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Concussion History and Heart Rate Variability During Bouts of Acute Stress

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Context: After a sport-related concussion, many athletes experience persisting neurophysiological alterations. These alterations may be absent at rest but emerge during moments of physiological stress. Unnoticed and untreated neurophysiological dysfunction may negatively affect long-term neurologic health in adolescent athletes, as they are at a critical point in development.

Objective: To assess cardio-autonomic functioning in athletes with and those without a history of concussion by quantifying measures of heart rate variability (HRV) during times of physical and mental exertion.

Design: Case-control study.

Setting: Research laboratory.

Patients or Other Participants: Thirty-four male Hockey Quebec Midget-AAA hockey players were separated into those with (n = 16; age = 16.06 ± 0.73 years, body mass index = 23.29 ± 1.79) and those without (n = 18; age = 15.98 ± 0.62 years, body mass index = 23.60 ± 2.49) a history of concussion.

Intervention(s): All athletes underwent a series of HRV recording sessions (1) at rest, (2) while completing a cognitive task at rest, and (3) while completing a cognitive task after a bout of submaximal aerobic exercise.

Main Outcome Measure(s): Time-domain measures of HRV, including mean NN intervals, SD of NN intervals, and root mean square of successive NN interval differences, were quantified for each assessment.

Results: No differences in characteristics were evident between groups. No between-groups differences in HRV at rest were observed. However, during the cognitive task at rest and after aerobic exercise, athletes with a history of concussion demonstrated a higher SD of NN intervals (78.1 ± 4.3 versus 63.2 ± 4.1 milliseconds and 71.2 ± 4.3 versus 65.2 ± 3.8 milliseconds, respectively; $F_{1,31} = 4.31$, $P = .046$) and root mean square of successive NN interval differences (75.8 ± 6.0 versus 59.0 ± 5.6 milliseconds and 74.0 ± 5.5 versus 59.0 ± 5.2 milliseconds, respectively; $F_{1,31} = 4.88$, $P = .04$) than athletes without a history of concussion.

Conclusions: Concussive injuries may result in long-term cardio-autonomic dysfunction. These deficits may not be present at rest but may be triggered by physiological stress.

Key Words: sport-related concussion, student-athletes, cognition

Key Points

- Heart rate variability assessments provided noninvasive indicators of neurologic health and recovery after head injury.
- Acute bouts of stress may trigger cardio-autonomic dysfunction that is not present when assessed under resting conditions.
- Persisting alterations in cardio-autonomic and neurologic function suggested that concussions are not transient injuries and may have long-term consequences on neurologic health.

Concussive injuries are characterized by an initial onset of various physical, somatic, and emotional symptoms that typically subside within 7 to 10 days after injury.[1] However, accumulating evidence indicates that a substantial proportion of individuals experience neurophysiological and neuropsychological deficits beyond this standard recovery window.[2] Youth populations may be particularly vulnerable, as they are at critical stages in their neurologic development.[3] Consequently, youth athletes appear to be more likely to experience adverse outcomes after injury and more susceptible to persistent symptoms than their adult counterparts.[4] If overlooked, these deficits can negatively influence neurologic health and development as well as academic achievement.[5]

Although most investigators have focused on central nervous system functioning, peripheral neural communication may also be affected by brain injury.[6] The primary function of the autonomic nervous system (ANS) is to regulate homeostatic balance of physiological systems (ie, cardiovascular, respiratory, and endocrine) via its 2 integrated branches: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). Adequate regulation of the dynamic interplay between the SNS and PNS is an essential bodily function that allows these systems to readily adapt to meet changing situational demands.

The interactions between ANS branches are often assessed by evaluating cardio-autonomic function using digital electrocardiogram (ECG) recordings and offline computation of metrics of heart rate variability (HRV).[7] *Heart rate variability* refers to temporal fluctuations in the natural beat-to-beat rhythm of the heart that may be influenced by changes in the psychological and physiological states of an individual. Measured at rest, HRV indicates the capacity of the ANS to respond to changes, with increased values of HRV associated with a more efficient and balanced system.[8] Conversely, when either a physical or mental challenge is incurred, the increased psychological and physiological demand initiates a shift toward SNS dominance (vagal withdrawal), resulting in decreased HRV.[9,10] Thus, any deviation from these expected patterns may reflect poor self-regulation or resiliency to situational stressors or more general neurologic impairment that is caused by an acute disturbance or chronic morbidity.[11]

Previous researchers[12] have proposed that resting HRV is negatively altered during the acute phase of concussion recovery. These alterations in resting HRV appear to dissipate in a timeframe that mirrors the resolution of clinical symptoms.[13] In contrast, other investigators[14] showed that during periods of physiological stress, HRV remained altered beyond the acute phase of recovery, even in asymptomatic athletes. The authors of these reports suggested that alterations in HRV after concussion may not be detectable when assessed at rest. This point is crucial for student-athletes, whose typical day is characterized by periods of physical and mental exertion. Accordingly, the purpose of our study was to examine the relationship between concussion history and cardio-autonomic function by comparing HRV in adolescent athletes with and those without a history of concussion after bouts of mental, physical, and combined mental and physical stress. Based on the earlier findings, we hypothesized that asymptomatic individuals with a history of concussion would demonstrate similar HRV profiles at rest as matched control individuals. However, we predicted that latent alterations in HRV would emerge during cognitive task performance, with the greatest alteration after the combined bout of acute exercise and a cognitive task.

METHODS

Participants

As part of structured preseason medical screening and performance testing organized by Hockey Québec, Midget-AAA (ages = 15–18 years), participating adolescents from the surrounding area took part in our assessment battery. All participants and parents were instructed on the purpose and procedures before the study. To ensure that each participant met the inclusion criteria, we conducted a structured interview to gather relevant demographic data and medical history. All athletes reported that they were not taking any prescription or over-the-counter medications. Athletes with a diagnosed history of neurologic disease, psychiatric illness, non–sport-related brain injury, learning disability, attention deficit/hyperactivity disorder, or any conditions with a known influence on cardio-autonomic function were excluded. A waiver of assent and consent to analyze de-identified data was obtained from the local institutional review board.

After the screening process, individuals were assigned to either the control group (n = 18) or history-of-concussion group (n = 16). A past diagnosis of concussion was confirmed via medical record review and by a neuropsychologist (not an author). To prevent the possibility of an athlete with an undiagnosed concussion being included, we asked participants, "Following a blow to the head, neck, or body, have you ever experienced any of the following symptoms: headache, dizziness, confusion, blurred vision, balance problems, sensitivity to light and/or noise, fatigue, drowsiness, difficulty falling asleep, emotional, irritable, sad, or anxious?" Control participants who responded *yes* to any symptoms were excluded from the analyses. All participants in the history-of-concussion group were asymptomatic at the time of testing and currently engaged in regular team activities.

Procedures

To minimize any effects of diurnal variation on cardio-autonomic function, all participants completed testing at approximately the same time of day (late morning). They were instructed to adhere to their normal eating habits and abstain from consuming any caffeinated beverages on the day of testing. All testing took place in a quiet room with regulated ambient temperature and stable humidity. The experimental procedure is illustrated in Figure 1A.

After arriving at the laboratory, participants were outfitted with a Zephyr (Medtronic) BioHarness strap, complete with BioModule sensor, which was used to collect continuous electrocardiographic (ECG) and respiratory data throughout testing. All ECG data were collected at a sampling frequency of 250 Hz. Participants underwent a 5-minute, eyes-open resting ECG assessment (HRV_{REST}). They then performed a series of baseline cognitive tasks, which are more thoroughly described herein and consisted of both homogeneous and heterogeneous conditions of the switch task (HRV_{COG1}). After the switch task, participants completed a bout of continuous, steady-state aerobic exercise on a stationary cycle ergometer. Finally, after a 10-minute rest period, they underwent a second round of cognitive testing, using an identical version of the switch task completed earlier (HRV_{COG2}). Total testing time was approximately 90 minutes.

Switch Task. The color-shape switch task is commonly used to investigate both working memory and cognitive behavior.[15] Briefly, under 2 task conditions, participants were asked to respond according to specific rule sets mapped to either the color (COLOR-response) or shape (SHAPE-response; Figure 1B). They were then asked to complete the MIXED rule-response condition and apply either the color or shape rule, depending on the outline (solid and dashed) or the shape (Figure 1B).

Before each single-rule–set condition, participants completed 15 practice trials to familiarize themselves with the task. They then performed 1 block (30 trials) of each condition (COLOR-response and SHAPE-response). After the single-rule–set blocks, they completed 3 blocks of the MIXED rule-response condition, consisting of 60 trials each. Before the first block, participants performed a set of 30 practice trials. In the MIXED rule-response condition, the 2 rule sets were altered in an equiprobable and random manner.

The switch task was presented using the Psykinematix (version 1.5.1; KyberVision Japan LLC) software, and

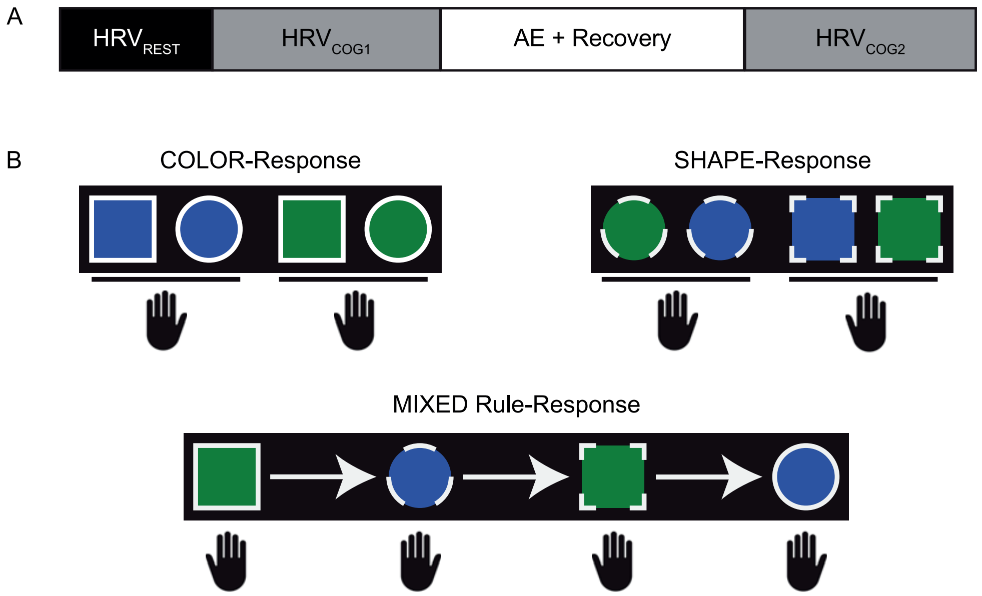

Figure 1. **Experimental protocol for heart rate variability recording sessions at rest, while completing a cognitive task at rest, and while completing a cognitive task after a bout of submaximal aerobic exercise (AE). A, Task stimuli and response mappings for the switch task. B, During the COLOR-response condition, participants were instructed to respond with their left hand if the presented stimulus was blue and with their right hand if the stimulus was green. During the SHAPE-response condition, participants were instructed to respond with their left hand if the presented stimulus was a circle and with their right hand if the stimulus was a square. For the MIXED rule-response condition, participants were instructed to respond according to the COLOR-response rule set (ie, green-right) if the stimulus had a solid white border and the SHAPE-response rule set (ie, square-right) if the stimulus had a dashed white border. Abbreviations: HRV, heart rate variability; HRV_{COG1}, HRV while completing a cognitive task at rest; HRV_{COG2}, HRV while completing a cognitive task after a bout of submaximal AE; HRV_{REST}, HRV at rest.**

responses were recorded using a serial-port response pad (model RB-540; Cedrus Corp). Task stimuli were displayed centrally on a black background and consisted of circles or squares (7 cm × 7 cm, 4° visual angle), in either blue or green, with a white outline. All stimuli were presented until participants responded, with a maximum response duration of 2000 milliseconds and a 50-millisecond intertrial interval. Before each task, they received standardized oral instructions, and written instructions were provided on the monitor in front of them. Participants were asked to respond as quickly and accurately as possible.

Aerobic Exercise. The aerobic exercise protocol was carried out using a cycle ergometer (Lode). To begin, all participants completed a 5-minute incremental warmup. The warmup period was followed by a 20-minute steady-state exercise period at approximately 60% to 70% of the athlete's age-predicted (220 − age) maximum heart rate. Participants were instructed to maintain a cadence of approximately 60 rpm while the load (in watts) was adjusted to maintain the calculated target heart rate. After the 20-minute exercise period, participants were guided into a 2-minute active cool-down (unloaded cycling) and 10-minute seated, resting recovery.

Outcome Measures

Raw ECG waveforms were processed using Kubios HRV (version 2.0; Biosignal Analysis and Imaging Group). The RR intervals were quantified as the time interval between successive R peaks in the QRS complex gathered from the raw ECG recording. We then normalized the data by manually inspecting the RR intervals to identify ectopic beats and any artifacts caused by movements, creating normalized RR intervals (NN intervals). Next, a 10% Hanning window was applied to the remaining ECG data. Electrocardiograms collected during the HRV_{REST} were segmented into 2-minute epochs to match the duration of each switch-task block. Previous researchers[16] have validated time-domain measurements collected during ultrashort (<5 minutes) HRV recordings.

We calculated linear, time-domain indices of HRV for each 2-minute epoch of the HRV_{REST} and for each 2-minute block of the MIXED rule-response condition of the switch task for HRV_{COG1} and HRV_{COG2}. These time-domain parameters included the mean NN interval (NNmean), SD of NN intervals (SDNN), and root mean square of successive NN interval differences (RMSSD). Measures of HRV can be modulated by differences in respiration rate. To correct for potential differences in breathing during each assessment, we computed individual respiration rates.

Statistical Analysis

Independent-samples *t* tests were conducted to identify any differences in characteristics between the groups. To compare resting HRV and the effect of physiological stressors on cardio-autonomic function group (control, history of concussion) × time (HRV_{COG1}, HRV_{COG2}), we performed repeated-measures analyses of covariance for each outcome measure with HRV_{REST} performance entered as the covariate. The Greenhouse-Geisser correction was applied to any measure for which the assumption of sphericity was violated. If we observed a main effect or interaction, we applied the Bonferroni correction post hoc. All statistical analyses were completed using SPSS statistical software (version 25; IBM Corp). The α level was set a priori at $P \leq .05$.

Table 1. Patient and Injury Characteristics (Mean ± SD)

Characteristic	Group Control (n = 18)	 History of Concussion (n = 16)
Age, y	15.98 ± 0.62	16.06 ± 0.73
Height, m	1.78 ± 0.05	1.79 ± 0.06
Mass, kg	74.84 ± 7.62	74.62 ± 7.63
Body mass index	23.60 ± 2.49	23.29 ± 1.79
Time in sport, y	10.7 ± 1.94	10.6 ± 1.54
Previous concussion(s), No.	NA	1.2 ± 0.43
Age at last concussion, y	NA	13.97 ± 1.67
Time since last concussion, mo	NA	24.13 ± 17.7

Abbreviation: NA, not applicable.

RESULTS

Participants

The groups did not differ in age, body mass index, or number of years playing sport ($P > .05$), suggesting successful matching between groups (Table 1).

The HRV Parameters

Cardio-autonomic profiles of each group and condition are presented in Table 2. Univariate analysis did not show any interaction or main effect for respiration rates ($P > .05$). Therefore, the respiration rate was not included in further HRV analyses. We did not observe group differences at HRV_{REST} ($P > .05$). Our repeated-measures analyses of covariance revealed a main effect of group for SDNN ($F_{1,31} = 4.31$, $P = .046$, $\eta p^2 = 0.122$) and RMSSD ($F_{1,31} = 4.88$, $P = .04$, $\eta p^2 = 0.136$). Pairwise comparisons showed that, during both HRV_{COG1} and HRV_{COG2}, individuals with a history of concussion had greater SDNN and RMSSD than their matched control participants (Figure 2). No other interactions or main effects were found between groups.

DISCUSSION

We aimed to examine HRV indices of cardio-autonomic function in adolescent athletes with a history of concussion under periods of acute stress. The main findings of our study were as follows: at rest, athletes with a history of concussion did not demonstrate any differences in cardio-autonomic function relative to matched control individuals. During both HRV_{COG1} and HRV_{COG2}, athletes with a history of concussion exhibited elevated HRV (SDNN and RMSSD) compared with matched control participants. We are the first to demonstrate similar trends after a bout of mental exertion in the chronic stage of concussion recovery.

Previous researchers[9,10] suggested that bouts of both physical and mental exertion in healthy populations were characterized by reductions in HRV (reduced vagal activity) as the body adjusted to meet the increased demands. During exercise, as the intensity of exercise increases, the increased metabolic demand of the body results in a subsequent increase in heart rate and SNS input to the heart.[17] On the other hand, increased mental load is associated with increased activation of the prefrontal brain regions.[18] Our matched control individuals without a history of concussion displayed this pattern of reduced HRV during both HRV_{COG1} and HRV_{COG2}. However, athletes with a history of concussion showed uncharacteristic elevations in HRV.

Whereas athletes with a history of concussion demonstrated cardio-autonomic dysregulation during acute bouts of increased stress, we did not see any differences in HRV at rest. This finding adds to the findings of numerous researchers who suggested that stressors may exacerbate functional deficits not observed under resting conditions. Previous investigators showed that asymptomatic individuals with a history of concussion experienced abnormal HRV in response to exercise[19] and prolonged recovery of HRV metrics after exercise.[20] These results in addition to ours suggest that abnormal cardio-autonomic responses to stress may indicate persistent disruptions in the ANS, limiting its ability to appropriately regulate physiological systems after concussion. However, some authors noted that HRV and other measures of ANS function recovered within the first few weeks after injury,[21] even during periods of acute stress.[14] It is possible that these differences are mediated by factors such as recovery status, postinjury management, concussion history, time since injury, and emotional status.[20,22] We attempted to account for these factors, but more work is needed to further identify how these confounding variables affect HRV after concussion.

Although the exact mechanisms underlying cardio-autonomic dysfunction after concussion are unknown, current theories suggest that HRV provides a means of quantifying the efficiency of neural communication among the central nervous system and other physiological systems (ie, cardiovascular). These theories propose that modulations of vagal tone (PNS activity) serve as a biological response to prepare the body to meet current or anticipated

Table 2. Heart Rate Variability Measures (Mean ± SE)

Measure	At Rest Control Group	 History of Concussion Group	During Cognitive Task at Rest[a] Control Group	 History of Concussion Group	After Submaximal Aerobic Exercise[a] Control Group	 History of Concussion Group
Mean heart rate, beats/min	66.7 ± 1.9	68.2 ± 1.6	69.4 ± 1.3	67.2 ± 1.4	69.0 ± 1.3	69.1 ± 1.3
Respiration rate, breaths/min	16.6 ± 0.2	16.9 ± 0.2	18.7 ± 0.1	18.2 ± 0.2	18.82 ± 0.1	18.3 ± 0.1
Mean NN interval, ms	919.6 ± 26.3	896.6 ± 23.3	878.9 ± 16.6	914.1 ± 17.6	885.6 ± 14.5	882.8 ± 15.3
SD of NN intervals, ms[b]	76.1 ± 7.1	74.0 ± 4.9	63.2 ± 4.1	78.1 ± 4.3	65.2 ± 3.8	71.2 ± 4.3
Root mean square of successive NN interval differences, ms[b]	63.7 ± 6.1	60.8 ± 5.6	59.0 ± 5.6	75.8 ± 6.0	59.0 ± 5.2	74.0 ± 5.5

[a] Model-adjusted values.

[b] Group main effect ($P < .05$).

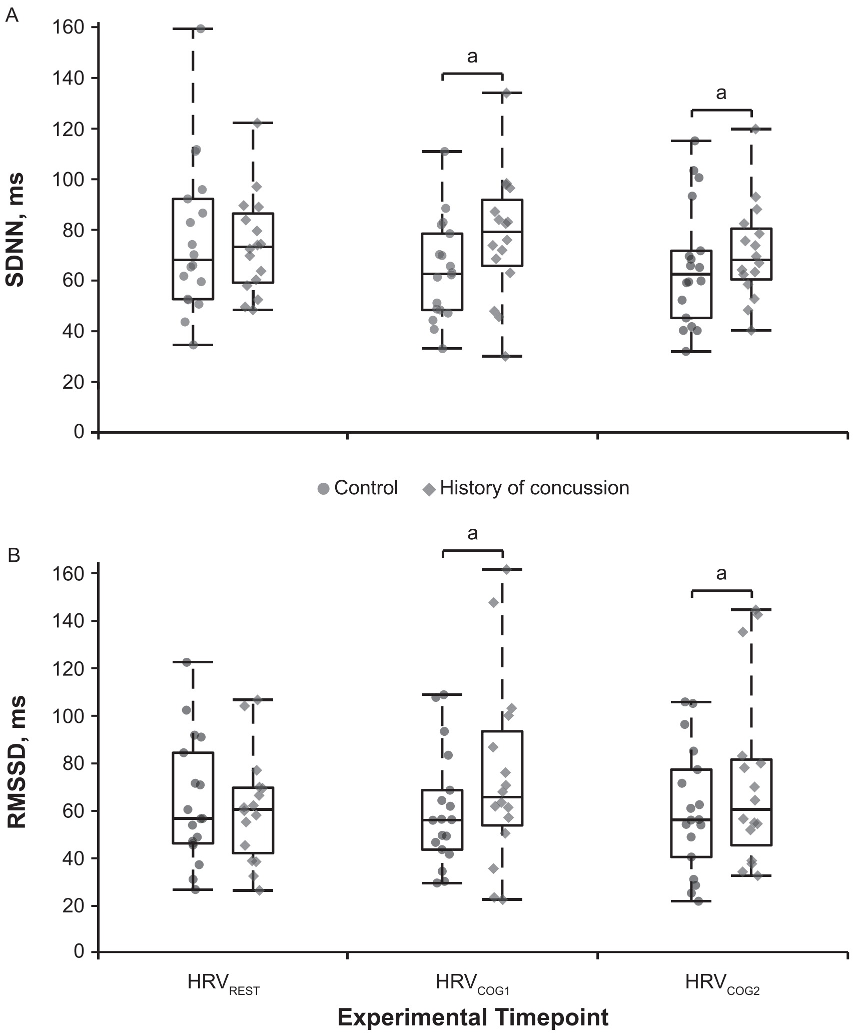

Figure 2. Group and individual, A, SD of NN intervals and, B, root mean square of successive NN interval differences comparisons between healthy control athletes and athletes with a history of concussion across the 3 experimental timepoints. Each boxplot depicts the median (horizontal line), with the edges of the box representing the upper (75th) and lower (25th) bounds of the interquartile range. Whiskers represent the most extreme data points. ᵃ Group effect ($P < .05$). Abbreviations: HRV, heart rate variability; HRV_{COG1}, HRV while completing a cognitive task at rest; HRV_{COG2}, HRV while completing a cognitive task after a bout of submaximal aerobic exercise; HRV_{REST}, HRV at rest; RMSSD, root mean square of successive NN interval differences; SDNN, SD of NN intervals.

demands and to efficiently carry out goal-directed behaviors.[23] Frontolimbic structures in the central autonomic network (ie, prefrontal cortex, hypothalamus, amygdala, and hippocampus) are heavily involved in the organization and execution of goal-directed behaviors.[24] Additionally, these brain regions exert top-down control over the ANS and the intrinsic nervous system of the heart.[25] Furthermore, these brain regions and the interconnections among them are some of the areas and processes most frequently affected by concussions.[26] Accordingly, the different HRV responses observed in athletes with a history of concussion during acute bouts of either mental or physical stressors could indicate improper or inefficient communication among physiological systems in response to the current situational demands.

Regardless of the underlying mechanism, the fact remains that concussive injuries are characterized by widespread impairment that may affect several neurologic systems, including the cardio-autonomic pathways. Also, these deficits may persist for months or years after the initial injury. If unattended, these deficits may impede typical neurologic development and increase the individual's susceptibility to long-term cardiovascular and mental health concerns.[27]

Our study had limitations. First, given the sample of only male adolescent athletes and the known sex differences in HRV, our findings may not be generalizable to a female population[28] or older, more physiologically mature athletes. Second, the Midget-AAA hockey system in Canada involves elite-level athletes for that age group, and HRV has been associated with age[29] and fitness.[30] Whereas no age differences were present in our sample, we did not assess individual fitness levels. Testing took place before the start of the season, and the athletes were of similar age, body mass index, and level of competition. Therefore, it is reasonable to assume that all participants had comparable fitness levels. Third, HRV is known to be sensitive to emotional status.[11] We excluded anyone presenting with a psychological or psychiatric condition, but we did not quantify acute emotional status and sleep patterns. Future authors should consider these potentially confounding factors, as they have been shown to affect HRV and other measures of cardio-autonomic function.

CONCLUSIONS

Our study is one of the first to investigate the long-term effect of concussive injuries on the cardio-autonomic responses to the bouts of physiological stress common in the everyday lives of student-athletes. Our findings indicated that concussion-related deficits in cardio-autonomic function may persist beyond the acute phase of injury. We also demonstrated that HRV may be used as a nonspecific indicator of neural health and recovery. Heart rate variability measurements are relatively fast and simple and dynamic enough to be collected under various testing conditions (exercise, cognitive tasks). Furthermore, our results highlighted the importance of assessing athletes under periods of physiological stress commonly experienced in everyday life, as deficits may not emerge under resting conditions. Measurements of HRV may help in the diagnosis of concussive injuries and the management of symptoms and provide objective biomarkers to inform return-to-play and return-to-learn policies.

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