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

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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.

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,14-15 personal history of migraine,16 preinjury mental health problems17 and concussion history17 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 speed21) 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, neuropsychologist, 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.25 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 \( \chi^2 \) 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
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

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

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

*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).
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 \((\geq 2\) 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, 86.4% of males and 92.7% of females tested negative on the VOMS using the two-point symptom provocation difference. 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).
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
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. 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. Sufrinko and colleagues also found components of the VOMS to be predictive of recovery time.

The findings from this study suggest that the VOMS, when used in combination with other assessments, can help identify athletes at risk of prolonged recovery and can guide clinical management. However, further research is needed to confirm these findings and to understand the mechanisms underlying prolonged recovery following SRC.
of the VOMS to be related to SRC recovery time (n=69), but lacked the ability to predict recovery time. 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. 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

<table>
<thead>
<tr>
<th>VOMS positive test threshold</th>
<th>Sensitivity (95% CI)</th>
<th>Specificity (95% CI)</th>
<th>PPV (95% CI)</th>
<th>NPV (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>5.1 (1.1 to 14.2)</td>
<td>85.0 (79.9 to 89.2)</td>
<td>7.5 (2.5 to 20.2)</td>
<td>78.9 (77.6 to 80.2)</td>
</tr>
<tr>
<td>≥1</td>
<td>93.2 (83.5 to 98.1)</td>
<td>16.7 (12.2 to 21.9)</td>
<td>21.1 (19.7 to 22.6)</td>
<td>91.1 (79.3 to 96.5)</td>
</tr>
<tr>
<td>≥2</td>
<td>86.4 (75.0 to 94.0)</td>
<td>28.5 (22.9 to 34.5)</td>
<td>22.4 (20.3 to 24.7)</td>
<td>89.8 (81.7 to 94.5)</td>
</tr>
<tr>
<td>≥3</td>
<td>81.4 (69.1 to 90.3)</td>
<td>43.9 (37.6 to 50.4)</td>
<td>25.8 (22.7 to 29.0)</td>
<td>90.8 (45.4 to 56.9)</td>
</tr>
<tr>
<td>≥4</td>
<td>72.9 (59.7 to 83.6)</td>
<td>55.3 (48.8 to 61.6)</td>
<td>28.1 (24.0 to 32.4)</td>
<td>89.5 (84.7 to 92.9)</td>
</tr>
<tr>
<td>≥5</td>
<td>64.4 (50.9 to 76.5)</td>
<td>62.6 (56.2 to 68.7)</td>
<td>29.2 (24.3 to 34.6)</td>
<td>88.0 (83.7 to 91.3)</td>
</tr>
<tr>
<td>≥6</td>
<td>52.5 (39.1 to 65.7)</td>
<td>68.3 (62.1 to 74.1)</td>
<td>28.4 (22.6 to 34.9)</td>
<td>85.8 (82.0 to 88.9)</td>
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<tr>
<td>≥7</td>
<td>47.5 (34.3 to 60.9)</td>
<td>70.7 (64.6 to 76.3)</td>
<td>27.9 (21.8 to 35.1)</td>
<td>84.9 (81.3 to 87.9)</td>
</tr>
<tr>
<td>≥8</td>
<td>44.1 (31.2 to 57.6)</td>
<td>72.4 (66.3 to 77.9)</td>
<td>27.6 (21.2 to 35.1)</td>
<td>84.1 (81.0 to 87.3)</td>
</tr>
<tr>
<td>≥9</td>
<td>44.1 (31.2 to 57.6)</td>
<td>73.2 (67.2 to 78.6)</td>
<td>28.2 (21.6 to 35.9)</td>
<td>84.5 (81.2 to 87.4)</td>
</tr>
<tr>
<td>≥10</td>
<td>44.1 (31.2 to 57.6)</td>
<td>73.2 (67.6 to 79.0)</td>
<td>28.5 (21.9 to 36.3)</td>
<td>84.6 (81.3 to 87.5)</td>
</tr>
</tbody>
</table>

| 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.
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.

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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.
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