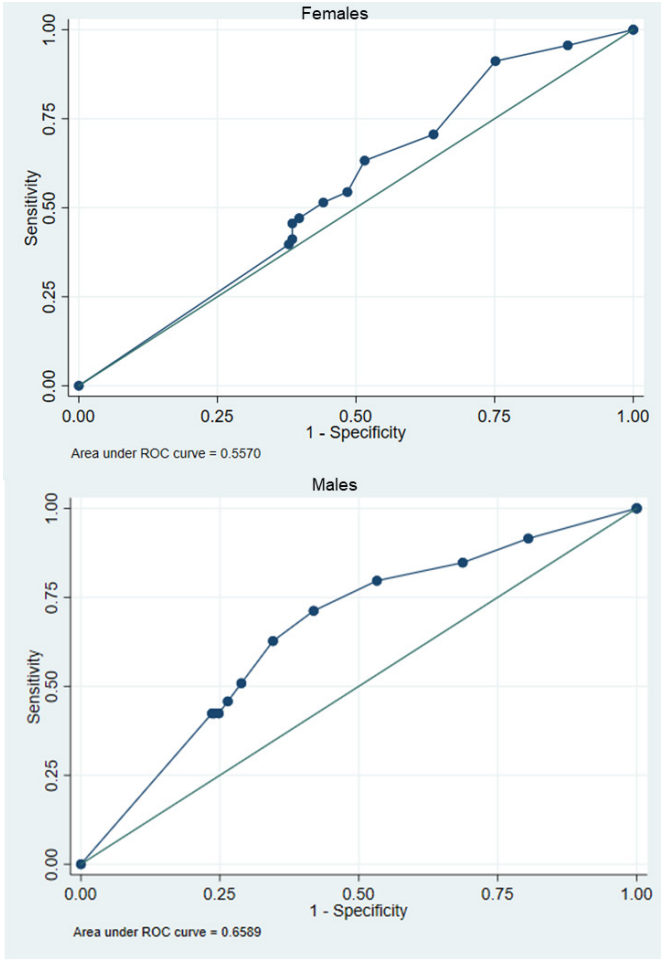

Figure 2 Receiver operating characteristics (ROC) for vestibular and ocular motor screening tool to classify those who will have a protracted sport-related concussion recovery by sex among a sample of paediatric patients in a clinic setting, 2017–2020. Positive for protracted recovery is defined as recovery of ≥30 days.

potential for differential misclassification. However, each medical professional had specialised training in concussion diagnosis and evaluation, and was trained by a single neuropsychologist who also oversaw all VOMS and concussion testing. Further, due to a lack of consensus in the literature on the relations between premorbid factors and concussion recovery, we did not account for some factors that may be associated with concussion recovery, including history of migraines, psychological problems and loss of consciousness. This same point can be made for the use of a 30-day threshold for protracted recovery. It is possible and likely that the ability of the VOMS as a prognosticator for protracted recovery may differ with other previously used protracted recovery thresholds.[10 30 35] Fourth, while this study's sample was relatively large, the analytical sample was limited in size to 549 patients of limited generalisability. This also limited our ability to stratify analyses on the basis of age groups (children and adolescents), as has been found to be related to recovery time.[8] Further research on a larger, more diverse sample will help account for individual differences, random error and potential modifying effects by age. Finally, this study was conducted in a specialty concussion clinic that takes a rehabilitative approach to recovery. Future research is necessary to evaluate the utility of VOMS to other settings outside of the original data collection site for replication purposes, as there is likely a difference in results within the specialised concussion centre setting when compared with emergency medicine and primary care settings. This may account for patients within the current study with recoveries over 100 days. Additionally, as part of the current study site's approach to rehabilitation, positive findings on VOMS often result in prescriptive home exercise programmes or referral to physical therapy. Though beyond the scope of this study, variation in adherence to rehabilitation could have impacted recovery time in the sample.

CONCLUSION

Although these results indicate VOMS is not sufficient as a stand-alone prognostic tool in determining who will have a protracted recovery, it does demonstrate that elements of the VOMS test are significantly related to recovery time, and therefore future clinical practice may include VOMS as a necessary element of a larger prognostic evaluation for protracted recovery. Consistent with previous research,[11 33] the results from this study indicated highly variable and individualised nature of concussion recovery among adolescents. Future research should examine the effect of various treatments on concussion recovery time, as well as the potential effect of vestibular dysfunction trajectories during the recovery period, to further refine the estimated time to recover. The findings from these studies will improve the ability for clinicians to predict the time to recover from a concussion among adolescent athletes, which may inform future policies and guidelines on returning to play.

Twitter Gregory Knell @greg_knell

Contributors GK had full access to all of the data in the study and takes responsibility for the integrity of the data and accuracy of the data analysis. GK, TC and SOB were responsible for the concept and design of the study, acquisition, analysis and interpretation of data. GK was responsible for the drafting of the manuscript. TC and SOB were responsible for the critical revision of the manuscript for important intellectual content. GK was responsible for the statistical analysis. SOB supervised the project.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests None declared.

Patient consent for publication Not required.

Ethics approval The study was approved by the coordinating site's institutional review board (IntegReview IRB 112017-006).

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement No data are available. Deidentified participant data can be made available upon request to the corresponding author.

ORCID iD
Gregory Knell http://orcid.org/0000-0002-5067-544X

REFERENCES

1 McCrory P, Meeuwisse W, Dvořák J, *et al*. Consensus statement on concussion in sport-the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med* 2017;51:838–47.
2 Bryan MA, Rowhani-Rahbar A, Comstock RD, *et al*. Sports- and Recreation-Related concussions in US youth. *Pediatrics* 2016;138. doi:10.1542/peds.2015-4635
3 Baker DR, Kulick ER, Boehme AK, *et al*. Effects of the New York State Concussion Management and Awareness Act ("Lystedt Law") on Concussion-Related Emergency Health Care Utilization Among Adolescents, 2005-2015. *Am J Sports Med* 2018;46:396–401.
4 Gibson TB, Herring SA, Kutcher JS, *et al*. Analyzing the effect of state legislation on health care utilization for children with concussion. *JAMA Pediatr* 2015;169:163–8.
5 Green L. *Legal perspectives: recommendations on state concussion laws*, 2019.
6 Wiebe DJ, D'Alonzo BA, Harris R, *et al*. Association between the experimental kickoff rule and concussion rates in ivy League football. *JAMA* 2018;320:2035–6.
7 Kerr ZY, Chandran A, Nedimyer AK, *et al*. Concussion incidence and trends in 20 high school sports. *Pediatrics* 2019;144:e20192180.
8 Ledoux A-A, Tang K, Yeates KO, *et al*. Natural progression of symptom change and recovery from concussion in a pediatric population. *JAMA Pediatr* 2019;173:e183820.
9 Silverberg ND, Gardner AJ, Brubacher JR, *et al*. Systematic review of multivariable prognostic models for mild traumatic brain injury. *J Neurotrauma* 2015;32:517–26.
10 Zemek R, Barrowman N, Freedman SB, *et al*. Clinical risk score for persistent Postconcussion symptoms among children with acute concussion in the ED. *JAMA* 2016;315:1014–25.
11 Iverson GL, Gardner AJ, Terry DP, *et al*. Predictors of clinical recovery from concussion: a systematic review. *Br J Sports Med* 2017;51:941–8.
12 Brook EM, Luo X, Curry EJ, *et al*. A heads up on concussions: are there sex-related differences? *Phys Sportsmed* 2016;44:20–8.
13 Covassin T, Moran R, Elbin RJ. Sex differences in reported concussion injury rates and time loss from participation: an update of the National collegiate athletic association injury surveillance program from 2004-2005 through 2008-2009. *J Athl Train* 2016;51:189–94.
14 Cancelliere C, Hincapié CA, Keightley M, *et al*. Systematic review of prognosis and return to play after sport concussion: results of the International collaboration on mild traumatic brain injury prognosis. *Arch Phys Med Rehabil* 2014;95:S210–29.
15 Kerr ZY, Zuckerman SL, Wasserman EB, *et al*. Concussion symptoms and return to play time in youth, high school, and College American football athletes. *JAMA Pediatr* 2016;170:647–53.
16 Morgan CD, Zuckerman SL, Lee YM, *et al*. Predictors of postconcussion syndrome after sports-related concussion in young athletes: a matched case-control study. *J Neurosurg Pediatr* 2015;15:589–98.
17 Abrahams S, Fie SM, Patricios J, *et al*. Risk factors for sports concussion: an evidence-based systematic review. *Br J Sports Med* 2014;48:91–7.
18 Miller JH, Gill C, Kuhn EN, *et al*. Predictors of delayed recovery following pediatric sports-related concussion: a case-control study. *J Neurosurg Pediatr* 2016;17:491–6.
19 Mihalik JP, Register-Mihalik J, Kerr ZY, *et al*. Recovery of posttraumatic migraine characteristics in patients after mild traumatic brain injury. *Am J Sports Med* 2013;41:1490–6.
20 Corwin DJ, Zonfrillo MR, Master CL, *et al*. Characteristics of prolonged concussion recovery in a pediatric subspecialty referral population. *J Pediatr* 2014;165:1207–15.
21 Sufrinko AM, Marchetti GF, Cohen PE, *et al*. Using acute performance on a comprehensive neurocognitive, vestibular, and ocular motor assessment battery to predict recovery duration after sport-related concussions. *Am J Sports Med* 2017;45:1187–94.
22 Anzalone AJ, Blueitt D, Case T, *et al*. A positive Vestibular/Ocular motor screening (VOMS) is associated with increased recovery time after sports-related concussion in youth and adolescent athletes. *Am J Sports Med* 2017;45:474–9.
23 Eagle SR, Puligilla A, Fazio-Sumrok V, *et al*. Association of time to initial clinic visit with prolonged recovery in pediatric patients with concussion. *J Neurosurg Pediatr* 2020;26:165–70.
24 Sufrinko AM, Marchetti GF, Cohen PE, *et al*. Using acute performance on a comprehensive neurocognitive, vestibular, and ocular motor assessment battery to predict recovery duration after sport-related concussions. *Am J Sports Med* 2017;45:1187–94.
25 Whitney SL, Eagle SR, Marchetti G, *et al*. Association of acute vestibular/ocular motor screening scores to prolonged recovery in collegiate athletes following sport-related concussion. *Brain Inj* 2020;34:842–7.
26 Mucha A, Collins MW, Elbin RJ, *et al*. A brief Vestibular/Ocular motor screening (VOMS) assessment to evaluate concussions: preliminary findings. *Am J Sports Med* 2014;42:2479–86.
27 Mulligan IJ, Boland MA, McIlhenny CV. The balance error scoring system learned response among young adults. *Sports Health* 2013;5:22–6.
28 McCrory P, Meeuwisse WH, Aubry M, *et al*. Consensus statement on concussion in sport: the 4th International Conference on concussion in sport held in Zurich, November 2012. *Br J Sports Med* 2013;47:250–8.
29 Kontos AP, Jorgensen-Wagers K, Trbovich AM, *et al*. Association of time since injury to the first clinic visit with recovery following concussion. *JAMA Neurol* 2020;77:435–40.
30 Gibson S, Nigrovic LE, O'Brien M, *et al*. The effect of recommending cognitive rest on recovery from sport-related concussion. *Brain Inj* 2013;27:839–42.
31 Haider MN, Leddy JJ, Wilber CG, *et al*. The predictive capacity of the buffalo concussion treadmill test after sport-related concussion in adolescents. *Front Neurol* 2019;10:395.
32 Meehan WP, Taylor AM, Berkner P, *et al*. Division III collision sports are not associated with neurobehavioral quality of life. *J Neurotrauma* 2016;33:254–9.
33 Makdissi M, Schneider KJ, Feddermann-Demont N, *et al*. Approach to investigation and treatment of persistent symptoms following sport-related concussion: a systematic review. *Br J Sports Med* 2017;51:958–68.
34 Ellis MJ, Cordingley D, Vis S, *et al*. Vestibulo-Ocular dysfunction in pediatric sports-related concussion. *J Neurosurg Pediatr* 2015;16:248–55.
35 Lau BC, Collins MW, Lovell MR. Cutoff scores in neurocognitive testing and symptom clusters that predict protracted recovery from concussions in high school athletes. *Neurosurgery* 2012;70:371–9.