

Subacute Heart Rate Variability as a Predictor of Outcomes after Concussion in Adolescents

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Abstract

Accurate, objective methods for tracking recovery after concussion are essential, yet reliable predictors of adolescent outcomes remain limited. Heart rate variability (HRV), reflecting the coordination between central and peripheral nervous systems, may reveal hidden impairments and serve as an early indicator of symptom progression. This study explored the connection between HRV and recovery trajectories in adolescents and evaluated its potential as a prognostic tool. Fifty-five adolescents (ages 12–17) presenting with concussion at a local sports medicine clinic underwent an initial subacute assessment within 15 days of injury, followed by a post-acute evaluation. Data collected included self-reported clinical and depressive symptoms, neurobehavioral assessments, and cognitive testing. Short-term HRV measurements were obtained via photoplethysmography during both rest and stress conditions. Analyses showed significant links between HRV and clinical, neurobehavioral, and cognitive outcomes at the subacute stage. Critically, subacute HRV measures were able to predict reduced neurobehavioral and cognitive performance at follow-up. These findings indicate that HRV assessed shortly after concussion could function as a predictive biomarker, identifying underlying neurological dysfunction and signaling potential long-term cognitive challenges.

Keywords: Cognition, Concussion, pediatrics, Adolescence, Heart rate variability, Neurobehavioral function

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Introduction

Clinical management of concussion in adolescents has largely depended on self-reported symptoms and neuropsychological testing to assess recovery status [1-3]. However, the reliability and validity of these traditional measures have been questioned [4], as evidence suggests that adolescents and young adults may underreport the severity of their symptoms [5-8]. Furthermore, post-concussion symptoms are often nonspecific, complicating clinicians' ability to detect hidden functional deficits that can persist beyond the typical four-week recovery period [9, 10]. Between 2001 and 2012, adolescents (ages 10–19) experienced the largest rise in concussion incidence (>140%) among all age groups [11]. This developmental stage coincides with critical neurological maturation, which may contribute to the heightened vulnerability of

adolescents to prolonged deficits compared to adults [12, 13]. The limitations of conventional clinical assessments raise concerns, as premature return to sports or academic activities may increase the risk of reinjury [14] or symptom recurrence [15]. Consequently, there is a pressing need for objective indicators that can more accurately guide post-concussion management in this population.

Heart rate variability (HRV) is a widely accepted measure of cardio-autonomic regulation [16] and has recently gained attention as a potential biomarker for tracking concussion recovery [17]. HRV reflects beat-to-beat heart rate fluctuations mediated by the vagus nerve, providing insight into parasympathetic nervous system modulation of the sinoatrial node [18, 19]. According to the Neurovisceral Integration model, HRV is functionally linked to the regulation of cognitive and behavioral

processes [20]. Research suggests that HRV can indirectly reflect top-down neural activity from prefrontal regions, as both cognitive and behavioral tasks that engage the prefrontal cortex influence HRV [21, 22]. In healthy individuals, higher HRV indicates adaptive autonomic reactivity capable of maintaining physiological stability at rest [23, 24]. Under physiological stress, normal responses involve vagal withdrawal and a temporary reduction in HRV to meet neurometabolic demands [25, 26]. Deviations from typical HRV patterns, whether at rest or in response to stress, may signal underlying dysfunction, such as that caused by traumatic brain injury (TBI) [27, 28]. Preliminary studies indicate that individuals with concussion may exhibit abnormal HRV, characterized by either exaggerated or blunted autonomic responses compared to uninjured controls [29–33]. These alterations in HRV may correspond with cognitive and neurobehavioral deficits that could remain undetected through standard clinical assessment, particularly in adolescents.

Emerging evidence links HRV metrics to symptom severity and post-concussion cognitive deficits [34, 35]. However, the literature has yet to establish HRV as a predictive marker for adolescent concussion outcomes. Accordingly, the present study aimed to (1) explore associations between subacute HRV—both at rest and during brief physiological stress—and clinical, depressive, neurobehavioral, and cognitive outcomes following adolescent concussion, and (2) assess the predictive utility of subacute HRV for post-acute recovery. We hypothesized that (1) HRV would correlate with outcomes during the subacute evaluation and (2) subacute HRV

would serve as a predictor of post-acute concussion outcomes.

Experimental section

Procedure

This study represents a retrospective analysis of data derived from a larger investigation into clinical concussion evaluations. A total of 412 youths suspected of recent concussion were assessed at a pediatric sports medicine clinic. Concussion diagnoses were confirmed during the initial evaluation by the attending physician (JPH) using the Consensus Statement on Concussion in Sport [1] and American Academy of Neurology guidelines [36]. Participants were instructed to return for a follow-up assessment approximately three weeks later. All data were de-identified before analysis. The study was approved by the Health Sciences South Carolina Institutional Ethics Review Board (Reference #: Pro00075286). Written consent was waived, as the evaluations were part of standard clinical care.

Participants

Of the youths screened, 74 adolescents (~18%) were initially diagnosed with concussion during the subacute evaluation (3–15 days post-injury) and returned for a post-acute follow-up within 60 days. Participants with medical histories likely to affect post-concussion outcomes or autonomic function were excluded. Ultimately, 55 adolescents (13.3%) met the inclusion criteria and were included in the final analyses (**Figure 1**).

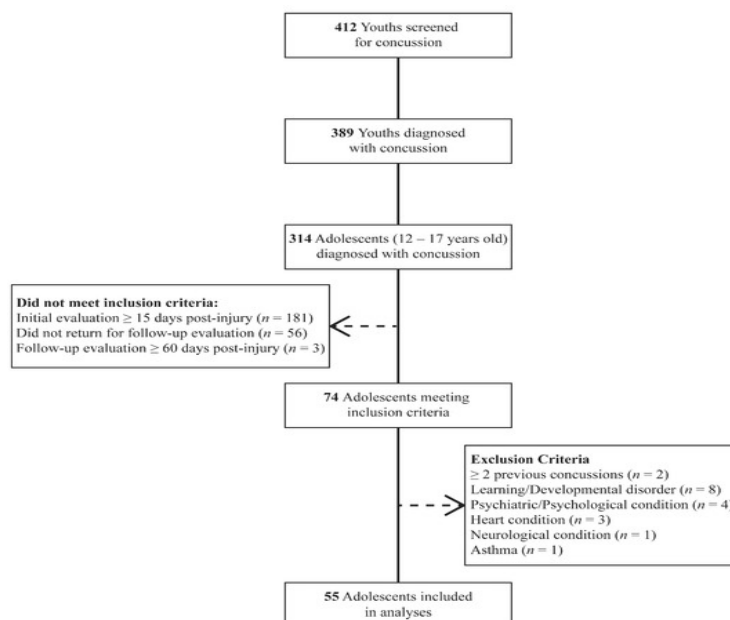


Figure 1. Flow diagram of the sample participants

Measures

Demographics and health background

Information regarding participants' age, sex, ethnicity, medical history, sports involvement, and details of their injuries was collected from parents or legal guardians. These data were used to determine study eligibility and to account for factors that could influence recovery from adolescent concussion, such as prior concussion incidents, body mass index (BMI), time since the injury, and level of athletic participation.

Heart rate variability (HRV)

Heart rate variability was recorded using an EmWave Pro Plus infrared ear sensor (HeartMath, Boulder Creek, CA, USA). Participants sat quietly and followed a paced breathing rate of 0.13 Hz (equivalent to 7.5 breaths per minute) during a continuous 5-minute measurement. Data collection was conducted under standardized lighting and temperature conditions and at roughly the same time of day for all participants.

Raw HRV signals were processed using Kubios HRV Standard version 3.0.2 (Biosignal Analysis and Medical Imaging Group, Kuopio, Finland), with artifacts identified and corrected before analysis. A 10% Hanning window was applied to the cleaned data, followed by calculation of both time-domain and nonlinear HRV indices, in accordance with guidelines from the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [37].

Time-domain indices were derived from successive intervals between QRS complexes generated by sinus node depolarization, referred to as RR intervals [37]. After excluding artifacts and ectopic beats, these were termed normal-to-normal (NN) intervals. Key measures included:

- HR dispersion: the average variation between the highest and lowest heart rate within each respiratory cycle.
- SDNN: the standard deviation of NN intervals, representing overall cardiac variability.
- RMSSD: the root mean square of successive NN differences, reflecting parasympathetic (vagal) activity [24, 38, 39].

HR dispersion specifically captures respiratory sinus arrhythmia (RSA), the normal cyclical change in heart rate that occurs with respiration, independent of vagal influence [24].

Nonlinear indices, which can be altered after concussion [40], were also computed. Sample entropy (SampEn) was calculated via an autoregressive model to quantify the complexity or unpredictability of heart rate patterns [24, 38], with lower values indicating more regular, less variable rhythms.

An additional 1-minute HRV measurement was performed during isometric handgrip contraction (IHGC) to evaluate physiological adaptability to stress. Since nonlinear measures are not validated for recordings shorter than 5

minutes, only time-domain indices were considered for this task [41].

Assessment of clinical symptoms

The Rivermead Post-Concussion Symptoms Questionnaire (RPQ), a 16-item self-report measure, was used to evaluate the severity of post-concussion symptoms relative to pre-injury status [42]. A validated three-factor framework assessed:

- Somatic symptoms (e.g., headache, nausea, dizziness)
- Emotional symptoms (e.g., irritability, restlessness, frustration)
- Cognitive symptoms (e.g., forgetfulness, slower thinking, poor concentration) [43]

Higher scores within each domain indicated more pronounced symptom severity.

Depressive symptoms

The presence and severity of depressive symptoms in participants were assessed using the Beck Youth Inventory–Second Edition, Depression Scale (BYI-2), a self-report tool consisting of 20 items [44]. Items evaluate experiences such as sadness, pessimism, feelings of guilt, diminished pleasure, and fatigue. The BYI-2 has demonstrated strong reliability over repeated assessments (test–retest: 0.74–0.93) and aligns well with other validated measures of youth depression [44]. Higher scores indicate more pronounced depressive symptomatology.

Neurobehavioral function

Parents completed the Behavior Rating Inventory of Executive Function–Parent Version (BRIEF-P) to provide insight into their child's executive functioning in everyday contexts at home and school [45]. The instrument consists of 86 items and has been shown to possess robust internal consistency (0.80–0.98) and acceptable test–retest reliability (0.72–0.84) [45]. BRIEF-P results are summarized in two indices: the Behavioral Regulation Index, capturing skills such as inhibitory control, cognitive flexibility, and emotional regulation, and the Metacognition Index, covering abilities like task initiation, working memory, planning and organization, material organization, and self-monitoring. Elevated scores reflect greater deficits in executive functioning.

Cognitive performance

Cognitive function was evaluated using a modified CogState Brain Injury Testing Battery (CogState Ltd., Melbourne, Australia) comprising three computerized tasks: Groton Maze Learning (GML), Groton Maze Delayed-Recall (GMR), and One-Back (ONB). In the Groton Maze tasks, performance metrics included the rate of correct moves per second and total errors, providing

indicators of cognitive efficiency and working memory. For the ONB task, accuracy (proportion correct), mean reaction time (milliseconds), and reaction time variability were analyzed to assess attention and working memory. These tasks have previously demonstrated reliability and validity across age ranges and clinical populations [46–48]. To mitigate practice effects, participants completed practice trials prior to each task [49].

Data analysis

All statistical procedures were carried out using SPSS version 27.0 (IBM Corporation, Armonk, NY, USA). Non-normal distributions prompted natural-logarithm transformations for RPQ, BYI-2, and BRIEF-P scores. Accuracy in the ONB task was adjusted using an arcsine square root transformation, and ONB mean reaction times were log-transformed. Paired-sample *t*-tests examined differences between subacute and post-acute evaluations. Multivariate linear regression models were applied to explore (1) the relationship between HRV metrics and

concussion outcomes at the subacute stage and (2) the predictive value of HRV measures from the subacute phase for post-acute outcomes. Models accounted for potential confounders, including age, sex, previous concussion history, BMI, time since injury, and athletic status. Assumptions of linearity, homoscedasticity, absence of multicollinearity, and lack of influential outliers were verified. Statistical significance was set at $p < 0.05$.

Results and Discussion

Participant characteristics

Tables 1 and 2 summarize participant demographics, injury characteristics, and HRV measures. **Table 2** provides descriptive statistics (means, standard deviations, and percentiles) for HRV both at rest and during the isometric handgrip contraction (IHGC) during the subacute evaluation.

Table 1. Participant demographic information and injury characteristics

Participant Data (n = 55)	
Demographic Information	
Age (years)	14.5 ± 1.4
BMI (kg/m ²)	24.4 ± 6.1
Biological Sex, N (%)	
Males	31 (56.4)
Females	24 (43.6)
Ethnicity, N (%)	
Caucasian	22 (40)
African American	21 (38.2)
Latino/Hispanic	2 (3.6)
Native American	1 (1.8)
Other/Unknown	9 (16.4)
History of Concussion, N (%)	
No History	43 (78.2)
One Prior Concussion	12 (21.8)
Athlete Status, N (%)	
Athlete	41 (74.5)
Nonathlete	14 (25.5)
Injury Characteristics	
Cause of Injury, N (%)	
Sport or Recreation	37 (67.3)
Motor Vehicle Accident	11 (20.0)
Other (fall, accident, etc.)	7 (12.7)
Days from Concussion	
Subacute Evaluation (3–15 days)	9.0 ± 4.5
Post-Acute Evaluation (15–60 days)	29.2 ± 10.2

Note: Data are reported as mean ± SD, unless otherwise noted. BMI: body mass index.

Table 2. Descriptive HRV values for concussed participants at the subacute evaluation

HRV Variable	Mean ± SD	25th Percentile	50th Percentile	75th Percentile
Resting State				
HR dispersion	28.8 ± 8.8	25.0	28.0	32.4
SDNN	71.4 ± 29.7	47.8	68.0	94.3
RMSSD	79.2 ± 35.9	49.7	71.5	103.3
SampEn	1.75 ± 0.21	1.68	1.76	1.90

Isometric Handgrip Contraction				
HR dispersion	29.8 ± 1.3	21.7	29.6	35.7
SDNN	114.4 ± 6.9	83.3	106.1	143.7
RMSSD	93.9 ± 8.1	53.0	75.5	111.8

Abbreviations: HRV, heart rate variability; HR, heart rate; SDNN, standard deviation of normal-to-normal (NN) intervals; RMSSD, root mean square of successive NN interval differences; and SampEn, sample entropy.

Table 3 displays the mean values and standard deviations for outcome variables measured at the subacute and post-acute time points. Analysis using paired-sample t-tests revealed that both clinical and depressive symptoms showed a marked decline between the two evaluations ($p < 0.001$). Most indicators of neurobehavioral functioning remained largely unchanged across time, except for the

Organization of Materials scale, which exhibited a modest but statistically significant improvement (Cohen's $d = 0.313$, $p = 0.024$). In terms of cognitive performance, significant gains were observed from the subacute to post-acute assessment ($p < 0.05$), although improvements were not detected for GMR total errors or the variability of ONB reaction times.

Table 3. Descriptive outcome values for concussed participants at the subacute and post-acute evaluations

Outcome Variable		Mean ± SD	Cohen's d	p-Value
RPQ subdomain				
Somatic	Subacute	11.0 ± 6.9	0.931	<0.0001 *
	Post-Acute	5.6 ± 6.9		
Emotional	Subacute	4.3 ± 3.6	0.985	<0.0001 *
	Post-Acute	2.0 ± 3.2		
Cognitive	Subacute	4.9 ± 3.2	1.067	<0.0001 *
	Post-Acute	2.0 ± 2.7		
BYI-2 Depression Scale				
Total Score	Subacute	0.67 ± 0.44	0.637	<0.0001 *
	Post-Acute	0.41 ± 0.47		
BRIEF-P subdomain				
Behavioral Regulation Index	Subacute	36.9 ± 8.5	0.112	0.412
	Post-Acute	36.5 ± 10.3		
Metacognition Index	Subacute	66.5 ± 17.3	0.247	0.073
	Post-Acute	63.8 ± 17.0		
CogState				
GML correct moves per second	Subacute	0.60 ± 0.16	0.884	<0.0001 *
	Post-Acute	0.73 ± 0.17		
GML total errors	Subacute	59.4 ± 16.9	0.586	<0.0001 *
	Post-Acute	50.8 ± 16.5		
GMR correct moves per second	Subacute	0.85 ± 0.24	0.520	<0.0001 *
	Post-Acute	0.97 ± 0.30		
GMR total errors	Subacute	7.6 ± 4.4	0.165	0.225
	Post-Acute	6.8 ± 4.4		
ONB reaction time (ms)	Subacute	1071.2 ± 319.2	0.307	0.027 *
	Post-Acute	990.0 ± 269.5		
ONB RT variability	Subacute	0.15 ± 0.03	0.102	0.451
	Post-Acute	0.14 ± 0.04		
ONB accuracy (%)	Subacute	84.5 ± 15.4	0.308	0.026 *
	Post-Acute	89.0 ± 0.10		

Note: Cohen's d and p -values were derived from paired-sample t-tests. * denotes statistical significance ($p < 0.05$). RPQ, Rivermead Post-Concussion Symptoms Questionnaire; BYI-2, Abbreviations: Beck Youth Inventory-2; BRIEF-P, Behavior Rating Inventory of Executive Function; GML, Groton Maze Learning; GMR, Groton Maze Recall; and ONB RT, One-back task reaction time.

Clinical symptoms

Multivariate regression analyses revealed notable links between resting heart rate variability and symptom severity during the subacute phase. Adolescents exhibiting higher SDNN ($\beta = -0.308$, $sR^2 = 0.082$) and RMSSD ($\beta = -0.293$, $sR^2 = 0.072$) values at rest reported fewer somatic symptoms, suggesting that greater baseline HRV corresponds with reduced physical symptom burden

following concussion. In contrast, elevated HR dispersion at rest was positively associated with both emotional ($\beta = 0.355$, $sR^2 = 0.104$) and cognitive ($\beta = 0.341$, $sR^2 = 0.097$) symptom scores, indicating that increased variability across the respiratory cycle may relate to heightened non-physical symptom severity at the subacute evaluation. Importantly, subacute HRV measures did not serve as significant predictors of self-reported symptom severity on the RPQ during the post-acute follow-up (**Table 4**).

Table 4. Multivariate regression analyses for the Rivermead Post-Concussion Symptom Questionnaire (RPQ) ^a

HRV Variable	Subacute RPQ Symptom Domain								
	Somatic			Emotional			Cognitive		
	β	sR ²	p	β	sR ²	p	β	sR ²	p
Resting State									
HR dispersion	0.180	0.027	0.200	0.355	0.104	0.009 *	0.341	0.097	0.016 *
SDNN	-0.308	0.082	0.023 *	0.101	0.009	0.463	-0.024	0.000	0.870
RMSSD	-0.293	0.072	0.033 *	0.114	0.011	0.413	-0.042	0.001	0.774
SampEn	0.169	0.023	0.238	-0.180	0.026	0.205	-0.081	0.005	0.584
Isometric Handgrip Contraction									
HR dispersion	0.012	0.000	0.929	0.240	0.055	0.064	-0.161	0.025	0.232
SDNN	-0.163	0.024	0.226	0.154	0.021	0.253	-0.120	0.013	0.391
RMSSD	-0.047	0.002	0.726	0.212	0.042	0.109	-0.077	0.005	0.576
Post-Acute RPQ Symptom Domain									
Resting State									
HR dispersion	-0.002	0.000	0.986	0.046	0.002	0.735	0.124	0.013	0.380
SDNN	0.024	0.001	0.851	0.001	0.000	0.993	-0.009	0.000	0.948
RMSSD	0.073	0.005	0.573	0.066	0.004	0.627	0.033	0.001	0.815
SampEn	-0.047	0.001	0.725	-0.018	0.000	0.898	0.034	0.001	0.820
Isometric Handgrip Contraction									
HR dispersion	0.007	0.000	0.954	-0.028	0.001	0.826	-0.045	0.002	0.736
SDNN	0.026	0.001	0.837	-0.003	0.000	0.981	-0.053	0.003	0.701
RMSSD	0.033	0.001	0.794	-0.013	0.000	0.920	-0.009	0.000	0.945

^a Age, sex, history of concussion, BMI, time since injury, and athletic status were entered into the adjusted models. * denotes predictor significance ($p < 0.05$). sR², squared semi-partial correlations. Abbreviations: HRV, heart rate variability; HR, heart rate; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive NN interval differences; and SampEn, sample entropy.

Depressive symptoms

Analysis indicated that heart rate variability measured during the subacute phase showed no significant

correlation with depressive symptom scores, as assessed by the BYI-2, at either the subacute or post-acute time points (Table 5).

Table 5. Multivariate regression analyses for the Beck Youth Inventory–Depression Scale (BYI-2) ^a

HRV Variable	Subacute BYI-2 Scores			Post-Acute BYI-2 Scores		
	β	sR ²	p	β	sR ²	p
Resting State						
HR dispersion	-0.031	0.000	0.840	0.024	0.000	0.867
SDNN	-0.107	0.010	0.474	0.098	0.008	0.482
RMSSD	-0.073	0.004	0.632	0.132	0.015	0.345
SampEn	-0.002	0.006	0.569	-0.112	0.010	0.438
Isometric Handgrip Contraction						
HR dispersion	-0.019	0.000	0.892	0.030	0.001	0.820
SDNN	-0.055	0.003	0.706	0.051	0.002	0.709
RMSSD	0.051	0.002	0.724	0.031	0.008	0.820

^a Age, sex, history of concussion, BMI, time since injury, and athletic status were entered into the adjusted models. No significance was observed ($p > 0.05$). sR², squared semi-partial correlations. Abbreviations: HRV, heart rate variability; HR, heart rate; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive NN interval differences; and SampEn, sample entropy.

Neurobehavioral function

Multivariate regression results indicated that higher resting SDNN ($\beta = 0.334$, sR² = 0.096) and RMSSD ($\beta = 0.303$, sR² = 0.078) during the subacute phase were linked to worse scores on the Behavioral Regulation Index of the BRIEF-P, suggesting that elevated HRV at rest corresponds with greater difficulties in behavioral

regulation. Conversely, lower sample entropy (SampEn) values at rest were associated with poorer Behavioral Regulation Index performance ($\beta = -0.376$, sR² = 0.114), indicating that reduced complexity in heart rate patterns relates to greater behavioral regulation challenges. No significant relationships were observed between any subacute HRV measure and the Metacognition Index of the BRIEF-P at the subacute evaluation (Table 6).

Table 6. Multivariate regression analyses for the Behavior Rating Inventory of Executive Function (BRIEF-P) ^a

HRV Variable	Subacute BRIEF-P Index	
	Behavioral Regulation Index	Metacognition Index

HRV Variable	β	sR^2	p	β	sR^2	p
Resting State						
HR dispersion	0.010	0.000	0.948	0.071	0.004	0.627
SDNN	0.334	0.096	0.017 *	0.102	0.009	0.476
RMSSD	0.303	0.078	0.034 *	0.080	0.005	0.580
SampEn	-0.376	0.114	0.009 *	-0.126	0.013	0.392
Isometric Handgrip Contraction						
HR dispersion	0.196	0.036	0.149	0.210	0.042	0.117
SDNN	0.133	0.016	0.345	0.019	0.000	0.893
RMSSD	0.068	0.004	0.628	-0.038	0.001	0.784
Post-Acute BRIEF-P Index						
Resting State						
HR dispersion	0.058	0.003	0.691	0.122	0.013	0.424
SDNN	-0.039	0.001	0.784	-0.130	0.015	0.387
RMSSD	-0.010	0.000	0.946	-0.132	0.015	0.387
SampEn	-0.045	0.002	0.764	0.025	0.000	0.875
Isometric Handgrip Contraction						
HR dispersion	0.015	0.000	0.914	0.011	0.000	0.940
SDNN	-0.062	0.003	0.661	-0.161	0.023	0.276
RMSSD	0.001	0.000	0.995	-0.133	0.016	0.359

^a Age, sex, history of concussion, BMI, time since injury, and athletic status were entered into the adjusted models. * denotes predictor significance ($p < 0.05$). sR^2 , squared semi-partial correlations. Abbreviations: HRV, heart rate variability; HR, heart rate; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive NN interval differences; and SampEn, sample entropy.

Examination of individual BRIEF-P subscales showed that the post-acute Organization of Materials scores were significantly influenced by subacute resting HRV. Specifically, adolescents with lower SDNN ($\beta = -0.301$, $sR^2 = 0.078$) and RMSSD ($\beta = -0.345$, $sR^2 = 0.101$) at rest tended to perform worse on this subscale at the post-acute evaluation (**Figure 2**). The Organization of Materials scale assesses a child's capacity to establish and maintain structured and orderly arrangements in their external environment [45]. No other executive function subscales from the BRIEF-P demonstrated significant associations with subacute HRV measures.

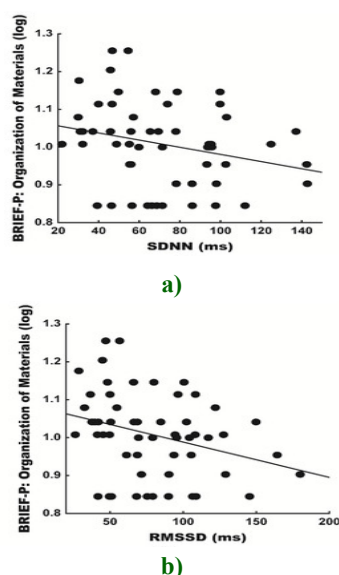


Figure 2. Scatterplots depict the relationships between subacute resting HRV and post-acute scores on the

BRIEF-P Organization of Materials subscale. Unadjusted analyses indicated trends for SDNN ($\beta = -0.255$, $sR^2 = 0.065$, $p = 0.061$) and RMSSD ($\beta = -0.302$, $sR^2 = 0.091$, $p = 0.025$). After adjusting for covariates, both SDNN ($\beta = -0.301$, $sR^2 = 0.078$, $p = 0.043$) and RMSSD ($\beta = -0.345$, $sR^2 = 0.101$, $p = 0.021$) significantly predicted post-acute Organization of Materials performance

Cognitive performance

Regression analyses examining cognitive outcomes revealed that, during the subacute evaluation, adolescents with higher resting SDNN ($\beta = -0.318$, $sR^2 = 0.087$) and RMSSD ($\beta = -0.346$, $sR^2 = 0.101$) exhibited slower rates of correct moves on the Groton Maze Learning (GML) task (**Table 7**). Resting HR dispersion was also linked to several cognitive indices: it was negatively associated with correct moves on the Groton Maze Delayed-Recall (GMR) task ($\beta = -0.318$, $sR^2 = 0.084$), positively related to GMR total errors ($\beta = 0.496$, $sR^2 = 0.204$; **Table 8**), positively correlated with ONB reaction time variability ($\beta = 0.495$, $sR^2 = 0.203$), and inversely associated with ONB accuracy ($\beta = -0.298$, $sR^2 = 0.074$; **Table 9**).

During the isometric handgrip contraction (IHGC), higher RMSSD was associated with slower ONB reaction times ($\beta = 0.241$, $sR^2 = 0.054$) and increased variability in reaction times ($\beta = 0.343$, $sR^2 = 0.108$; **Table 9**). HR dispersion during IHGC predicted lower GML performance ($\beta = -0.278$, $sR^2 = 0.074$; **Table 7**) and greater variability in ONB reaction times ($\beta = 0.402$, $sR^2 = 0.154$; **Table 9**). Additionally, higher sample entropy (SampEn) values were linked to improved ONB accuracy ($\beta = 0.313$, $sR^2 = 0.079$; **Table 9**), suggesting that more

complex heart rate patterns may support better attentional performance.

Table 7. Multivariate regression analyses for Groton Maze Learning (GML) ^a

HRV Variable	Subacute Cognitive Performance (GML)					
	GML Correct Moves Per Second			GML Total Errors		
	β	sR ²	p	β	sR ²	p
Resting State						
HR dispersion	-0.117	0.011	0.407	0.287	0.068	0.057
SDNN	-0.318	0.087	0.019 *	0.144	0.018	0.340
RMSSD	-0.346	0.101	0.011 *	0.139	0.016	0.359
SampEn	0.196	0.031	0.170	-0.093	0.007	0.552
Isometric Handgrip Contraction						
HR dispersion	-0.278	0.074	0.031 *	0.071	0.004	0.621
SDNN	-0.224	0.045	0.095	0.011	0.000	0.940
RMSSD	-0.249	0.057	0.059	0.030	0.001	0.839
Post-Acute Cognitive Performance (GML)						
Resting State						
HR dispersion	-0.006	0.000	0.964	0.147	0.019	0.274
SDNN	-0.151	0.020	0.266	-0.023	0.000	0.865
RMSSD	-0.143	0.017	0.298	-0.035	0.001	0.795
SampEn	0.298	0.070	0.032 *	-0.130	0.013	0.353
Isometric Handgrip Contraction						
HR dispersion	-0.247	0.059	0.052	0.028	0.001	0.830
SDNN	-0.167	0.023	0.208	-0.152	0.020	0.247
RMSSD	-0.093	0.008	0.480	-0.127	0.015	0.327

^a Age, sex, history of concussion, BMI, time since injury, and athletic status were entered into adjusted models. * denotes predictor significance ($p < 0.05$). sR², squared semi-partial correlations. Abbreviations: HRV, heart rate variability; HR, heart rate; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive NN interval differences; and SampEn, sample entropy.

Table 8. Multivariate regression analyses for Groton Maze Recall (GMR) ^a

HRV Variable	Subacute Cognitive Performance (GMR)					
	GMR Correct Moves per Second			GMR Total Errors		
	β	sR ²	p	β	sR ²	p
Resting State						
HR dispersion	-0.318	0.084	0.030 *	0.496	0.204	0.001 *
SDNN	0.096	0.008	0.531	-0.262	0.059	0.071
RMSSD	-0.251	0.053	0.087	0.041	0.001	0.792
SampEn	0.254	0.052	0.091	-0.170	0.023	0.282
Isometric Handgrip Contraction						
HR dispersion	-0.188	0.033	0.175	0.109	0.011	0.452
SDNN	-0.186	0.031	0.193	0.069	0.004	0.645
RMSSD	-0.263	0.063	0.060	0.127	0.012	0.390
Post-Acute Cognitive Performance (GMR)						
Resting State						
HR dispersion	-0.128	0.014	0.355	0.316	0.085	0.026 *
SDNN	-0.242	0.051	0.075	0.013	0.000	0.926
RMSSD	-0.268	0.061	0.050	0.037	0.001	0.798
SampEn	0.260	0.054	0.066	-0.087	0.006	0.564
Isometric Handgrip Contraction						
HR dispersion	-0.213	0.043	0.101	-0.041	0.002	0.763
SDNN	-0.256	0.077	0.054	-0.081	0.006	0.566
RMSSD	-0.230	0.049	0.081	-0.090	0.007	0.517

^a Age, sex, history of concussion, BMI, time since injury, and athletic status were entered into adjusted models. * denotes predictor significance ($p < 0.05$). sR², squared semi-partial correlations. Abbreviations: HRV, heart rate variability; HR, heart rate; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive NN interval differences; and SampEn, sample entropy.

Table 9. Multivariate regression analyses for One-Back task (ONB) ^a

	Subacute Cognitive Performance (ONB)		
	ONB Mean RT (ms)	ONB RT Variability	ONB Accuracy (%)

HRV Variable	β	sR^2	p	β	sR^2	p	β	sR^2	p
Resting State									
HR dispersion	0.052	0.002	0.666	0.495	0.203	0.001 *	-0.298	0.074	0.049 *
SDNN	0.061	0.003	0.611	0.218	0.041	0.126	-0.271	0.063	0.068
RMSSD	0.077	0.005	0.523	0.185	0.029	0.201	-0.212	0.038	0.160
SampEn	-0.095	0.007	0.438	-0.122	0.012	0.412	0.313	0.079	0.041 *
Isometric Handgrip Contraction									
HR dispersion	0.090	0.008	0.424	0.402	0.154	0.002 *	-0.195	0.036	0.169
SDNN	0.150	0.020	0.194	0.252	0.057	0.069	-0.175	0.028	0.233
RMSSD	0.241	0.054	0.032 *	0.343	0.108	0.011 *	-0.174	0.028	0.229
Post-acute Cognitive Performance (ONB)									
Resting State									
HR dispersion	-0.098	0.008	0.492	-0.010	0.000	0.948	-0.373	0.118	0.008 *
SDNN	0.175	0.026	0.215	0.042	0.001	0.780	-0.206	0.037	0.149
RMSSD	0.186	0.029	0.192	0.066	0.003	0.667	-0.156	0.021	0.280
SampEn	-0.278	0.062	0.055	0.040	0.001	0.800	0.119	0.011	0.427
Isometric Handgrip Contraction									
HR dispersion	0.213	0.043	0.109	0.066	0.004	0.649	-0.319	0.097	0.016 *
SDNN	0.278	0.070	0.042 *	0.037	0.001	0.804	-0.177	0.028	0.205
RMSSD	0.328	0.099	0.014 *	0.055	0.003	0.707	-0.230	0.049	0.094

^a Age, sex, history of concussion, BMI, time since injury, and athletic status were entered into adjusted models. * denotes predictor significance ($p < 0.05$). sR^2 , squared semi-partial correlations. Abbreviations: RT, reaction time; HRV, heart rate variability; HR, heart rate; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive NN interval differences; and SampEn, sample entropy.

Additionally, higher sample entropy (SampEn) values significantly predicted better performance on the GML task, reflected by more correct moves per second at the post-acute assessment ($\beta = 0.298$, $sR^2 = 0.070$; Table 7). Consistent with the subacute findings, increased HR dispersion at rest was linked to poorer cognitive outcomes, as indicated by higher GMR total errors ($\beta = 0.316$, $sR^2 = 0.085$; Table 8). Moreover, HR dispersion—both at rest ($\beta = -0.373$, $sR^2 = 0.118$) and during IHGC ($\beta = -0.319$, $sR^2 = 0.097$)—predicted ONB accuracy at the post-acute evaluation (Table 9). During IHGC, SDNN ($\beta = 0.278$, $sR^2 = 0.070$) and RMSSD ($\beta = 0.328$, $sR^2 = 0.099$) were significant predictors of ONB reaction time at the post-acute assessment (Table 9).

This study aimed to examine the relationships between heart rate variability (HRV), both at rest and during physical exertion, and concussion outcomes in adolescents. Our results indicate that subacute HRV measures were linked to clinical symptoms and aspects of neurobehavioral function but did not predict the severity of post-acute symptoms. Similarly, HRV metrics did not correlate with depressive symptoms at either evaluation. In contrast, HRV obtained at rest and during isometric handgrip contraction did predict post-acute neurobehavioral regulation and cognitive performance, suggesting potential utility for clinicians in identifying individuals at risk of prolonged deficits.

After concussion, decoupling of the autonomic nervous system (ANS) and cardiovascular system often occurs [50], manifesting as sympathetic hyperarousal (e.g., altered norepinephrine regulation) and dysregulation of the hypothalamic–pituitary axis (e.g., elevated cortisol). Concurrently, cerebral glucometabolic uncoupling increases neurometabolic demand [51]. According to the

Neurovisceral Integration Model, HRV serves as an index of the functional efficiency of communication between higher-order prefrontal brain regions and cardiovascular regulatory systems [16, 38]. Effective connectivity among these networks is thought to be essential for coordinating adaptive behavioral responses that meet metabolic demands [52]. Concussive injuries temporarily disrupt functional brain connectivity [53–55], which in turn can impair cardio-autonomic regulation, often reflected in altered HRV.

Our findings revealed that lower SDNN and RMSSD values were associated with more severe somatic symptoms at the subacute stage. This aligns with prior observations of reduced resting HRV during the acute and subacute phases, which typically coincide with active symptomatology [29, 30]. It has been proposed that an ability to reduce basal metabolic activity acutely after concussion is critical for neuronal recovery [51, 56]. At rest, the ANS exerts a vagal “brake” on sympathetic activity, protecting the oxygen-demanding central nervous system from metabolically costly processes [57]. Therefore, the observed association between higher HRV and reduced symptom severity may reflect the beneficial role of an early hypometabolic state in facilitating recovery. By the post-acute stage, however, HRV at rest often shows minimal differences between concussed and non-injured adolescents [28, 58, 59], potentially explaining the lack of predictive associations between subacute HRV and post-acute clinical symptoms in this study.

In contrast to our hypotheses, HRV measures did not relate to depressive symptoms at either time point. This finding diverges from prior research suggesting that HRV may forecast subsequent depression in adult females with mild

traumatic brain injury (mTBI) [60]. Differences in study populations and assessment tools may account for these discrepancies, as previous studies utilized the adult Beck Depression Inventory, which includes items distinct from the BYI-2 used here [61]. Additionally, sex-specific factors—such as menstrual cycle phase, menarche status, regularity of cycles, and use of hormonal contraceptives—may influence post-injury symptom trajectories and quality of life [62]. Given the adolescent age range and combined-sex analyses in this study, such variables could have masked potential associations. Future research with larger female samples may clarify sex-specific influences on HRV and post-concussion depressive outcomes.

At the subacute evaluation, we found that higher measures of vagal activity, specifically SDNN and RMSSD, were associated with poorer behavioral regulation scores and slower performance on the Groton Maze Learning (GML) task, as reflected by correct moves per second. Additionally, greater HRV during the physical exertion task was linked to slower reaction times and increased reaction time variability on the One-Back (ONB) task at this same time point (RMSSD). These observations align with previous studies reporting that concussed adolescents may show a counterintuitive relationship between elevated HRV and worsened emotional and cognitive outcomes [35]. Recent research suggests that following concussion, some patients demonstrate an inappropriate rise in vagal tone in response to cognitive or physiological stressors compared to healthy peers [32, 33]. This failure to appropriately suppress vagal activity may indicate a reduced capacity to mobilize resources in response to environmental demands [63]. Consistent with this, higher SDNN and RMSSD during the exertion task also predicted slower ONB performance at the post-acute evaluation, suggesting that acutely concussed adolescents with elevated HRV may struggle to regulate vagal withdrawal during stress.

Interestingly, higher subacute resting HRV predicted better post-acute scores on the Organization of Materials scale (SDNN and RMSSD), indicating enhanced “external” organizational skills. These seemingly contradictory findings highlight the complexity of the relationship between resting versus stress-induced HRV and cognitive/organizational outcomes in adolescents, warranting further investigation.

Beyond conventional HRV metrics, HR dispersion demonstrated consistent associations with concussion outcomes across time points. Individuals with greater HR dispersion reported more severe emotional and cognitive symptoms and performed worse on cognitive tasks during the subacute assessment. Moreover, higher HR dispersion, both at rest and during stress, predicted poorer performance on the GMR and ONB tasks at the post-acute evaluation. These findings support prior work by Brandt *et al.*, who identified respiratory sinus arrhythmia (RSA)

indices as potential predictors of adverse outcomes following mild traumatic brain injury [64].

Preliminary evidence also points to HRV complexity measures, such as approximate entropy (ApEn) or sample entropy (SampEn), as relevant during concussion recovery [40, 65]. Consistent with this, lower SampEn values at the subacute evaluation were associated with poorer behavioral regulation and ONB accuracy. Additionally, reduced SampEn at the subacute stage predicted slower GML performance at the post-acute assessment, indicating that diminished HRV complexity may reflect persistent neurobehavioral and cognitive impairments. Although both HR dispersion and SampEn show promise as predictors of post-concussion outcomes, their utility as reliable physiological biomarkers for clinical use remains to be fully established.

Overall, these findings advance our understanding of HRV’s relationship with concussion outcomes. Notably, this study provides the first evidence that HRV may predict neurobehavioral and cognitive performance beyond the subacute phase of injury. This challenges prior perspectives that treated HRV as a nonspecific indicator of dysfunction with limited predictive power. Instead, our results suggest that HRV could serve as a practical, non-invasive tool for clinicians to identify adolescents at risk for prolonged neurobehavioral and cognitive impairments, allowing early intervention and tailored management strategies to optimize recovery outcomes.

Although these findings highlight a specific association between HRV and concussion outcomes, several limitations must be acknowledged. First, despite adjusting for age in our regression analyses, individual variations in physiological maturity among this adolescent sample may not be fully captured. Additionally, the current results do not provide insights into differences among female participants across menstrual cycles or types of hormonal contraception; even though both sexes were included, factors such as menarche, cycle phase, and contraceptive use can affect HRV. Moreover, since this study was conducted in a clinical rather than laboratory setting, we cannot identify the central biochemical or psychophysiological mechanisms that underlie the observed relationships between HRV and functional outcomes. The absence of pre-injury baseline measurements also limits our understanding of how sport-related or sub-concussive impacts may influence neuronal integrity and modify these relationships over time. While BMI and physical activity were controlled, objective assessments of cardiorespiratory fitness were not included, which could also affect resting HR and HRV. Therefore, further research is necessary to clarify the predictive value of HRV across diverse populations and demographic contexts.

Conclusion

This study is the first to indicate that resting HRV and HRV during physical exertion may serve as predictors of neurobehavioral and cognitive outcomes in the post-acute stage of concussion. These results align with established models of cardio-autonomic regulation, which emphasize the link between HRV and cognitive processes such as learning, memory, and attention. Consequently, our findings provide both theoretical and empirical support for incorporating HRV into the clinical assessment and management of concussions. HRV measurement is practical in clinical settings because it is noninvasive, cost-effective, and can be obtained under various conditions, including rest, exercise, or cognitive tasks. It also requires less specialized training or space compared with other psychophysiological measures and can be recorded via simple ear clips or three-lead ECGs. Nevertheless, additional studies are warranted to explore HRV's relationship with concussion outcomes across a wider range of populations and demographic factors to better inform its clinical utility and limitations.

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