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Post-exertion neurocognitive test failure among student-athletes following concussion

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Abstract

Objective: The purpose of the present study was to examine post-exertion (PE) neurocognitive performance among student-athletes following concussion who were asymptomatic and returned to baseline normal neurocognitive test levels at rest. This study examined the neurocognitive performance of a sub-set of student-athletes who 'failed' to perform at baseline levels of neurocognitive function, i.e. exhibited downward reliable change index (RCI) alterations following a moderate exertional protocol during recovery from concussion.

Method: A retrospective records review was carried out of Immediate Post-concussion Assessment and Cognitive Testing (ImPACT) and neuropsychological consultation data among athletes with sports-related concussion from a network of 22 schools and one junior hockey programme.

Results: Fifty-four student-athletes met inclusion criteria and participated in the study. A total of 27.7% of concussed student-athletes who were symptom-free and returned to baseline on ImPACT at rest (i.e. no longer demonstrated performance deficits on neurocognitive tests) exhibited cognitive decline following moderate physical exertion. The PE cognitive changes were not simply general performance effects, but significant changes in memory ability in the presence of intact processing speed functions. The PE-Pass and PE-Fail groups did not, however, differ on post-concussive symptoms or concussion history.

Conclusions: Clinicians' return-to-play evaluation protocols should include post-exertional computerized neurocognitive testing.

Keywords: *Sports concussion, ImPACT, neuropsychological testing, post-concussive symptoms*

Introduction

In the clinical management of sports-related concussion, it has long been the standard of care that athletes should not return to contact sports action and risk further injury until they are symptom-free [1]. Once an athlete is asymptomatic at rest, a graduated return to sports activity is recommended, beginning with light non-contact exercise and progressing to full contact sports action [2–4]. If post-concussive symptoms re-emerge during the course of this return to play regimen, the athlete's recovery is considered incomplete and additional recovery time under conditions of controlled activity is recommended. An athlete should not return to play until he or she has demonstrated the ability to remain symptom-free with full physical exertion.

In recent years, neurocognitive testing has become a cornerstone of the concussion recovery evaluation process [3–5]. Moreover, researchers have reported that a number of athletes who claimed to be symptom-free continued to demonstrate subtle changes in cognitive efficiency [6, 7]. It has,

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therefore, been recommended that athletes should not return to play until they are both asymptomatic and their neurocognitive test results have returned to pre-injury baseline levels. For cases in which a pre-injury baseline test is unavailable, athletes should not return to play at least until their scores have reached levels reasonably consistent with their educational and clinical histories.

If it is expected that recovering athletes should return to normal levels of neurocognitive efficiency at rest and remain symptom-free with exercise, then it also stands to reason that neurocognitive test performance should remain stable following moderate exertion as the athlete resumes physical activity, particularly since the literature in the area of exercise and cognitive function has shown that moderate levels of exertion tend to enhance subsequent cognitive performance [8]. Post-exertion (PE) testing protocols for athletic trainers and team physicians have generally consisted of supervised workouts with general monitoring for recurrence of post-concussive symptoms using self-report data along with brief clinical sideline testing. However, such protocols have not typically included computerized neurocognitive reassessment. Given the unreliable nature of self-reported symptoms in athletes, a group typically motivated to return to play and minimize symptoms [9], the sensitivity of computerized neurocognitive testing to incomplete recovery and the importance of identifying any indicators that an athlete may not remain stable in his/her baseline functioning prior to return to contact sports action; post-exertion neurocognitive testing appears to be a logical tool to consider. Cognitive instability after moderate physical exertion may potentially indicate an incomplete recovery from concussion and warrant additional recovery time before returning to play.

Surprisingly, few studies have explored the relationship between physical exertion and neurocognitive test performance in athletes recovering from concussion. Covassin et al. [10] investigated the effect of 'maximal' exertion on neurocognitive task performance using the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) battery. ImPACT is a computer-administered neurocognitive test battery and symptom report that includes measures of verbal and visual memory (immediate and delayed), visual motor speed, reaction time and impulse control, as well as self-reported symptoms (see Lovell [11] for a more detailed description of ImPACT). Following baseline testing, the researchers administered ImPACT a second time to exertion group subjects immediately following completion of a VO2 maximal exercise testing protocol, and to control subjects following a 15 minute rest period. Covassin et al. [10] reported diminished performance for the exertion group, but not the control group, on the initial word memory sub-test, which is one of the three sub-test components of the verbal memory composite. No other cognitive domains or tests were affected throughout the remainder of the test battery. They concluded that the performance deficit was due to fatigue immediately following the maximal exercise protocol. It should be noted, however, that the Covassin et al. [10] study involved maximal exertion, that the observed decline in verbal memory was relatively small and that no other significant effects were reported. Moreover, the study was limited to healthy recreational athletes, with no examination of concussed individuals. Although this study highlighted the importance of avoiding administration of baseline neurocognitive testing immediately following maximal physical exertion, the researchers did not examine how post-exertion neurocognitive performance would be affected in athletes recovering from concussion.

Majerske et al. [12] also examined the relation between level of post-concussion self-reported physical activity and neurocognitive test performance on ImPACT among athletes recovering from concussive injury (up to 33 days post-injury). They reported that individuals with the poorest cognitive performance were those who self-reported the highest and lowest levels of recent physical activity. The researchers speculated that the low level group likely limited their physical activity levels because of their ongoing symptoms and neurocognitive deficits, whereas the high level group may have exacerbated their symptoms and neurocognitive deficits by engaging in more extensive physical and cognitive (i.e. school) activity. This study highlighted the need to examine the relationship of physical exertion to neurocognitive performance following concussion. Although Majerske et al. [12] provided a logical extension to the Covassin et al. [10] study by including individuals with concussion, it was limited by its use of self-reported physical activity levels and lack of post-exertion neurocognitive testing.

Research objectives

The purpose of the present study was to examine post-exertion (PE) neurocognitive performance among student-athletes recovering from a concussion who had reached the point of being both asymptomatic and demonstrating normal neurocognitive test scores at rest (i.e. no longer exhibited downward RCI alterations). More specifically, this study examined the neurocognitive performance of a sub-set of student-athletes who did not maintain or 'failed' to perform at baseline levels of neurocognitive function following a moderate exertional protocol during recovery from concussion. The following research questions were addressed:

- What percentage of student-athletes meeting study inclusion criteria who undergo PE neurocognitive testing following moderate exertion fail to maintain baseline levels of performance?
- Do student-athletes who fail such PE neurocognitive testing present with a distinctive concussion history (e.g. prior concussion with loss of consciousness or post-traumatic amnesia)? Is a history of concussion (i.e. prior to the current injury) predictive of PE test failure?
- Are specific neurocognitive deficits related to PE test failure (e.g. diminished memory or processing speed)? That is, do student-athletes who fail PE testing demonstrate a distinctive neurocognitive profile?
- Is PE neurocognitive test failure associated with post-concussive symptom total and symptom factor scores (see [13] for a review of post-concussive symptom clusters, i.e. somatic, cognitive, sleep and affective symptoms)?
- Do male and female student-athletes who fail PE testing demonstrate similar neurocognitive performance profiles?

Method

Research design

A retrospective records review was carried out of sports-related concussion cases from a network of 22 schools and one junior hockey programme using ImPACT in conjunction with neuropsychological consultation. Concussive injuries and associated ImPACT test sessions took place during a 2-year period (from September 2008 through September 2010). The 2nd author reviewed ImPACT reports. The lead author and the 2nd author determined whether student-athletes fulfilled study inclusion criteria. The independent variable was group (PE-Pass and PE-Fail) and the dependent variables were recovery time (days), neurocognitive test composite scores (verbal memory, visual memory, reaction time, visual motor processing speed, impulse control), individual ImPACT sub-tests and total concussion symptom and symptom factor scores. All subjects completed the ImPACT battery at least four times: (a) baseline, (b) post-injury (P1), (c) when they were symptom-free and back to baseline neurocognitive levels (RTB), as evidenced by a lack of any RCI alterations, and (d) following an exertional protocol (PE). Some subjects were tested on more than four occasions, given that they required additional time and multiple resting ImPACT tests to return to baseline. Tests conducted between a subject's initial post-injury assessment (P1) and RTB test were, therefore, not included in this analysis.

Letters of permission were obtained from the 15 schools and one junior hockey programme from which cases were drawn and the University of Pittsburgh Institutional Review Board approved the present study.

Participants

Fifty-four student-athletes from 15 schools and one junior hockey programme met study inclusion criteria. Inclusion criteria were: (a) being a high school- or junior high school-aged athlete, (b) incurring a sport-related concussion which resulted in acute symptoms and one or more clinically significant decline in neurocognitive performance (i.e. RCI) at the initial post-injury test session and (c) having a valid neurocognitive baseline test within the past 2 years. Athletes were excluded from the study if they reported a history of brain surgery, learning disorder, ADHD, special education, previous treatment for depressive or anxiety symptoms, seizure disorders, speech pathology or substance abuse.

Definitions and measures

Concussion. A concussion was defined as 'a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces' (p. 756) [4] and met the following criteria: (1) presence of acute post-concussive signs and symptoms as determined by a sports-medicine professional, (2) decrease from baseline levels in at least one post-concussion neurocognitive score determined by RCIs and (3) increase from baseline levels in post-concussion symptoms determined by RCIs. Within the context of these data being collected among cases seen for clinical evaluation within a network of schools/programmes using ImPACT, concussion diagnosis was based upon the presence of head trauma and the athletic trainer's observation of post-concussive symptoms. Moreover, the lead author, a clinical neuropsychologist specializing in the assessment of concussive injury, confirmed the diagnosis. Student-athletes were under the care of licensed athletic trainers and/or other sports-medicine professionals who provided concussion education and counselling.

Immediate post-concussion assessment and cognitive testing (ImPACT). The ImPACT computerized neurocognitive test battery was used to assess neurocognitive function and post-concussion symptoms in the current study. The ImPACT test comprises three general sections that include demographic information, the 22-item Post-concussion Symptom Scale (PCSS) and six neurocognitive test modules. The ImPACT test modules are aggregated into five composite scores: verbal memory, visual memory, visual motor speed, reaction time and impulse control. The PCSS items include typical post-concussion symptoms such as headache, dizziness, fogginess, memory problems, sleep problems and emotional symptoms. Test–re-test reliability, validity and specificity/sensitivity data for ImPACT are reported elsewhere [14–16].

Concussion history. The ImPACT demographics and health history questionnaire includes a subsection documenting the student-athlete's concussion history. In this section the athlete self-reports whether he or she has suffered a concussive injury (prior to the present injury) and has previously experienced specific concussive symptoms. That is, the student-athlete was instructed to indicate whether he/she has experienced prior concussive injuries (i.e. number of concussions excluding the current injury) and whether those prior injuries were associated with loss of consciousness, amnesia or confusion.

Post-exertion pass and fail group classification. Participants were grouped into PE-Pass and PE-Fail based on post-exertion neurocognitive performance. Previously published RCIs [17] were used to determine group assignment. Student-athletes who did not demonstrate any RCIs on their post-exertion ImPACT composite scores were classified as PE-Pass, whereas participants who exhibited one or more RCIs on any post-exertion ImPACT composite score were classified as PE-Fail.

Procedures

All participants completed pre-season baseline ImPACT testing. The validity of baseline neurocognitive test performance was determined according to recommended parameters outlined in the ImPACT manual [11]. None of the baseline tests were flagged as potentially invalid according to validity indicators built into the testing software. Valid baselines were defined as having scores in the areas of verbal and visual memory, visual motor speed and reaction time (composite scores) at or above the 15th percentile (low average range or higher), impulse control composite at or below a score of 20 and a total symptom score at or below 18. Note that, although the majority of student-athletes ($n = 49$) obtained relatively low total symptom scores at baseline (≤ 7), several individuals ($n = 5$) obtained scores ≥ 10. Since individuals in the latter group met other inclusion criteria, they were not excluded. Note that 29 individuals obtained a score of 0 on the PCSS at baseline. These cut-off levels were established in order to increase the likelihood that baseline scores represented normal performances for subjects and to lessen the chance of including student-athletes with undiagnosed pre-existing cognitive impairments.

Participants also completed an initial post-injury ImPACT test. Periodic post-injury neurocognitive testing and interpretation, and consultation were provided to all participants until they were symptom-free and their neurocognitive test scores returned to baseline levels (i.e. no longer exhibited downward RCI alterations). The athletic trainer (AT) who was managing the student's recovery, in consultation with the lead author, made the determination that the student-athlete was symptom-free. That is, the AT and the lead author judged the student to be clear of all post-concussive symptoms (based on the AT's observations and the lead author's review of the student's ImPACT symptom checklist). The student in his/her symptom checklist on ImPACT did not indicate continuing post-concussive symptoms. This does not mean that all students had PCSS scores of 0; rather, none of the symptoms endorsed by students (if symptom scores were >0) were judged to be lingering concussion symptoms. For example, a student could have reported some trouble sleeping or irritability, but if in the authors' determination it was not judged these were post-concussive for that student, it was concluded that the student was symptom-free. Student-athletes then participated in a physical exertion protocol at their respective school or sport club that included 15–25 minutes of moderate (i.e. ~60–80% HR) cardiovascular exercise (e.g. stationary cycling, treadmill running, elliptical) and/or non-contact sport-specific activities (e.g. dribbling, skating). Following a brief (~5–10 minute) rest period, all participants completed a post-exertion ImPACT test. All post-exertion protocols and testing were supervised by an AT with the following exception: An emergency medical technician supervised the PE protocol for the junior hockey programme.

Data analysis

Since ImPACT composite score distributions were severely skewed, non-parametric tests including the Mann-Whitney U-test and Spearman's rho were employed. To determine whether a specific cognitive deficit profile is associated with PE test failure, the Mann-Whitney U-test was used to compare the ImPACT performance profile of student-athletes who passed PE testing to those who failed PE neurocognitive testing. Performance on each of the

Table I. Demographic and concussion history information (mean ± SD).

Group	PE-Fail	PE-Pass	Total
Number	15	39	54
Age (years)	15.47 ± 1.84	15.46 ± 1.35	15.46 ± 1.48
Educational Level (years)	9.13 ± 1.72	9.33 ± 1.40	9.28 ± 1.48
Number of Concussions (lifetime excluding current)	0.06 ± 0.25	0.43 ± 0.82	0.33 ± 0.72
Concussion to P1 (days)	3.60 ± 3.43	3.03 ± 1.99	3.19 ± 2.45
Concussion to RTB (days)	11.40 ± 6.60	14.07 ± 9.57	13.33 ± 8.87
Concussion to PE (days)	13.93 ± 6.68	20.74 ± 16.48	18.85 ± 14.70
Concussion History: Frequency (%)			
Concussion with Loss of Consciousness	0	7.6%	5.5%
Concussion with Confusion	0	20.5%	14.8%
Concussion with Anterograde Amnesia	0	10.2%	7.4%
Number of athletes reporting prior concussive injury (lifetime excluding current concussion)			
One Concussive Injury	1	4	5
Two Concussive Injuries	0	5	5
Three Concussive Injuries	0	1	1

P1, Post-Injury 1 (resting); RTB, return to baseline (i.e. final resting test session before PE test); PE, Post-Exertion Test (PE-Pass *vs.* PE-First Fail).

five ImPACT composites and individual ImPACT sub-tests, as well as PCSS totals for the PE-Fail and PE-Pass groups were compared. Percentile rank values for verbal and visual memory, visual motor speed and reaction time composite scores were used in the analyses. It was also ascertained whether post-exertion groups differed in the number of days between the concussive injury and the first post-injury test, RTB test and the initial PE test. Non-parametric tests were used to determine whether PE test failure was associated with a distinctive concussion history or post-concussive symptom severity. PE-Pass and -Fail participants were compared on each of four post-concussive symptom clusters: (1) somatic (e.g. headache, dizziness); (2) cognitive (e.g. memory problems, fogginess); (3) sleep dysregulation (e.g. more/less sleep); and (4) affective changes. Spearman's rho was used to determine whether specific symptom cluster scores at P1 were associated with ImPACT composite scores at PE. Finally, to determine whether female and male student-athletes demonstrated similar test profiles, the smaller sub-sample of PE-Pass and PE-Fail female student-athletes was analysed separately. Given the number of group comparisons, a significance level of $p < .01$ was used for all statistical tests.

Results

Demographic information and concussion history

Fifty-four student-athletes (43 male, 11 female) met study criteria and were included in analyses. Fifty student-athletes were right-handed, three were left-handed and one had mixed dominance. Based on post-exertion neurocognitive performance, 15 student-athletes (27.7%) were categorized into the PE-Fail group (i.e. had downward RCI changes) and 39 student-athletes (72.2%) were categorized into the PE-Pass group. Demographic and concussion history data are presented in Table I. It is important to note that 10 student-athletes (seven PE-Pass, three PE-Fail) who reported previous treatment for non-migraine or migraine headache were included in the study. Six student-athletes had repeated a grade (four PE-Pass, two PE-Fail). Several private schools participating in the present study recommend or require (on occasion) that students transferring in at the junior high or high school level repeat a grade in order to establish a firmer academic foundation as they enter a more demanding academic setting. As such, repeating a grade did not reflect a learning disability or developmental delay in the current sample and the six student-athletes who repeated a grade were included in the study. Also note that one included participant reported a history of meningitis.

Participants in the PE-Pass and PE-Fail groups did not differ in level of education, age or neurological history (including prior treatments for headache or migraine). Post-exertion groups did not differ in the number of days from concussion to PE test (concussion-to-PE interval) (PE-Pass = 20.7 days, PE-Fail = 13.9 days, U = 208.0, $p = 0.102$). Nor did PE groups differ in terms of the number of days between concussion and the first post-injury (P1) test (PE-Pass = 3.0 days, PE-Fail = 3.6, U = 284.5, $p = 0.875$) or the RTB test session (PE-Pass = 14.0 days, PE-Fail = 11.4, U = 232.5, $p = 0.245$).

Neurocognitive performance on ImPACT composites

Verbal memory. Significant group differences on the verbal memory composite were revealed at PE. Post-exertion fail subjects scored significantly lower on

Table II. ImPACT composite and PCSS scores: mean ± SD, Mann-Whitney U-test values.

	PE-Fail ($n = 15$)	PE-Pass ($n = 39$)	U	p
Verbal Memory Composite				
Baseline	68.9 ± 19.5	70.6 ± 24.4	268.5	0.643
Post-injury 1	40.7 ± 30.4	56.0 ± 30.8	206.0	0.095
RTB	66.2 ± 21.8	80.7 ± 16.3	165.0	0.014
Post-exertion	40.4 ± 25.4	80.1 ± 17.8	65.0	<0.001
Visual Memory Composite				
Baseline	47.8 ± 21.3	64.8 ± 26.6	176.0	0.024
Post-injury 1	32.3 ± 26.7	45.2 ± 27.4	214.5	0.132
RTB	60.7 ± 21.3	70.0 ± 23.8	233.0	0.250
Post-exertion	56.2 ± 27.9	82.4 ± 20.7	125.0	0.001
Visual Motor Speed Composite				
Baseline	52.7 ± 26.5	60.3 ± 24.2	246.5	0.374
Post-injury 1	52.4 ± 35.1	48.9 ± 30.1	276.5	0.757
RTB	75.2 ± 21.4	73.5 ± 21.7	277.0	0.765
Post-exertion	71.0 ± 22.9	79.3 ± 21.7	225.5	0.195
Reaction Time Composite				
Baseline	46.0 ± 17.6	60.0 ± 23.5	190.5	0.049
Post-injury 1	46.0 ± 32.4	51.9 ± 33.9	259.0	0.517
RTB	70.6 ± 26.1	75.8 ± 23.2	260.0	0.530
Post-exertion	76.1 ± 26.2	82.7 ± 18.9	242.0	0.329
Impulse Control Composite				
Baseline	7.2 ± 6.6	5.5 ± 4.8	264.5	0.586
Post-injury 1	8.2 ± 8.6	7.0 ± 5.7	283.5	0.861
RTB	5.7 ± 3.9	4.8 ± 3.7	254.5	0.460
Post-exertion	6.6 ± 4.0	5.0 ± 4.0	202.5	0.080
Post-Concussion Symptom Scale (PCSS)				
Baseline	1.8 ± 4.1	2.5 ± 4.1	248.5	0.355
Post-injury 1	13.3 ± 13.7	14.4 ± 11.5	267.0	0.622
RTB	1.6 ± 3.0	1.3 ± 3.7	276.5	0.720
Post-exertion	0.8 ± 1.6	0.4 ± 1.3	263.0	0.418

RTB, return to baseline (i.e. final resting test session before PE test).

the verbal memory composite in comparison to individuals in the PE pass group (see Table II). The PE groups did not differ significantly in baseline verbal memory composite scores. Group differences at P1 did not reach significance. PE groups did not differ on the interval between the concussive injury and the first P1, RTB and PE test sessions ($p > 0.10$). Nevertheless, to control for the effects of significant and non-significant group differences at assessment points prior to PE testing as well as the interval (i.e. number of days) between the concussive injury and the PE test session, analysis of covariance (ANCOVA) was carried out with the aforementioned scores used as covariates. Group differences on PE verbal memory composite scores remained significant with $F(1,48) = 28.2$, $p < 0.000$.

Visual memory. Post-exertion group differences on the visual memory composite at PE were significant (see Table II); however, groups did not differ significantly at BSL, P1 and RTB. After statistically controlling for BSL, P1 and RTB visual memory composite scores and concussion-to-PE interval (most recent concussion to PE test—number of days), group differences on visual memory composite at PE remained significant ($F(1,48) = 7.80$, $p = 0.007$).

Processing speed

Group differences on measures of processing speed (visual motor speed and reaction time composite scores) at all assessment points were not significant. As shown in Table II, no significant between-group differences were supported at any stage (i.e. at BSL, P1, RTB and PE) on the visual motor speed and reaction time composites.

Impulse control

Post-exertion pass and fail groups did not differ on the impulse control composite at BSL, P1, RTB and PE (see Table II). Group differences at PE, however, approached significance with PE-Fail participants scoring higher than PE-Pass participants. Note that a higher impulse control composite score indicates poorer task performance. After controlling for BSL, P1 and RTB impulse control composite scores (PE-Fail subjects obtained higher scores at each assessment point) and concussion-to-PE interval,

Table III. ImPACT symptom cluster scores at P1 assessment: mean ± SD, Mann-Whitney U-test values.

	PE-Fail ($n = 15$)	PE-Pass ($n = 39$)	U	p
Somatic	7.20 ± 6.67	7.51 ± 6.02	279.0	0.794
Cognitive	3.13 ± 3.48	3.46 ± 3.70	285.0	0.883
Sleep dysregulation	2.13 ± 2.94	2.48 ± 2.56	247.0	0.364
Affective	0.86 ± 1.92	1.00 ± 2.84	276.5	0.671

Table IV. Association (Spearman's rho) between symptom cluster totals at P1 and composite scores at PE.

	Somatic	Cognitive	Sleep	Affective
PE-Fail group ($n = 15$)				
PE Verbal memory	−0.35	−0.07	−0.01	−0.19
PE Visual memory	−0.28	−0.28	−0.15	−0.07
PE Visual motor speed	−0.48	−0.38	−0.31	−0.45
PE Reaction time	0.03	0.16	−0.16	0.26
PE Impulse control	−0.03	0.00	−0.29	−0.14
PE-Pass group ($n = 39$)				
PE Verbal memory	−0.36	−0.23	−0.17	−0.06
PE Visual memory	−0.09	0.01	0.01	0.18
PE Visual motor speed	−0.15	−0.07	0.01	−0.19
PE Reaction time	−0.25	−0.20	−0.29	−0.18
PE Impulse control	−0.01	−0.09	−0.24	−0.38

group differences at PE did not approach significance ($F[1,48] = 0.71$, $p = 0.403$).

Post-concussive symptoms

PE-Fail subjects did not score significantly higher on the PCSS at PE. Group differences at each evaluation point were not significant (see Table II). PE-Pass and -Fail participants were also compared in terms of post-concussive symptom clusters at P1 presentation with no significant group differences observed (see Table III).

Analysis of the relation between ImPACT composite scores at PE and symptom cluster scores at P1 was conducted. The results did not support any significant relationships within the PE-Fail group (see Table IV). However, within the PE-Fail group, there were non-significant negative correlations between somatic symptom cluster scores at P1 and verbal memory, visual memory and visual motor speed at PE. Non-significant inverse associations between cognitive symptom cluster scores at P1 and visual memory and visual motor speed scores at PE were also observed. Visual motor speed at PE correlated negatively with sleep and affective symptom cluster scores at P1 (non-significant associations). A non-significant association between sleep symptom cluster scores at P1 and impulse control at PE was also observed; however, the relation was not in the expected direction. Within the PE-Pass group, P1 post-concussive somatic symptom cluster scores were inversely associated (non-significant relation) with performance on tests of verbal memory at PE (see Table IV). Affective and sleep symptom cluster scores at P1 correlated negatively with PE impulse control composite scores; however, the associations were not in the expected direction. Analysis also revealed a non-significant inverse association between sleep dysregulation at P1 and reaction time composite score at PE. Given the small sample size and the number of correlational analyses carried out, these results should be interpreted cautiously.

Individual ImPACT sub-tests at PE

Group comparisons for individual ImPACT sub-tests are presented in Table V. PE -Fail and -Pass groups differed significantly on tests of verbal and visual memory function. Among sub-tests of the verbal memory composite at PE, group differences were seen for word memory learning percentage correct (i.e. immediate recognition) and delayed memory percentage correct (i.e. delayed recognition); on the delayed condition the PE-Fail group had particular difficulty with correct recognition of target words. A significant difference was also seen for paired associate learning on the symbol match sub-test. Group differences on recall of consonant trigrams after a filled delay on the three letters sub-test (the third component of the verbal memory composite) did not achieve significance.

Among sub-tests of the visual memory composite at PE, differences were not seen in immediate recognition on the design memory sub-test, a visual-figural analogue of word memory that involves recognition of line designs, but the PE-Fail group had particular difficulty with recognition of distractor figures after a delay. Consequently, significant differences were seen between groups for the design memory delayed memory condition and for overall performance on this sub-test (i.e. total percentage correct). Group differences for recall of spatial location on the X's and O's sub-test, the other component of the visual memory composite, were not significant. None of the component sub-tests of the visual motor speed, reaction time and impulse control composites showed differences between groups at PE.

Female student-athletes: Neurocognitive performance on ImPACT composites

The smaller sub-sample of female student-athletes was also examined (PE-Pass = 7, PE-Fail = 4) (see Table VI). Note that female PE-Fail subjects were older than female PE-Pass subjects by an average of

Table V. Individual ImPACT sub-tests at PE: Mann-Whitney U-test values. PE-Fail ($n = 15$) *vs.* PE-Pass ($n = 39$).

	U	*p*
Word Memory		
Word memory: Hits-immediate	192.5	0.016
Word memory: Correct distractors-immediate	220.5	0.055
Word memory: Learning percentage correct	163.0	0.005
Word memory: Hits-delay	138.5	0.002
Word memory: Correct distractors-delay	235.5	0.233
Word memory: Delayed memory percentage correct	157.0	0.008
Word memory: Total percentage correct	149.5	0.005
Design Memory		
Design memory: Hits-immediate	234.5	0.236
Design memory: Correct distractors-immediate	189.5	0.035
Design memory: Learning percentage correct	173.5	0.019
Design memory: Hits-delay	227.5	0.188
Design memory: Correct distractors-delay	149.5	0.005
Design memory: Delayed memory percentage correct	159.5	0.009
Design memory: Total percentage correct	152.5	0.007
X's and O's		
X's and O's: Total correct-memory	185.0	0.034
X's and O's: Total correct-interference	259.5	0.523
X's and O's: Average correct RT-interference	251.5	0.427
X's and O's: Total incorrect-interference	205.0	0.089
X's and O's: Average incorrect RT-interference	263.5	0.574
Symbol Match		
Symbol match: Total correct-visible	213.0	0.028
Symbol match: Average correct RT-visible	280.0	0.809
Symbol match: Total correct-hidden	87.0	0.000
Symbol match: Average correct RT-hidden	289.5	0.954
Colour Match		
Colour match: Total correct	273.0	0.107
Colour match: Average correct RT	216.5	0.142
Colour match: Total commissions	274.0	0.512
Colour match: Average commissions RT	276.0	0.559
Three Letters		
Three letters: Total sequence correct	247.0	0.278
Three letters: Total letters correct	236.0	0.184
Three letters: Percentage of total letters correct	236.0	0.184
Three letters: Average time to first click	103.0	0.000
Three letters: Average counted	219.0	0.156
Three letters: Average counted correctly	226.0	0.199

1.5 years. The same pattern of group differences in verbal memory at PE was observed, but this was not statistically significant, possibly due to limited sample size. As with male subjects, no significant between-group differences were seen on measures of processing speed (visual motor speed, reaction time) or PCSS.

Discussion

The current study revealed that 27.7% of student-athletes with concussion who were symptom-free (as determined by self-report and clinical evaluation) and returned to baseline on ImPACT at rest (i.e. no longer exhibited downward RCI alterations) exhibited cognitive decline following a period of moderate exertion. Furthermore, the cognitive changes seen post-exertion were not simply general performance effects, but significant changes in memory ability in the presence of intact speed functions.

Athletic trainers and team physicians commonly monitor student-athletes for the recurrence of concussion symptoms following a period of exertion. They may not, however, routinely carry out post-exertion neurocognitive testing. In the present study, cognitive decline was not associated with symptom recurrence. This finding suggests that computerized neurocognitive testing during post-exertion evaluation may be uniquely sensitive to detect changes in clinical status that would identify recovering student-athletes who should not yet resume contact sports activity. It is therefore recommended that neurocognitive testing be included as a standard part of the post-exertion protocol, with such testing administered after moderate exertion, when evaluating student-athletes for readiness to return to contact sports activity following concussive injury.

PE-Pass and -Fail groups did not differ significantly on self-reported concussion history variables. It is worth noting, however, that group differences, albeit not significant, were not in the expected direction, with PE-Pass subjects reporting a greater number of prior concussive injuries (including concussions with confusion, loss of consciousness or anterograde amnesia). Moreover, post-concussive symptom severity at P1 (and PE) was not associated with subsequent PE test failure. This suggests that the neurocognitive decline during post-exertion testing observed in this study may reflect incomplete recovery unrelated to many of the clinical variables traditionally associated with concussion. Covassin et al. [10] have, to the authors' knowledge, presented the only other study that directly examines the relation between physical exertion and neurocognitive test performance using a computerized neurocognitive test (i.e. ImPACT). Although the Covassin et al. study and the present one both found declines in verbal memory performance, several differences are worth noting. First, the Covassin et al. [10] protocol involved immediate testing after maximal exertion. They suggested that the decline in verbal memory performance might have been due to subjects' difficulty focusing on the first sub-test (word memory) administered after participating in the maximal exertion protocol. In the present study, exertion was only moderate and subjects were generally allowed a longer period of rest prior to taking ImPACT. Moreover, in the present study, PE

Table VI. ImPACT composite and total symptom scores for female student-athletes; Mean ± SD, Mann-Whitney U-test values.

	PE-Pass ($n = 7$)	PE-Fail ($n = 4$)	U	p
Age (years)	15.0 ± 0.81	16.5 ± 0.57	2.00	0.019
Educational level (years)	8.7 ± 0.95	10.2 ± 0.95	3.50	0.038
Verbal Memory Composite				
Baseline	64.7 ± 23.3	67.5 ± 24.5	12.5	0.776
Post-injury 1	61.7 ± 33.4	61.2 ± 24.4	13.0	0.850
RTB	67.1 ± 21.4	64.2 ± 19.7	12.0	0.705
Post-exertion	71.0 ± 21.4	41.5 ± 21.1	4.5	0.072
Visual Memory Composite				
Baseline	65.4 ± 22.8	50.0 ± 33.5	9.00	0.344
Post-injury 1	46.7 ± 22.5	46.2 ± 34.8	12.0	0.705
RTB	62.1 ± 6.41	61.0 ± 29.6	9.00	0.341
Post-exertion	78.7 ± 16.3	72.0 ± 27.4	13.0	0.849
Visual Motor Speed Composite				
Baseline	58.5 ± 27.8	59.7 ± 31.7	14.0	1.00
Post-injury 1	46.0 ± 26.7	68.0 ± 31.8	7.00	0.186
RTB	72.1 ± 29.4	80.0 ± 22.3	10.0	0.449
Post-exertion	72.8 ± 32.8	75.0 ± 25.9	13.0	0.850
Reaction Time Composite				
Baseline	42.0 ± 22.8	46.0 ± 27.3	14.0	1.00
Post-injury 1	41.2 ± 30.4	20.0 ± 11.1	7.00	0.186
RTB	59.0 ± 29.5	76.5 ± 22.5	8.00	0.256
Post-exertion	75.5 ± 26.5	81.0 ± 17.6	12.0	0.703
Impulse Control Composite				
Baseline	6.1 ± 6.3	3.0 ± 1.4	8.00	0.244
Post-injury 1	7.1 ± 4.6	4.7 ± 4.1	9.50	0.385
RTB	5.1 ± 3.1	4.7 ± 4.8	11.0	0.561
Post-exertion	6.7 ± 4.8	4.7 ± 3.5	9.00	0.340
Post-Concussion Symptom Scale (PCSS)				
Baseline	2.8 ± 3.7	4.7 ± 7.6	14.0	1.00
Post-injury 1	17.1 ± 12.5	16.2 ± 19.4	11.0	0.570
RTB	0.4 ± 1.1	5.0 ± 4.5	4.00	0.029
Post-exertion	0.2 ± 0.7	2.5 ± 2.6	5.00	0.049

groups differed on three separate tests of memory function, not simply the initial sub-test. Second, post-exertion differences were seen only in verbal memory in Covassin et al.'s [10] study, but were observed in both verbal and visual memory in the current study. Third, the decline in the verbal memory composite score reported by Covassin et al. [10] was quite modest. In the present study, the decline in both verbal and visual memory performance following exertion among student-athletes in the PE-Fail group was more pronounced despite the fact that the exertion protocol was much less intense. Many of the preceding differences might also be attributable to the different samples. The participants in the Covassin et al. [10] study were healthy 'recreational' athletes (i.e. had not suffered a concussion), whereas the current study included only concussed student-athletes. In addition, age differences could have influenced the findings in the two studies. The current sample included only participants at the high school and junior high levels, whereas the Covassin et al. [10] study included only college-aged participants.

Limitations

In the current study, one obvious limitation was the relatively small sample size ($n = 54$). The age of the sample was also limited to high school/junior high-aged student-athletes and, therefore, the findings are not generalizable to other age groups. With regard to gender, the female sub-sample was quite small (11 female student-athletes met study inclusion criteria and only four had failed a PE examination). A direct comparison of male and female student-athletes was not carried out given the limited number of female subjects available for comparison in the present study. A detailed exploration of the relation between gender and pre- and post-injury neurocognitive test performance, while of considerable interest, is beyond the scope of the present study. In addition, the current study did not include a non-concussed control group, which could minimize potential threats to internal validity. Future studies should include greater numbers of female student-athletes to better determine whether male and female PE-Fail subjects exhibit similar deficit profiles. There is no study to date that has examined the relationship between ImPACT and academic performance. However, academic achievement/success has been linked to improved neurocognitive functioning in working memory, reaction time and processing speed on traditional (paper-and-pencil) tests. While the question of real-world deficits associated with the decline in post-exertion ImPACT scores is of great interest, it was outside the scope of the present retrospective records review. It is also important to emphasize that, in the present study, student-athletes provided medical, developmental and concussion history data during an ImPACT session (i.e. completed a self-administered questionnaire). An independent review of medical records by investigators in future studies would provide more reliable data in this area.

There was likely some variability in the implementation of the physical exertion protocol among athletic trainers at the different schools from which subjects were drawn. As a result, there may have been some variability in the level of exertion and time between exertion and the post-exertion testing. Finally, the moderate level of exertion in the current study was not individualized to each athlete's fitness level or relative to their body weight.

Conclusion

Investigators have reported that a history of concussive injury is associated with an elevated risk for additional concussion [18, 19]. Moreover, individuals presenting with a history of prior concussions may recover more slowly from subsequent concussive injuries [18]. Guskiewicz et al. [18] reported that university athletes with a current concussion and history of three or more prior concussions were more likely to demonstrate a slower recovery compared to individuals with a current concussion and a history of one or fewer prior concussions. Given the potential consequences of premature return-to-play following concussion, e.g. elevated risk for further concussive injury or more severe traumatic brain injury including the second impact syndrome [20, 21], it is the authors' recommendation that neurocognitive testing should be an integral component of the athletic trainer's post-exertion evaluation protocol and that student-athletes should not be cleared for full contact activity until they are able to demonstrate stability, particularly in memory functioning, on such post-exertion neurocognitive concussion testing.

Declaration of Interest: Co-authors Collins and Lovell are co-developers and co-owners of ImPACT Applications, Inc., a company that distributes computerized neurocognitive testing for mild traumatic brain injury, and McGrath is a credentialed ImPACT consultant. Co-authors Dinn, Kontos and Elbin have no conflicts of interest to report.

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