Derivation of the Buffalo Concussion Physical Examination risk of delayed recovery (RDR) score to identify children at risk for persistent postconcussive symptoms

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ABSTRACT

Objective The Buffalo Concussion Physical Examination (BCPE) is a brief, but pertinent physical examination designed for the subacute, outpatient assessment of concussion. The purpose of this study was to perform the BCPE on a larger sample and derive a scoring system to identify children at risk for Persistent Post-Concussive Symptoms (PPCS, recovery ≥30 days).

Methods This prospective, observational cohort study from September 2016 to March 2019 was performed at three university-affiliated concussion clinics. Male and female children (n=270, 14.92±1.86 years, range 8–18, 38% female) were diagnosed with a concussion within 14 days of injury and followed-up until recovery. Logistic regression was used with history and physical examination variables to predict PPCS and a weighted scoring metric was derived.

Results Out of 15 predictor variables, the main effects of 1 preinjury variable (≥3 previous concussions), 2 injury characteristic variables (days-since-injury and type-of-injury), 3 physical examination variables (orthostatic intolerance (OI), vestibulo-ocular reflex (VOR) and tandem gait) and 2 interaction terms (OI/VOR and tandem gait/type-of-injury) produced a score that was 85% accurate for identifying children with low-risk, medium-risk and high-risk for PPCS on cross-validation.

Conclusion The Risk for Delayed Recovery (RDR)-Score allows physicians in an outpatient setting to more accurately predict which children are at greater risk for PPCS early after their injury, and who would benefit most from targeted therapies. The RDR-Score is intended to be used as part of a comprehensive assessment that should include validated symptom checklists, mental health history and adjunct testing (eg, cognitive or physical exertion) where clinically indicated.

INTRODUCTION

Concussion, a form of traumatic brain injury, is a public health concern.[1] It is estimated that approximately 5%–10% of children in the USA will experience a concussion in their lifetime.[2] Children have the highest rates of concussion in sport and tend to require longer to recover than adults.[3–5] The typical duration of recovery in children is less than 1 month[6] but approximately 30% take longer to recover; this is called Persistent Post-Concussive Symptoms (PPCS).[7] Children with PPCS are far more likely to experience psychosocial adjustment issues and learning difficulties in school.[4 8 9] There are currently no objective blood or imaging biomarkers to diagnose concussion or to identify patients early who will take longer to recover.[10]

Concussion diagnosis is a clinical determination based on a thorough history, symptom checklists and behavioural screens, a physical examination and adjunct testing if applicable.[10] Concussion management that includes early and effective planning for school, social and/or sport adjustment for those with delayed recovery is known to effectively reduce stress for the child and the family[9 11] and improve outcome.[12 13] Components of what we call *PPCS planning* are individualised for each patient based on their predominant impairments. They include: (1) monitoring symptom precipitators, such as excessive screen use; (2) sleep hygiene strategies; (3) communication with school personnel regarding specific accommodations; (4) interventions for specific oculomotor, vestibular and/or exercise intolerance deficits and (5) counselling for improving social well-being.[14] Since physicians who see concussions infrequently may not be familiar with recommended rehabilitation strategies,[15] an important aspect of PPCS planning includes referral to specialists (eg, vision and vestibular therapists) with experience in concussion management.

Zemek *et al*[7] derived the *5P risk assessment score* consisting of nine variables (age, sex, two medical history components, four self-reported symptoms and tandem stance) used within 48-hours of injury that was 68% accurate predicting PPCS. This tool has also been shown to be effective in the subacute outpatient setting with 75% accuracy.[16] The Buffalo Concussion Physical Examination (BCPE) is a brief (5–7 min), pertinent physical examination protocol designed for the outpatient setting.[17] It assesses subsystems commonly affected after concussive head injury (eg, oculomotor and vestibular) and also includes key *red flags* for more serious injury that may prompt urgent referral.[17] The BCPE was derived and validated on a cohort of adolescents with sport-related concussion (SRC).[18] The purpose of this study was to perform the BCPE on a larger, more diverse sample of children to derive a scoring metric, independent of self-reported symptoms that within 14 days of injury could identify patients who would benefit from early PPCS planning. We hypothesised that this weighted scoring system, termed the *Risk of Delayed Recovery Score*

(*RDR-score*), would perform significantly better than the null model for predicting PPCS.

METHODS

Design and settings

This prospective cohort study was reviewed and approved by the University at Buffalo IRB and a waiver of consent was granted. The setting was three multidisciplinary university-affiliated concussion clinics in Buffalo, NY and Niagara Falls, NY from September 2016 to March 2019. Patients with suspected concussion were referred from the emergency department, athletic trainers, urgent care centres, school nurses and primary care physicians.

Patient and public involvement statement

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

Participants

Males and females, aged 8–18 years, diagnosed with concussion by sports medicine physicians within 14 days of injury. Participants were excluded if they had: (1) injury involving loss of consciousness for ≥30 min or post-traumatic amnesia for ≥24 hours; (2) lesion on CT/MRI (if performed) and/or focal neurologic sign consistent with intracerebral lesion or (3) history of moderate to severe brain injury (GCS≤12). Participants were removed from analysis if they (1) had a second concussive head injury before recovery, or (2) were lost to follow-up before clinical clearance.

Exposure and management of concussion

The exposure of interest for this study was a concussion diagnosed using recent Concussion in Sport Group guidelines,[10] including history (using a symptom checklist and behavioural screening questionnaires), concussion-like symptoms linked to a concussive head injury or injury to another part of the body with force transmitted to the head, a concussion-focused clinical assessment,[17] and adjunct tests if indicated (eg, exercise tolerance test).[19] Clinical management protocols were standardised among all study physicians. Participants were instructed to not participate in sports or other activities that pose a risk for further head injury, to engage in light aerobic exercise/physical activity[12] and to do social/work activities below their symptom-exacerbation thresholds. Following good medical standards of practice, cervical impairments (if present) were treated early with pharmacological and/or non-pharmacological therapies since untreated cervical injuries are a common comorbidity associated with delayed recovery.[20] Details regarding our practice's cervical management protocol are described in online supplemental file 2. If participants did not recover by 4 weeks from injury, a multidisciplinary approach was used that included, when clinically indicated, a physical therapist (for vestibular and cervical therapy), an occupational therapist (for vision therapy) and/or a neuropsychologist (for cognitive or mood-related issues).[21] The lead study physician (JJL) met with study physicians at quarterly department meetings to review/revise clinical management protocols per university teaching standards.

Predictor variables

Predictor variables were separated into three categories: (1) demographics; (2) injury characteristics; and (3) physical examination findings.

Demographics

Variables included: (1) age, (2) sex (male/female) and (3) number of previous concussions.

Injury characteristics

This included time-since-injury and type-of-injury. Time-since-injury is the difference in days from injury to initial clinic visit. Type-of-injury was classified according to injury severity into two groups: (1) single/low-velocity injury and (2) multiple/high-velocity injury. The latter included complex injuries such as multiple suspected concussive events without time for recovery in between (ie, overlapping concussion syndrome)[22] and high-velocity injuries such as motor vehicle accidents (MVAs) or falls from a height. In the context of SRC, most were classified as single/low-velocity except if the injury was very serious (described in detail in the limitations section) or if children who continued to play after the initial concussive head injury suffered another head injury within the same game. Children who continued to play without sustaining another distinct head injury were classified as single/low-velocity.

Physical examination

Predictor variables from the BCPE included (1) orthostatic intolerance[23] (OI, defined as reporting symptoms of lightheadedness or dizziness[24] using the 1 min standing[25] after 2 min supine[26] orthostatic manoeuvre); (2) ocular smooth pursuits (SP); (3) horizontal repetitive saccades; (4) vertical repetitive saccades; (5) vestibulo-ocular reflex (VOR); (6) near point convergence; (7) tandem gait;[27] (8) neck tenderness; (9) neck muscle spasm and (10) neck range of motion. Directions for each component of the BCPE have been published previously[17] and directions for the specific physical examination components that made it to the final scoring tool are provided in online supplemental file 2.

Main outcome

The main outcome measure was duration of recovery, calculated as the difference in days from injury to determination of clinical recovery from concussion. Participants were considered recovered clinically by their physician when they: (1) returned to a baseline level of symptoms at rest; (2) had a normal physical examination and (3) were able to exercise and return-to-school without exacerbation of concussion-like symptoms.[28] Athlete participants who needed clearance to begin a return-to-play protocol also had to demonstrate good exercise tolerance.[19] Since duration of recovery is subject to interval censoring in patients with longer recovery times (ie, not knowing the exact date of recovery due to large gaps between clinic visits after the first 4 weeks), the outcome used for predictive models was the binary variable PPCS (recovery time ≥30 days). This is elaborated on in online supplemental file 1 (pp 2–3).

Statistical analysis

Sample size was estimated based on number of components in the initial assessment for logistic regression using the 10 events per predictor variable per group rule of thumb[29,30] (4 demographic and 9 physical examinations) for a minimum sample size of 130 participants in each group (total 260 in two groups). This a priori sample size estimation did not account for unequal sample sizes, which is a major limitation of this manuscript and is discussed in more detail in the limitations section. Physical examination and demographic variables for the entire population were summarised using descriptive statistics. Recovery times were categorised as normal recovery (≤29 days) and delayed recovery (PPCS, ≥30 days). Distribution of the continuous outcome variable (recovery time in days) was assessed, and appropriate transformations were used if applicable. Results of the assessment of distribution and transformations are presented in online supplemental file 1 (pp 2–3).

Individual predictors were regressed to response variables. The distribution of discrete variables (time-since-injury and number of previous concussions) was regressed on response variables and acceptable cut-offs/stratifications were selected to maximise predictive potential. Time-since-injury was not a covariate in the same sense as the other predictors and was regressed on the response variables using Cox Proportional Hazard (Cox PH), Accelerated Failure Time (AFT) and binomial Generalised Linear Modelling (bGLM) models. The Cox PH and AFT models were considered as they are commonly used to model time to event data, while the bGLMs provided greater flexibility than logistic regression alone. For Cox PH, estimated hazard of stratified time-since-injury was plotted against recovery time and PH assumptions were assessed using Schoenfeld Global Test. For AFT and bGLM models, time-since-injury was incorporated as a continuous predictor and the linearity assumption was checked visually using a scatter plot of log recovery time against time-since-injury with a locally estimated scatterplot smoothing curve fitted on top. Four different AFT models were assessed; log-logistic, lognormal, Weibull and Inverse-Weibull which correspond to logistic, normal, extreme value (minimum) and extreme value (maximum) residual distributions, respectively, when fitting a linear regression model to the log-transformed recovery times. For the bGLM model, four different link functions were tested; logit, probit, log–log and complementary log–log that correspond to the survival functions for the log-logistic, lognormal, Weibull and Inverse-Weibull AFT models, respectively. Since the physical examination results of the BCPE can be expected to vary depending on how long after the injury the initial examination is performed, tests for interaction were performed between time-since-injury and these response variables to justify their inclusion as additive terms in the models.

Predictive models were built using Cox PH, AFT and bGLM for incidence of delayed recovery using: (1) physical examination components only; (2) all predictors and (3) all predictors and interactions. Forward stepwise selection was performed using the Akaike Information Criterion (AIC) to identify significant contributors to the model and the *best* model was selected to build a scoring system. Model fit was assessed visually for AFT models using quantile–quantile plots and for bGLM using the Hosmer-Lemeshow test. Collinearity was assessed by testing for independence between model predictors. Coefficients were multiplied by a common multiplier m to get integer values and *RDR-score* ranges for low risk (<30%), medium risk (30%–70%) and high risk (>70%). Finally, cross-validation was performed using leave-one-out cross-validation[31] to estimate final model performance and discrimination assessed using the C statistic.[32] Detailed results of the statistical analysis are provided in online supplemental file 1 and a brief summary is provided below. All data analyses were performed using the R programming language.[33]

RESULTS

From September 2016 to March 2019, 359 children and adolescents were evaluated in our university clinics and diagnosed with a concussion. Two hundred and eighty-four participants met eligibility criteria and were included in the study; however, 11 participants were lost to follow-up and three participants had a second head injury while they were still recovering and were removed from analysis. Hence, 270 concussed children and adolescents within 14 days of their injury (majority SRC) comprised the final sample. The 14 participants not included in the analysis did not significantly differ in age or sex. Sample demographics are presented in table 1.

Table 1 Univariate sample demographics

Sample (n)	270
Age, mean (SD)	14.92 (1.86) years
Sex, % male (n)	62% male (167)
Time-since-injury, median (IQR)	5 (4, 8) days
Initial visit symptom severity* median (IQR)	32 (18, 46.75)
Recovery time, median (IQR)	22 (11, 39) days
Delayed recovery, % (n)	36.3% (98)
Loss of consciousness, % (n)	5.9% (16)
Sport-related injury, % (n)	84.1% (227)
Single/low-velocity injury, % (n)	89.6% (242)
≥3previous concussion, % (n)	5.6% (15)
Abnormal OI, % (n)	46.3% (125)
Neck spasm, % (n)	7.0% (19)
Neck tenderness, % (n)	48.9% (132)
Abnormal neck ROM, % (n)	12.2% (33)
Abnormal SP, % (n)	59.3% (160)
Abnormal HS, % (n)	59.3% (160)
Abnormal VS, % (n)	54.4% (147)
Abnormal VOR, % (n)	45.6% (123)
Abnormal NPC, % (n)	20.0% (54)
Abnormal tandem gait, % (n)	42.2% (114)

*On Post-Concussion Symptom Scale (*max=132*).
HS, horizontal repetitive saccades; NPC, near point convergence; OI, orthostatic intolerance; ROM, range of motion; SP, smooth pursuits; VOR, vestibulo-ocular reflex; vs, vertical repetitive saccades.

Results of regression of individual predictors on response variables are presented in online supplemental file 1. A cut-off of or more previous concussions was identified to have the highest accuracy. P-values of the tests of independence between predictor and response variables are presented in figure 1. OI, sex, SPs, type of injury and time-since-injury all had a statistically significant association with log of recovery times at a Bonferroni-corrected significance level. OI, SP, type-of-injury, time-since-injury and VOR had a statistically significant association with incidence of delayed recovery at a Bonferroni-corrected significance level.

Physical examination covariates did not reach significance to be time-dependent; hence, time-since-injury was incorporated into the model as an independent covariate. Correlation between predictors was assessed and only two pairs of interaction (sex/neck tenderness and OI/VOR, (online supplemental file 1), figure 5.3) were significant at a $p<0.05$ level. Results of model selection predicting delayed Recovery are presented in table 2.

Delayed recovery was predicted for the Cox and AFT models if the median recovery time under the model was ≥30 days, and if the probability was >0.5 for bGLM. The best model was chosen based on highest accuracy and lowest AIC, which was the bGLM model with a complementary log–log link function using all predictor variables (history and physical examination) and interactions with stepwise selection. The C-statistic for this model was 0.74. A calibration plot for this model is presented in figure 2.

The *best* model predicting delayed recovery included the main effects of one demographic variable (≥3 previous concussion), two injury characteristic variables (time-since-injury and type of injury), three physical examination variables (OI, VOR and tandem gait)

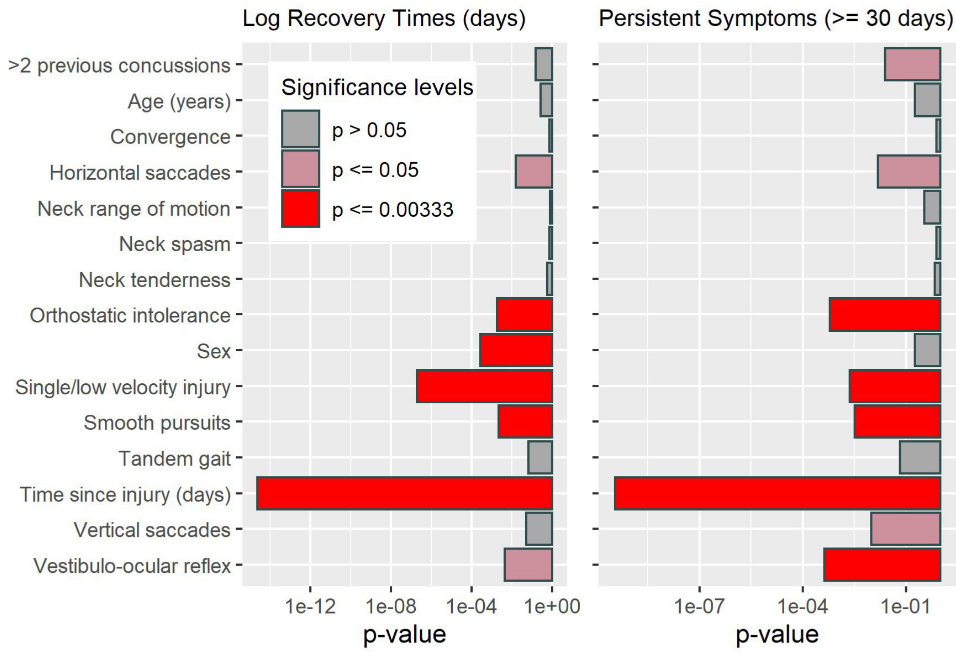

Figure 1 P-values of the tests of independence between all predictor variables and response variables with a Bonferroni-corrected level. P-values are plotted on a log scale, so the longer bars correspond to smaller p-values.

and two interaction terms. Details of the bGLM model with a complementary log–log link function are presented in table 3.

Coefficients from the bGLM model were multiplied by multipliers m to produce scaled, integer coefficients. An m=3.832 was chosen because it was the smallest multiplier with a low root mean square difference between the scaled coefficients and the nearest integers. Scaled integers were tabulated and ranges for low-risk, medium-risk and high-risk were made. Final values for the BCPE screening tool predicting delayed recovery are presented in table 4. After internal cross-validation, the BCPE RDR-Score for delayed recovery was 85% accurate. It misclassified 5% of participants as high-risk for delayed recovery (95% specificity) and misclassified 33% of participants as low-risk for delayed ecovery (67% sensitivity).

DISCUSSION

This prospective cohort study identified three variables from the history and three variables from a brief physical examination performed a mean of 6 days after injury that predicted PPCS with 85% accuracy. Current clinical practice recommendations include delaying focused therapies such as vestibular therapy or cognitive rehabilitation until 1 month after injury.[14] Therefore, experienced clinicians felt that there would be less harm in delaying treatment for a few weeks than prescribing therapies that would not impact the natural recovery seen in most youth patients after concussion. The high specificity of the RDR-score helps achieve this aim by minimising false positive assessment of high risk. We used the cut-off points that maximised accuracy of the decision rule. The ultimate decision regarding the provision of resources and services is up to the clinician and should be individualised to the needs of the patient. The purpose of this study was to give clinicians key information within the subacute evaluation phase after concussion to make treatment decisions to help patients at greater risk for PPCS avoid delayed recovery. This does not mean that clinicians should withhold low-resource information from any patient when first evaluated (eg, physical and cognitive activity guidance, basic sleep hygiene), but that those identified by the RDR-score as high risk additionally should receive specific PPCS planning as early as possible. Of the 270 participants in this study, 36% had delayed recovery,

Table 2 Summary of model selection

	Binomial GLM (complementary log–log)				AFT model (Inverse-Weibull)				Cox PH model (stratified by time-since-injury)			
Model	Accuracy (%)	Sensitivity (%)	Specificity (%)	AIC (# predictors)	Accuracy (%)	Sensitivity (%)	Specificity (%)	AIC (# Predictors)	Accuracy (%)	Sensitivity (%)	Specificity (%)	AIC (# predictors)
Models with main effects only												
Null model	64	0	100	356	64	0	100	2243	64	0	100	1927
Physical examination only	67 (63)	35 (31)	86 (82)	338 (10)	63 (62)	3.1 (0)	99 (99)	2262 (10)	75 (74)	48 (46)	92 (91)	1928 (10)
All predictors	76 (73)	54 (49)	89 (87)	278 (15)	74 (73)	45 (43)	91 (90)	2164 (15)	75 (73)	51 (47)	90 (88)	1915 (14)
Models including interaction terms												
All interactions	92 (66)	87 (48)	96 (77)	338 (120)	84 (70)	66 (46)	95 (84)	2167 (120)	80 (62)	71 (65)	85 (67)	1965 (105)
Stepwise selected models												
All predictors stepwise	77 (75)	57 (53)	89 (89)	266 (7)	73 (72)	43 (43)	92 (90)	2150 (6)	76 (73)	54 (47)	89 (88)	1901 (5)
All interactions stepwise	**78 (75)**	**56 (51)**	**91 (90)**	**263 (8)**	73 (72)	43 (43)	92 (90)	2150 (6)	75 (70)	45 (46)	92 (85)	1900 (7)

Pairs of numbers in a cell refer to performance on training and test data, with the upper number showing performance on the training data, and the lower number the cross-validation performance. For AFT and bGLM models, results are only given for the model with the lowest AIC.
AIC are presented with number of predictors in their model.
Bolded values indicate the final model used for the RDR Score.
AFT, accelerated failure time; AIC, Akaike information criterion; GLM, generalised linear modelling; PH, proportional hazard.

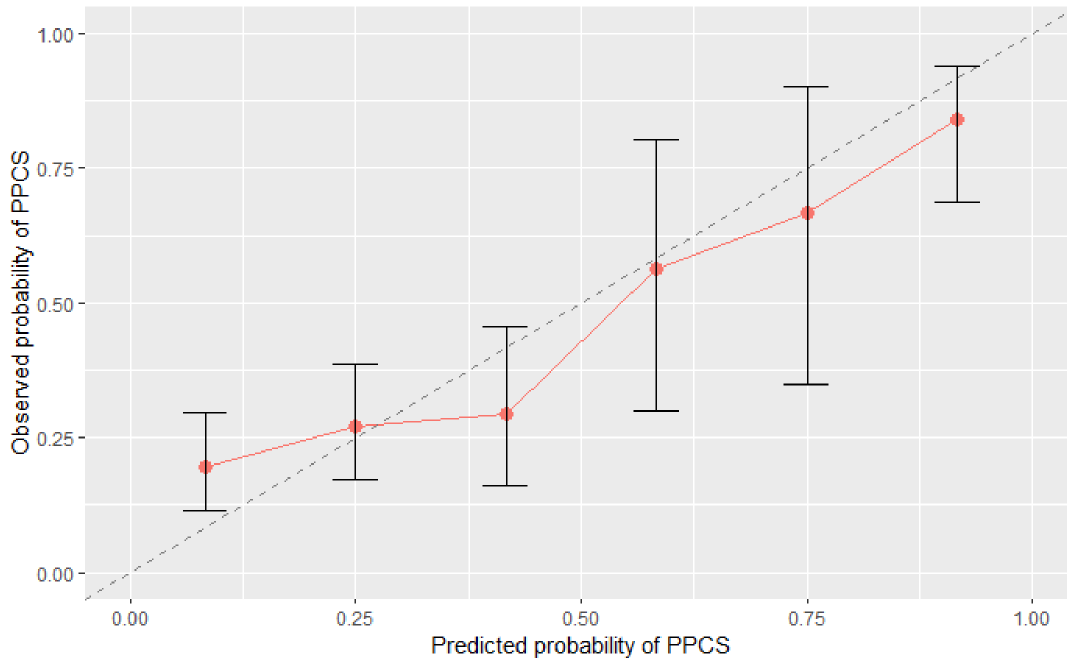

Figure 2 Calibration plot for the final model. PPCS, persistent post-concussive symptoms.

so the lower bound on the accuracy of any predictive model was set at 64%, simply by predicting that no participants would have delayed recovery regardless of their risk factors. Our BCPE RDR-score was 85% accurate when calculated during the early phase after injury after cross-validation, which was significantly better than the null hypothesis for predicting PPCS incidence.

PPCS planning should be based on the patient's underlying impairments.[14] This convenient risk calculation score identifies children who require early PPCS planning, but it can also be used with other clinical tools, including symptom checklists that identify mood-related and cognition-related impairments,[34] mental health[35] and migraine history[36] and treadmill testing[37] that identifies exercise intolerance. The information is used to individualise a treatment programme to reduce the risk of prolonged recovery. Children identified by the RDR-score as low-risk for PPCS should nevertheless be given low-resource guidance to help ensure that they will recover uneventfully, including education about avoiding symptom provocation, safe physical and cognitive activity levels, basic sleep hygiene and how to monitor recovery. A mobile calculator app (eg, *MD Calc*) or an Excel spreadsheet could be used to make a template with 'Yes or No" responses to the six items (with appropriate multipliers) to rapidly provide the RDR-score for physicians in the busy clinic setting. Two sample clinical scenarios using the BCPE RDR-score are provided in online supplemental file 2).

Some variables not included in our model have previously been identified as predictors of PPCS.[38] Female sex was a significant contributor to predicting PPCS in the Cox PH and AFT models, but not in the bGLM model, so it did not make it into the RDR-score. Female sex has historically[38] been associated with longer recovery times and it correlated with longer mean recovery time in our sample, but it was not predictive of the binary diagnosis of PPCS (≥30 days recovery). In a recent prospective study, however, male and female patients managed with early aerobic exercise recovered equally well.[39] Participants in our study were managed according to our clinics' protocols, which identify and treat symptom generators regardless of sex. There was also a

Table 3 Details of the final bGLM model with a complementary log–log link function

Variable	Coeff.	P > |z|	95% CI
Time-since-injury	0.26	<0.001	0.19 to 0.33
OI	1.31	<0.001	0.58 to 2.03
VOR	1.29	<0.001	0.56 to 2.02
≥3 previous concussion	1.08	0.018	0.18 to 2.0
Tandem gait	0.29	0.259	−0.22 to 0.80
High-velocity/multiple impact	0.50	0.290	−0.43 to 1.43
OI × VOR	−1.13	0.023	−2.11 to −0.17
High-velocity/multiple impact × tandem gait	1.27	0.103	−0.25 to 2.79
Intercept	−3.69	<0.001	−4.50 to −2.89

OI, orthostatic intolerance; VOR, vestibulo-ocular reflex.

Table 4 The Buffalo Concussion Physical Examination RDR-score for delayed recovery

Predictor	Description	Score
Days since injury	*n* (in days)	1 point per day
High velocity/multiple impact	No (0) or yes (1)	2 points
≥3 previous concussions	No (0) or yes (1)	4 points
OI	Normal (0) or abnormal (1)	5 points
VOR	Normal (0) or abnormal (1)	5 points
Tandem gait	Normal (0) or abnormal (1)	1 point
OI * VOR	1 if both are abnormal, 0 elsewise	−4 points
High velocity/multiple impact * tandem gait	1 if both are abnormal, 0 elsewise	5 points
RDR-score classifications		**Total score range**
Low risk (<30% risk of delayed recovery)		0–10
Medium risk (30%–70% risk of delayed recovery)		11–14
High risk (>70% risk of delayed recovery)		15+

OI, orthostatic intolerance; RDR, risk for delayed recovery; VOR, vestibulo-ocular reflex.

significant correlation between female sex and neck tenderness at the initial clinical assessment (mean 6 days after injury), and untreated concomitant cervical injuries have been associated with longer recovery times.[20 38] We typically treat neck injuries early according to recent guidelines,[10 15] so it is not surprising that neck examination components (tenderness, spasm, reduced ROM) were not associated with PPCS risk in our sample. Future research should investigate the benefits of early management in those with neck injuries after concussion.

Time-since-injury was challenging to incorporate and, of the methods assessed, the bGLM with a complementary log–log link function performed best. One-point per day till presentation at the clinic was assigned in our scoring system, so children presenting 14 days after injury with ongoing signs and symptoms of concussion automatically qualified for the high-risk category for PPCS and were therefore candidates for PPCS planning. These findings are consistent with research by Kontos *et al*[40] showing that recovery is delayed in those presenting to clinic later rather than sooner after injury. The increase in risk for PPCS for children presenting later could also be due to right censorship. Right censorship occurs when a subject is removed from the study before being included.[41] So children who appear to *wait a week and see* if they recover before being assessed by a physician but do not recover are at a higher risk for delayed recovery simply because children who recovered before being assessed by our clinicians were not included in the analysis. Further research investigating this relationship should be performed.

From the BCPE, the main effects of OI, VOR and tandem gait were included in the final predictive model. These elements assess the vestibular and autonomic,[42] vestibular and ocular[43] and dynamic vestibular[44] subsystems, respectively. Impairments in each of these subsystems have been associated with longer recovery in concussed children,[43 45] so we can be confident in including these in the BCPE RDR-score. While the majority of our subjects recovered from their vestibular deficits spontaneously, there is evidence that early vestibular rehabilitation may prevent persistent impairments;[20] so, in certain cases of significant vestibular impairment, early directed intervention with a physical or occupational therapist should be considered as part of *PPCS planning*.

There are two interaction terms in our score, one positive and one negative. The negative interaction term between OI and VOR was included in both the Cox PH and bGLM models. Examining the coefficients for this term, when both OI and VOR were present, the HR in the Cox PH model and the combined coefficients in the bGLM model were comparable to when they were included separately. Hence, the combined effect of OI and VOR was not additive, and we can be confident in including a negative interaction term for their co-occurrence in the scoring system. The main effects of OI and VOR were highly significant ($p<0.0005$), while the coefficients for the OI and VOR interaction term were significant at a 0.05 level. We can therefore be confident that these predictors are valid; however, we are less certain about the main effect of tandem gait and the positive interaction term multiple/high-velocity injury and tandem gait. While these have been included in the model by stepwise selection using AIC, their individual coefficients had lower significance ($p=0.259$ and 0.103, respectively). A larger sample size would allow this issue to be resolved with more confidence.

Limitations

Our a priori sample size estimate did not account for unequal outcomes. With an average PPCS incidence of ~30%, we should have collected a sample of 520 participants in total. Additionally, prior research has shown that generic rule-of-thumb sample size recommendations for multilevel logistic regression may not be reliable when distribution of predictors is not equal.[46] A minimum recommended sample size for a future validation study based on 20 predictors-per-variable,[47] 6 predictor variables from the BCPE RDR-score and 30 interaction pairs with a PPCS incidence of 36% would equal 2000 participants in total. Larger, multicentre studies should be performed to externally validate the integers of the scoring system.

Furthermore, our scoring system was developed using patients in a sports medicine clinic setting that incorporates early treatment for cervical injury; hence, this scoring system may not be predictive in children who are managed using older standards of care (ie, 'cocooning").[48] Nevertheless, our clinic is not a 'one stop shop" for concussion management and functions much as a primary care setting would in terms of referring patients to community providers for specialised treatment (eg, vision, vestibular, psychological and cognitive interventions). The majority of concussions in our sample were (1) from sport-related injuries (84%), (2) single/low-velocity injuries (90%) and (3) in older children 12–18 years of age. We had few cases of assaults and MVAs (which are associated with much longer recovery times).[7] These were classified as high-velocity injuries, and almost all met criteria for high-risk for PPCS so we are confident about including them in the RDR-score; however, there were very few complex injuries in our sample (n=28), which increases the risk for a type 1 error.[49] Future studies should validate the BCPE RDR-score in a more heterogeneous population. Our scoring system includes injury severity, which depends on an accurate patient history. This may not be reliable with children; hence, confirming details of the injury with observers is advised. Additionally, some SRC may not necessarily qualify as 'low-velocity" and may be associated with additional trauma (eg, musculoskeletal injury) that may delay recovery, so each case should be classified according to all of the clinical information. Finally, this scoring system does not incorporate subjective concussion symptom checklists or mood-related diagnoses, which are known to be associated with delayed recovery.[38 50] We did not include symptoms in our model because of concerns about under-reporting or over-reporting due to secondary gain motives.[51] Thus, the RDR-score can be used in concert with symptom checklists, mental health and migraine history, and adjunct testing to enhance overall predictive performance.

CONCLUSION

The RDR-score is an easy-to-use, clinically relevant scoring system that, within 14 days of injury, can identify children at risk for developing PPCS. It is 85% accurate using 3 components of the history (≥3 previous concussions, days since injury and severity of injury) and 3 components of the BCPE (OI, VOR and tandem gait) to classify children at low (<30% risk, score=0–10), medium (30%–70% risk, score=11–14) or high (>70% risk, score=15+) risk for developing PPCS. Physicians in multiple settings can use this tool to implement early *PPCS planning* for high-risk patients, take a *wait and see* approach for low-risk patients and decide on treatment recommendations based on patient-specific goals for children at medium-risk for developing PPCS. Early PPCS planning should be tailored to each patient based on underlying impairments, which are identified from a complete concussion evaluation consisting of

What are the findings?

- ► Using three components of the Buffalo Concussion Physical Examination and three components of the history, physicians can use the risk of delayed recovery (RDR)-score as a decision rule to identify children who would benefit most from early Persistent PostConcussion Symptom (PPCS) planning.
- ► The RDR-score classifies children within 14 days of injury into low-risk (<30%), medium-risk (30%–70%) or high-risk (>70%) for developing PPCS with 85% accuracy.
- ► This RDR-score was generated independent of symptom checklists, mood screeners or mental health history, so it can be used in concert with them without overlap in predictive capability.

How might it impact on clinical practice in the future?

- ► Interventions for concussion are usually delayed because the majority of impairments spontaneously recover within 1 month, however, 15%–30% of children take longer to recover and develop PPCS. Using the RDR-score decisions rule, clinicians can identify children who are at a high risk and begin planning for early intervention.
- ► Symptoms of PPCS are treated by identifying underlying symptom generators and providing directed interventions. Initial clinic evaluation of an acute concussion should include (1) a complete history including mental health history; (2) focused examination of the oculomotor, vestibular and cervical systems for common postconcussive impairments; (3) symptom checklists and (4) screens for changes in cognition and mood.
- ► Early planning for PPCS can include monitoring symptom exacerbators, communication with school personnel regarding accommodations, referral for specific oculomotor, vestibular and/or neurobehavioural interventions and sport-specific therapies.

history (including symptom checklists and behavioural screens), a concussion-focused physical examination and adjunct testing (eg, cognitive or exertional) where clinically indicated.

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Disclaimer The authors are well known in the field because of the Buffalo Concussion Treadmill Test (BCTT) and Buffalo Concussion Protocol, and the Buffalo Concussion Physical Exam (BCPE) shares the same moniker. There are no monetary gains associated with this naming pattern.

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