Concussion in Sports: Postconcussive Activity Levels, Symptoms, and Neurocognitive Performance

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Context: Evidence suggests that athletes engaging in high-intensity activities after concussion have more difficulties with cognitive recovery.

Objective: To examine the role postinjury activity level plays in postconcussive symptoms and performance on neurocognitive tests in a population of student-athletes.

Design: Retrospective cohort study with repeated measures of neurocognitive performance and symptom reporting.

Setting: University-based sports concussion clinic.

Patients or Other Participants: Ninety-five student-athletes (80 males, 15 females: age = 15.88 ± 1.35 years) were retrospectively assigned to 1 of 5 groups based on a postinjury activity intensity scale.

Main Outcome Measure(s): We employed a regression analysis for repeated measures to evaluate the relationship of activity intensity to symptoms and neurocognitive outcome up to 33 days after concussion. Postconcussion symptom scores and neurocognitive (verbal memory, visual memory, visual motor speed, and reaction time) scores served as the primary outcome measures.

Results: Level of exertion was significantly related to all outcome variables ($P < .02$ for all comparisons). With multivariate analysis, activity intensity remained significant with respect to visual memory ($P = .003$) and reaction time ($P < .001$).

Conclusions: Activity level after concussion affected symptoms and neurocognitive recovery. Athletes engaging in high levels of activity after concussion demonstrated worse neurocognitive performance. For these tasks, those engaging in moderate levels of activity demonstrated the best performance.

Key Words: exertion, rehabilitation, mild traumatic brain injuries, student-athletes

Key Points

- Symptom status and neurocognitive performance were affected by postconcussive activity levels and age and sex of the athlete.
- Younger adolescents experienced more pronounced deficits in verbal and visual memory than older teenagers after concussion.
- Moderate levels of exertion were associated with better symptom and neurocognitive performance prognosis, suggesting controlled exertion may improve outcome after concussion. More study in this area is needed.

More than 1 000 000 mild traumatic brain injuries (TBIs) occur each year in the United States.[1] The average incidence of mild TBI from all causes in the United States is estimated at 503 per 100 000, with bicycles and sports accounting for 26.4% in the 5-year-old to 14-year-old age group.[1] Conservative estimates indicate that more than 300 000 sport-related concussions occur each year in the United States[2]: more than 60 000 cases of concussions occur at the high school level, with football accounting for the majority of these.[3] Approximately 4% of high school and collegiate football players sustain concussions during each season.[3–5] With more than 1 250 000 student-athletes participating at the high school level,[6] this is an especially important population to examine. A discussion of sex differences in clinical measures of concussion has recently been published,[7] showing that males tended to perform better on visual memory, while females performed better on verbal memory tasks; females also typically endorsed a higher number of symptoms during preseason baseline screening. Epidemiologic studies on collegiate football players have also demonstrated that concussed players' symptoms typically resolved within 7 days and neurocognitive function returned to baseline levels within 5 to 7 days.[8] Not much is known about the age-related differences in postconcussive symptoms, and whether symptoms of concussion can significantly interfere with the cognitive activities student-athletes require for schoolwork is an area yet to be explored.

Concussion is a mild TBI that results from a biomechanical insult to the brain that initiates a destructive neurometabolic cascade of events.[9] The cascade begins with the release of excitatory neurotransmitters, which result in cellular membrane disruption and ionic imbalances. Increasing amounts of adenosine triphosphate (ATP) are required in an attempt to correct these ionic imbalances, and an increase in glucose metabolism is observed within the first 24 hours after concussion. This increased glucose metabolism, combined with an initial decrease in cerebral blood flow, results in a mismatch between the energy required and that available to brain structures. The increase in glucose metabolism is followed by a period of reduced glucose uptake and metabolism, which may last for as long as 1 month.[9] Exercise also modulates glucose uptake in the brain and increases cortisol in a dose-dependent manner, both of which could worsen the neuronal energy mismatch after concussion.[10,11]

Most of these studies have been performed on animal models. Although the generalizability to humans is limited, these models display many pathophysiologic and behavioral characteristics noted in the human condition. As such, they may provide us with some insight for clinical phenomena observed in human brain injuries. Further worsening of traumatically induced metabolic mismatch may occur with exercise or other types of activity. Worsening of postconcussive memory deficits and processing speed after cognitively demanding tasks has also been demonstrated.[12] In addition, variations in postconcussive symptoms with respect to subjective levels of stress have been reported.[13]

Given the proposed metabolic abnormalities associated with concussion, which may last longer than once believed, the decision on when and how to return an athlete to play has received attention as a national public health issue.[14] Postconcussive activity has been clinically noted to worsen symptoms and cognition after concussion. Most of the existing guidelines have been specifically developed for return to play rather than return to the functional activities of school, work, or daily chores. Therefore, we aimed to examine the role of postinjury activity level in postconcussive symptoms and performance on neurocognitive tests in a population of student-athletes. Our hypothesis was that athletes who engaged in high levels of activity after a concussion would have higher symptom severity scores and slower recoveries than those who engaged in lower activity levels during recovery.

METHODS

We used a retrospective cohort design to assess the relationship of symptom status and neurocognitive function after sport-related concussion in student-athletes. A retrospective chart review resulted in the inclusion of 95 participants in our study (80 males: age = 15.81 ± 1.35 years; 15 females: age = 16.31 ± 1.32 years) during the 2002–2003 and 2003–2004 academic years. All participants were evaluated through a university hospital system's sports medicine concussion program. This ongoing clinical program includes computerized neurocognitive tests to assist team medical staff in making return-to-play decisions after sport-related concussion. In order to provide us with the information necessary to answer our research questions, patient records needed to meet 4 criteria: (1) inclusion of the patient's current academic status, (2) information pertaining to postinjury activity level in sufficient detail to accurately categorize the patient, (3) the injury must have been sustained during sport participation, and (4) data from at least 2 clinical follow-up visits were available. Patients with a history of learning disability, seizure disorder, or attention deficit disorder were not included in our study. As some prescribed medications can adversely affect cognitive function, patients who were taking any form of medication at the time of injury and subsequent clinical evaluations were also excluded. Use of data from patient records was approved by a university institutional review board.

Table 1. Symptoms Rated in the Post-Concussion Symptom Scale[19a]

Headache	Sensitivity to light
Nausea	Sensitivity to noise
Emesis	Increased sadness
Balance problems	Nervousness
Dizziness	Feeling more emotional
Fatigue	Numbness or tingling
Trouble falling asleep	Feeling slowed down
Sleeping more than usual	Sensation of being "in a fog"
Sleeping less than usual	Difficulty with concentration
Drowsiness	Difficulty with memory
Irritability	Visual problems

[a] Each item is graded from 0 (asymptomatic) to 6 (severely symptomatic).

Using these criteria, our sample was obtained after screening 297 patient records. Most of the screened charts were excluded because either the concussion was not the result of sport participation or information pertaining to the patient's current academic status was not provided. Nine athletes were excluded from the analysis of neurocognitive scores due to insufficient normative data to calculate standard scores. Thus, 86 athletes were analyzed with standardized scores on neurocognitive tests.

Instrumentation

Immediate Postconcussion and Cognitive Test (ImPACT). The Immediate Postconcussion and Cognitive Test (ImPACT; ImPACT Applications, Inc, Pittsburgh, PA) is a computer-administered neuropsychological test battery consisting of 7 individual test modules that measure aspects of cognitive functioning, including attention, memory, reaction time, and information processing speed. A thorough description of the ImPACT test battery and rationale for the development of the individual tests have been provided previously.[15] Five forms of ImPACT exist, with the word memory stimuli and design memory stimuli different and alternating for each form. Also, each time the test is given, the stimuli are infinitely randomized (including the stimuli for each alternate form), further circumventing the typical practice effects one sees with paper-and-pencil testing. No practice effects have been demonstrated for 3 of 4 composite scores, with the information processing speed composite score having a minimal 3-point practice effect from time 1 to time 2.[16] The ImPACT has been previously shown to be a reliable[16] and valid[17] tool in the assessment of concussion. This test has also demonstrated good sensitivity and specificity in prior studies of young athletes.[18]

Postconcussion Symptom Scale (PCSS). The ImPACT also yields a Postconcussion Symptom Scale (PCSS) that is now being utilized throughout both amateur and professional sports.[19] This Likert scale consists of 22 symptoms commonly associated with concussion, which are graded from 0 (asymptomatic) to 6 (severely symptomatic). All the student-athletes were required to provide a self-report of symptoms based on the PCSS, which included both cognitive (attention deficits and perceived memory dysfunction) and noncognitive (headache, nausea, dizziness, sleep disturbance, emotional changes, and photophobia) symptoms (Table 1). Reliability and normative data for the PCSS have been previously established.[20]

Main Outcome Measures

Neurocognitive Function and Symptom Status. The ImPACT yields outcome measures for verbal memory, visual memory, visual motor speed, reaction time, and impulse control composites. A faster reaction time and a lower symptom score indicate a better response. Conversely, higher scores for verbal and visual memory and visual motor processing speed indicate better performance. Due to the psychometric properties of the ImPACT, we evaluated each composite score separately as an individual outcome measure. In order to do so, each composite score was converted to a standard score (Z-score) based on age- and sex-matched normative data available on the ImPACT developers' Web site; normative symptom data were derived from 707 high school students.[20] These standard Z-scores have been converted to percentiles for the purpose of presentation because most clinical certified athletic trainers are accustomed to viewing ImPACT results in this way. Symptom status was recorded as a total symptom score and was assessed by PCSS testing performed at each follow-up visit. Patients referred to our medical center are from the community, referred by other physicians, or sent to us by certified athletic trainers working in the area. Baseline testing results are often not available, so we did not include baseline as a time interval in our analyses.

Independent Variables

Concussion Grade and Return to Play. Concussion grade was determined by a single rater using the Colorado Concussion Scale (CCS),[21] with information obtained from chart review regarding the presence or absence of confusion, amnesia, and loss of consciousness immediately postconcussion. Return to play was a categoric variable scored as the athlete was returned to play (*yes*) or not returned to play (*no*) in the same event in which the concussion was sustained.

Activity Intensity Scale. An activity intensity scale (AIS) was developed for the purpose of this study and future studies. Level of activity was determined by a single rater for each time interval in which an evaluation occurred. The AIS consists of 5 categories designed to be ordinal in nature based on information recorded in the chart: no school or exercise activity (*0*), school activity only (*1*), school activity and light activity at home (eg, slow jogging, mowing the lawn) (*2*), school activity and sports practice (*3*), and school activity and participation in a sports game (*4*). Our AIS was not designed as a guide for return-to-play progression but rather as a categorization of the student-athlete's activity level (whether it was cognitive or physical) after injury. Data were derived from self-reported activity noted in the patient records by the clinician performing the clinical evaluation. In our study, the same investigator rated both the CCS and the AIS.

Reliability Assessment of Independent Variables

The CCS has been used for several years to evaluate concussion severity. Although the criteria for calculating injury severity (presence of confusion, amnesia, or loss of consciousness) intuitively lend themselves to the possibility of extracting this information from patient charts, to our knowledge, no authors to date have reported the reliability or validity of chart extraction of the information required to calculate this measure. Additionally, the information required to determine the AIS at each postinjury assessment point (time 1 through time 5) was taken from chart review. Student-athletes were included in the study if adequate information was available in the chart to assign a score. The AIS is a new measure for which reliability measurements have not been reported. As such, we established interrater reliability estimates for each of these measures using a subset of charts from student-athletes evaluated clinically at a university medical center's sports concussion program. Twenty-three charts, which included 64 separate evaluations, were reviewed by 2 independent raters; athletes included in the review met the same inclusion criteria as above. After reviewing the criteria associated with establishing CCS and AIS grades, each rater independently obtained information relevant to assessing CCS and AIS from each chart. The 2 raters then assigned a CCS grade for each athlete and an AIS score for each athlete evaluation. The 2 physicians had the CCS and AIS criteria in front of them as they independently evaluated the content of the patient charts for the purpose of the interrater reliability assessment. The principal investigator (a physical medicine and rehabilitation physician) continued to assign CCS and AIS grades for the remainder of the cases in our study. Two clinical neuropsychologists with more than 30 years of combined experience dealing with athletes who have sustained sport-related concussion conducted the initial and any follow-up clinical evaluations of the patients in our study. A standard clinical interview form was used, including questions pertaining to the type, frequency, duration, and intensity of both physical and cognitive exertion. Two physical medicine and rehabilitation physicians experienced in traumatic brain injury evaluation and rehabilitation conducted the initial chart review.

Data Analysis

We considered a number of independent variables for their relationship to postconcussive symptoms and neurocognitive performance. These variables included age, sex, concussion grade, self-reported history of concussions, return-to-play status, type of sport in which the concussion occurred, level of postinjury activity as assessed by the AIS, and time of evaluation (in days). Age was categorized as 13 to 15 (mean = 14.39 ± 0.66) or 16 to 18 (mean = 16.81 ± 0.65) years. Because the outcome measures were obtained in a clinical setting and at different periods of time after the injury, outcome data were organized into discrete and clinically relevant time periods (time postconcussion) in which the athlete completed testing as follows: day of injury to day 3 (time 1), between days 4 and 7 (time 2), between days 8 and 14 (time 3), between days 15 and 21 (time 4), and between days 22 and 33 (time 5). For those athletes who had 2 testing sessions within a specific time interval, ImPACT composite and symptom scores were averaged, and the higher of the AIS scores was used. In any given postconcussion time interval, no more than 5 athletes received 2 evaluations.

Table 2. Participants' Demographic Information and Injury Data

Variable	Number (Percentage)
Sex	
Males	80 (84.2)
Females	15 (15.8)
Sport	
Football	56 (59.0)
Other	39 (41.0)
Concussion grade[a]	
Grade 1	37 (39.0)
Grade 2	44 (46.3)
Grade 3	14 (14.7)
Prior concussions?[b]	
No	54 (58.1)
Yes	39 (41.9)
Return to play?	
Did not return to play	58 (61.1)
Returned to play	37 (39.0)

[a] Concussion grade was determined using the Colorado Concussion Scale.

[b] Data were missing for 2 participants.

Summary statistics, including mean and standard error of the mean (SEM) for all continuous variables, were calculated. The effect size was calculated based on the standardized mean difference between groups (ie, Cohen d).[22] Frequency distributions were determined for categoric variables. Because postconcussion symptoms and neurocognitive performance were measured at multiple time intervals for each patient, repeated measurement analyses were performed using a mixed-effects model with a compound symmetry covariance structure to test the overall time effect within a group for each outcome measure. With this technique, multivariate regression models were created to evaluate AIS and other clinically important factors affecting postconcussion symptoms and neurocognitive performance across a recovery period lasting as long as 33 days. All independent variables were considered when constructing each multivariate regression model, and interactions among time periods, sex, return to play, age, concussion grade, history of concussions, and sport were explored for each multivariate model. The reference category for the AIS in multivariate regression analysis was the category consisting of school activity and light activity at home, such as slow jogging or mowing the lawn (AIS category 2), as preliminary analysis suggested that athletes in this category achieved the best outcomes. Means adjusted for individual time-dependent covariance are reported for AIS in the multivariate table. Means presented in the multivariate table were also adjusted for other independent variables included in the models.

In order to assess interrater reliability for chart extraction of the CCS and the AIS, κ coefficients and associated confidence intervals were calculated for each of these variables. All analyses were performed using SAS (version 8; SAS Institute Inc, Cary, NC). The level of significance was set a priori at .05.

RESULTS

Descriptive Analysis

Demographic information and injury data regarding concussion grade, history of concussions, and return to play status are provided in Table 2. Unadjusted standardized percentile means for the verbal memory, visual memory, visual motor processing speed, and reaction time composites on the 86 athletes for whom standardized scores could be calculated are shown in Table 3. These data illustrate that the mean percentiles for each neurocognitive test at time 1 were considerably impaired relative to normative scores but displayed improvement over time. Data at time 5 demonstrated small decrements in all percentiles. Additional analysis of the athlete population at each follow-up time point suggests that a larger proportion of time 5 athletes were female, with as many as 53.3% of the female athletes still being followed at time 5, whereas only 26.3% of the male athletes were still being followed at this time ($P = .037$). None of the other independent variables—concussion grade, number of prior concussions, return to play, or age—were different between time 5 athletes and athletes evaluated at other time points. Thus, these independent variables did not appear to contribute to the likelihood of prolonged clinical follow-up of athletes in our sample in the same way that sex did.

Regression Analysis

Multivariate regression analysis revealed that adjusted symptom scores decreased ($P < .001$) at each time interval, suggesting an improvement in the self-report of symptoms over time. Neurocognitive scores demonstrated improvements ($P \leq .002$) over time. We observed a trend between total symptom score and intensity of activity after concussion ($P = .08$). Table 4 provides the adjusted means, standard errors, effect sizes, and percentile rankings pertaining to our multivariate analyses. Some of the largest effect sizes noted in the analysis were in activity intensity and outcome.

After adjusting for other variables, a main effect was noted for intensity of activity (AIS score) on visual memory ($P = .003$) and reaction time ($P < .001$) (Figure 1). Evaluation of adjusted means suggests that athletes

Table 3. Unadjusted Mean Standardized ImPACT Composite Z-Scores (Percentile Rank)

	Time Postconcussion				
Composite score	Time 1	Time 2	Time 3	Time 4	Time 5
Verbal memory	−1.77 (3.14)	−0.77 (19.22)	−0.74 (23.58)	−0.11 (45.22)	−0.90 (33.72)
Visual memory	−1.34 (9.85)	−0.64 (22.96)	−0.34 (37.45)	−0.06 (50.80)	−0.27 (49.60)
Visual motor	−0.91 (17.36)	−0.42 (32.64)	−0.06 (51.20)	0.53 (68.08)	0.08 (59.48)
Reaction time[a]	1.73 (3.36)	0.72 (21.19)	0.41 (35.57)	−0.42 (68.79)	−0.32 (67.36)

[a] A higher reaction time composite Z-score indicates slower performance. Increases in composite Z-scores would result in a lower percentile rank.

Table 4. ImPACT Scores: Multivariate Analysis for Postconcussion Symptoms and Neurocognitive Scores[a]

	Verbal Memory				Visual Memory				Visual Motor Speed				Reaction Time[b]				Symptom Score		
Variables	Adjusted Mean	Standard Error	Effect Size	Percentile	Adjusted Mean	Standard Error	Effect Size	Percentile	Adjusted Mean	Standard Error	Effect Size	Percentile	Adjusted Mean	Standard Error	Effect Size	Percentile	Adjusted Mean	Standard Error	Effect Size
Age, y	**P = .02**		0.53		**P = .03**		0.50		P = .91		0.03		P = .35		0.21		P = .28		0.24
13–15 (n = 33)	−1.52	0.36		6.43	−0.81	0.25		20.90	−0.49	0.25		31.21	1.04	0.30		14.92	23.19	3.41	
16–18 (n = 53)	−0.69	0.31		24.51	−0.30	0.22		38.21	−0.46	0.22		32.28	0.77	0.26		22.06	19.62	2.97	
Sex	P = .24		0.35		P = .19		0.40		**P = .05**		0.60		P = .76		0.09		P = .47		0.22
Female (n = 13)	−0.78	0.24		21.77	−0.83	0.17		20.33	−0.09	0.17		46.41	0.83	0.21		20.33	19.52	2.34	
Male (n = 73)	−1.43	0.51		7.64	−0.28	0.38		38.97	−0.86	0.36		19.49	0.98	0.42		16.35	23.29	4.80	
Colorado Concussion Scale grade	P = .89				P = .80				P = .37				P = .92				P = .58		
1 (reference) (n = 35)	−1.05	0.33		14.69	−0.64	0.22		26.11	−0.72	0.23		23.58	0.95	0.27		17.11	19.3	3.11	
2 (n = 37)	−1.22	0.34	0.11	11.12	−0.48	0.23	0.16	31.56	−0.45	0.24	0.25	32.64	0.97	0.28	0.02	16.60	20.56	3.16	0.09
3 (n = 14)	−1.05	0.51	0.00	14.69	−0.54	0.35	0.09	29.46	−0.26	0.36	0.40	39.74	0.80	0.43	0.11	21.19	24.36	4.80	0.33
Prior concussions	P = .68		0.26		P = .55		0.29		P = .25		0.43		P = .72		0.07		P = .15		0.16
0 (n = 48)	−1.03	0.31		15.15	−0.48	0.21		31.56	−0.33	0.21		37.07	0.96	0.26		16.85	19.05	2.89	
≥1 (n = 36)	−1.18	0.37		11.90	−0.63	0.26		26.43	−0.62	0.26		26.76	0.85	0.31		19.77	23.76	3.48	
Return to play	P = .64		0.26		**P = .0006**		0.29		P = .76		0.43		P = .95		0.07		P = .96		0.16
No (n = 51)	−1.02	0.31		15.39	−1.24	0.21		10.75	−0.44	0.22		33.00	0.91	0.26		18.14	21.33	2.94	
Yes (n = 35)	−1.19	0.37		11.70	0.13	0.33		44.83	−0.51	0.26		30.50	0.90	0.31		18.41	21.49	3.48	
Sport	P = .62		0.26		P = .78		0.29		P = .36		0.43		P = .79		0.07		P = .57		0.16
Football (n = 51)	−1.00	0.30		15.87	−0.51	0.21		30.50	−0.33	0.21		37.07	0.86	0.25		19.49	22.57	2.82	
Other (n = 35)	−1.21	0.42		11.31	−0.60	0.29		27.43	−0.62	0.29		26.76	0.95	0.35		17.11	20.25	3.96	
Activity intensity scale	P = .79				**P = .003**				P = .63				**P = .0005**				P = .08		
0 (n = 35)	−1.19	0.42	0.15	11.70	−0.44	0.31	0.33	33.00	−0.29	0.29	0.01	38.59	0.30	0.38	0.02	38.21	22.88	4.19	0.27
1 (n = 77)	−1.25	0.31	0.21	10.56	−0.08	0.23	0.11	46.81	−0.42	0.22	0.12	33.72	0.47	0.27	0.13	31.92	23.19	3.03	0.32
2 (reference) (n = 57)	−0.90	0.33		18.41	0.06	0.24		52.39	−0.28	0.23		38.97	0.25	0.29		40.13	17.29	3.21	
3 (n = 26)	−1.28	0.43	0.21	10.03	−0.68[c]	0.32	0.57	24.83	−0.51	0.30	0.19	30.50	0.48	0.39	0.13	31.56	14.82	4.31	0.13
4 (n = 9)	−0.90	0.60	0.00	18.41	−1.65[c]	0.45	1.29	4.95	−0.87	0.42	0.51	19.22	3.03[c]	0.57	1.70	<0.20	28.86	6.21	0.65
Time interval	**P = .001**				**P = .002**				**P = .0001**				**P < .0001**				**P = < .0001**		
1 Injury day to day 3 (reference) (n = 45)	−2.14	0.36		1.62	−1.28	0.27		10.03	−1.24	0.25		10.75	2.35	0.32		0.94	35.43	3.57	
2 Days 4–7 (n = 52)	−1.15[c]	0.33	0.66	12.51	−0.82	0.24	0.38	20.61	−0.74[c]	0.23	0.48	22.96	1.20[c]	0.29	0.75	11.51	25.48[c]	3.22	0.60
3 Days 8–14 (n = 59)	−1.05[c]	0.33	0.66	14.69	−0.44[c]	0.24	0.65	33.00	−0.34[c]	0.23	0.78	36.69	0.79[c]	0.30	0.93	21.48	20.46[c]	3.31	0.83
4 Days 15–21 (n = 28)	−0.41[c]	0.42	1.00	34.09	−0.14[c]	0.30	0.87	44.43	0.10[c]	0.29	1.11	53.98	0.01[c]	0.39	1.35	49.60	12.38[c]	4.27	1.23
5 Days 22–33 (n = 28)	−0.77[c]	0.41	0.77	22.06	−0.10[c]	0.30	0.87	46.02	−0.16[c]	0.29	0.87	43.64	0.18[c]	0.38	1.22	42.86	13.29[c]	4.14	1.18

[a] Means of standardized composite scores, adjusted for time-dependent covariance as well as other variables, in the multivariate model are presented. Symptom scores were not converted to Z-scores. Sex and return-to-play interaction was significant (*P* = .0005).

[b] Higher reaction time Z-scores represent slower performance.

[c] Mean values differed from the reference group at the $\alpha = .05$ level. Athletes improved over time in all categories through time 4. Activity level over time after concussion affected neurocognitive performance on visual memory: athletes with activity intensity ratings of 3 and 4 were more impaired than those with ratings of 2. Additionally, those with ratings of 4 reacted more slowly than those with ratings of 2.

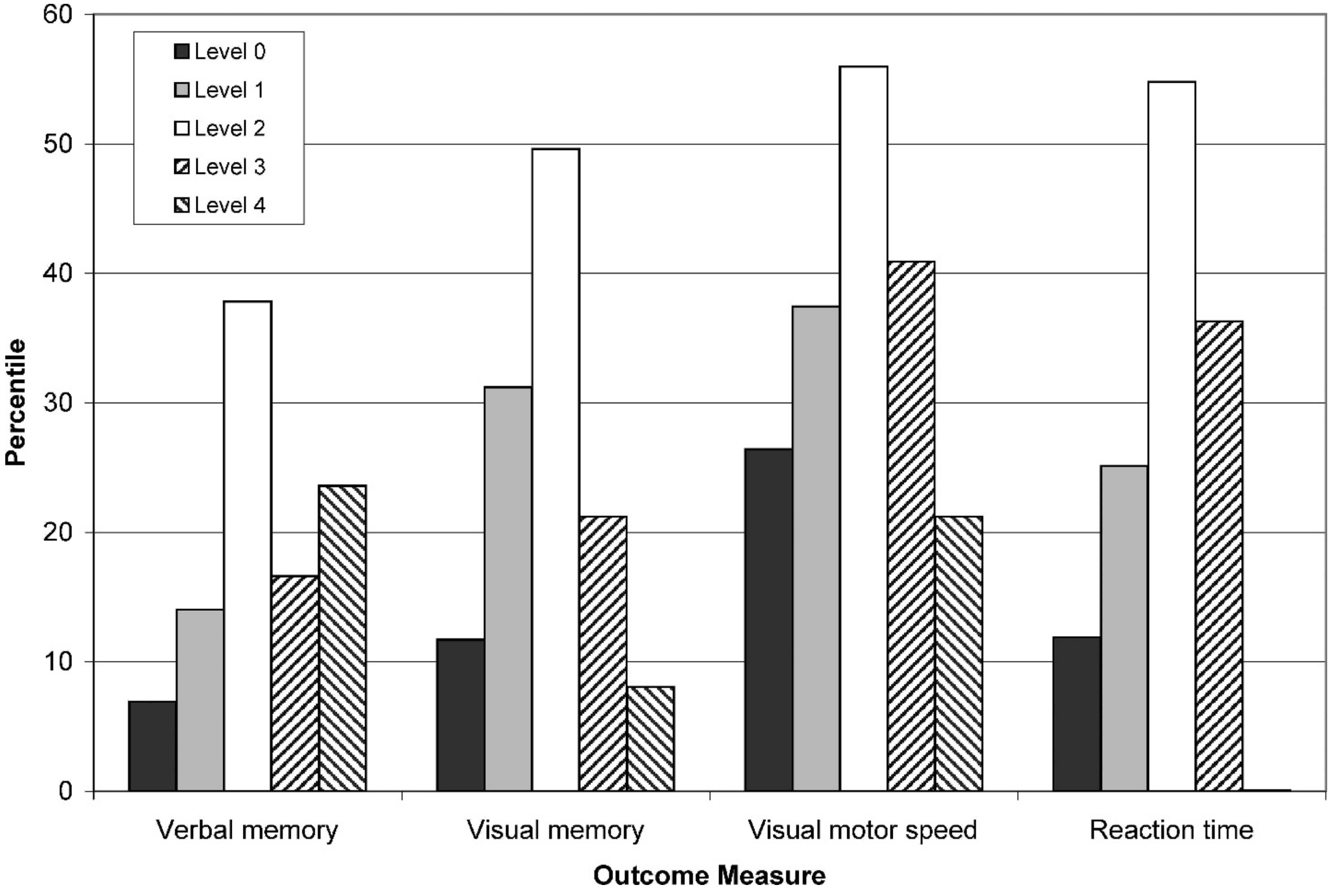

Figure 1. Effects of exertion on recovery. Athletes participating in school activity and light activity at home (eg, slow jogging, mowing the lawn) performed better than athletes experiencing other levels of exertion. Percentiles of time-adjusted mean scores were derived from the multivariate analysis. "Level" refers to the activity intensity scale in which 0 indicates no school or exercise activity and 4 indicates school activity and full sport participation.

engaging in the highest activity levels (AIS = 4) over time had the worst visual memory (adjusted mean score = −2.22), scoring below the 2nd percentile. In fact, adjusted mean comparisons from the multivariate analysis suggest that athletes with AIS = 3 and AIS = 4 were more impaired in visual memory than AIS = 2 ($P \leq .05$ all comparisons). Additionally, reaction times were the worst for the AIS = 4 group (adjusted mean score = 3.51), with performance below the 1st percentile. Comparison of adjusted means derived from the multivariate analysis suggests that athletes with an AIS = 4 had slower reaction times than those with AIS = 2. Those athletes who returned to play in the same contest performed better over time on visual memory subtests than those who did not return to play ($P < .001$).

Age was also associated with verbal memory ($P = .02$) and visual memory ($P = .03$) over time, with younger athletes performing more poorly on both composite scores. Concussion grade was not associated with any of the outcome measures. Females performed worse on visual motor speed than males ($P = .05$). Analyses evaluating interactions among independent variables demonstrated an interrelationship among sex, return to play, and performance on visual memory tests ($P < .001$). For females, those who did not return to play had lower visual memory scores than those who did return to the event in which the concussion occurred (Figure 2). In fact, those females returning to play in the same contest had an adjusted mean performance that was above average normative values. In contrast, no such relationship was observed in males.

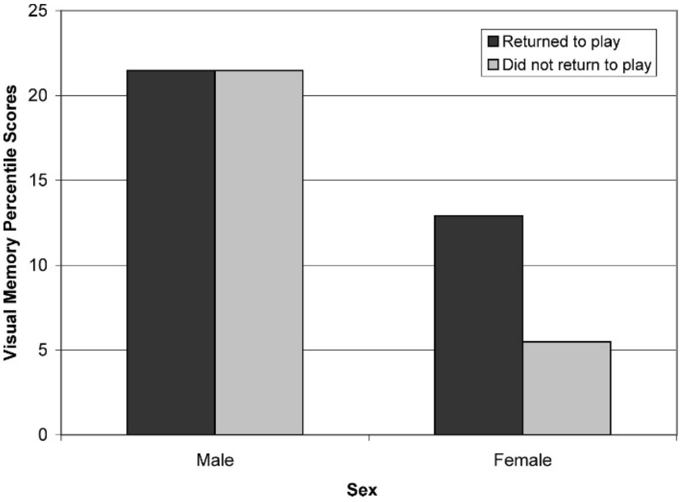

Figure 2. Visual memory between the sexes and return-to-play status. Percentiles of adjusted mean scores were derived from the multivariate analysis. Only significant interaction terms are reported.

Reliability Assessment of Outcome Measures

The κ coefficient for obtaining similar CCS scores for 2 independent raters through chart review was 0.87 (95% confidence interval = 0.70, 1.04), and the κ coefficient for delineating the AIS score with 2 independent raters was 0.87 (95% confidence interval = 0.78, 0.97). These results indicate excellent interrater reliabilities for each of these measures.

DISCUSSION

The results of this study demonstrate an important relationship between postconcussion activity and performance on visual memory and reaction time neurocognitive tests. Although we found no statistically significant relationship between symptom scores and levels of activity following injury, clinical trends were observed in our sample. The fact that only 2 ImPACT composite scores were sensitive to cognitive changes after concussion is not surprising; different cognitive domains are known to be served by different brain regions and systems. Also, speed and reaction time can be considered to be more subcortical functions and memory functions more cortical in nature. In other words, cerebral concussion injuries can affect various neural networks. Therefore, every test in a concussion battery is unlikely to be significant in a particular sample. Thus, our belief that clinicians should use a multifaceted approach to the evaluation and management of head injuries, paying careful attention to address the many aspects of brain function that may be impaired after injury, is strengthened. Younger athletes demonstrated worse postconcussion neurocognitive performance than the older athletes in our sample. Sex associations were noted with postconcussion management and neurocognitive performance. Additionally, the results suggest that an AIS score can be reliably assigned based on chart review by independent observers and that the visual memory composite score appears to be more sensitive than other neurocognitive scores in identifying poor outcomes.

Exertion

The poor performance in the high activity group (AIS level 4) over the course of postinjury assessments might best be explained by the effect of exertion on neurocognitive performance. Exercise is considered an integral aspect of most rehabilitation protocols relating to athletic injuries; however, the scientific understanding of rehabilitation in the context of concussion remains inconclusive at best. In animal studies, researchers[23,24] have demonstrated that voluntary exercise in the uninjured brain results in an upregulation of trophic factors, specifically brain-derived neurotrophic factor, which contributes to experiential neural plasticity. However, recent studies in animals have shown that after experimental TBI, rats engaging in voluntary exercise early after injury performed more poorly on tasks of learning acquisition and memory and had a reduction in plasticity-related proteins compared with nonexercising injured rats and healthy rats that underwent a sham treatment.[25] In contrast, injured rats subjected to a delayed voluntary exercise paradigm showed increases in neurotrophins and better performance on cognitive tasks,[25] indicating that the timing of voluntary exercise after injury is important. These animal studies lend some support to our findings, which indicate poorer performance on visual memory and reaction time composite tests in athletes who engaged in the highest activity level (AIS = 4) after concussion.

Although physical activity has been the primary focus of postconcussion activity restrictions, cognitive activity should also be considered. All of the athletes in this study were student-athletes and, therefore, involved in some sort of cognitive activity after concussion. Given that both mental and physical exertion can change the metabolic activity of the brain,[10] cognitive activities could also potentially worsen the metabolic mismatch after concussion. Our results suggest that cognitive rehabilitation interventions and other cognitive activities (eg, schoolwork) in the population with mild TBI may need to be studied for their effects on central nervous system physiology after TBI and tailored so that they are not detrimental to recovery. For the high school or collegiate athlete, this might include reducing coursework, shortening the school day, rescheduling examinations, and offering personal one-on-one class sessions, in addition to reducing physical exertional demands. Anecdotally, in these chart reviews, cognitive activities associated with school appeared to be an issue for many concussed athletes. Although we did not separate this aspect out with the AIS, future investigators should quantify how cognitive activities specifically contribute to recovery and perhaps even study a graded return to school or cognitive activities.

Postconcussion symptoms, visual memory, and reaction time with activity levels over time were related in these student-athletes. Our effect sizes suggest that athletes who engaged in the highest level of activity tended to demonstrate the worst neurocognitive scores and slowest reaction times, while on average, those who engaged in the intermediate levels of activity had the best scores and fastest reaction times. We speculate that most athletes in the highest-intensity activity group probably experienced a less severe initial injury, but by continuing with high levels of activity, they began to present similarly to those athletes experiencing a more severe or symptomatic initial injury. Conversely, athletes who were initially most symptomatic may have been more inclined to limit their activity after injury. Due to the retrospective design employed in this study, we are unable to determine if this is true. Future prospective studies should better document these findings in order to more appropriately answer these research questions. The AIS was somewhat sensitive to symptom reporting and reached statistical significance with 2 composite scores of neurocognitive function. Visual motor processing speed and verbal memory were not related to the AIS. However, the visual motor processing speed composite was not sensitive to any independent variables, and the verbal memory composite was sensitive only to age. Lack of associations with performance within each of these domains may be due to heterogeneity of the injury, the sensitivity of the AIS scale, the sensitivity of the composite scores, or all 3 factors.

Overall, athletes performing the best on neurocognitive tests and reporting the lowest symptom scores engaged in intermediate levels of activity after concussion; hence, further investigation into possible mechanisms to explain this relationship is needed. One possible way to prospectively investigate the effects of exertion (both cognitive and physical) would be to reevaluate athletes 7 days after a full return to play categorized into 2 groups: those returning to play based on a traditional management protocol (eg, American Academy of Neurology return-to-play guidelines[26]) and those cleared for return after a multifaceted protocol including symptom scoring, computerized neuropsychological testing, assessment of postural stability, and modification and supervision of physical exertion, as well as tapering of academic and cognitive tasks. Outcome measures could consist of neurocognitive test scores, postural stability, academic achievement, and on-field performance measures, to name a few.

Age

Previous authors[27,28] have reported conflicting results regarding the relationship of age and recovery from TBI, but most have examined only severe injury and the extremes of age, with both the elderly and infants and toddlers having the worst outcomes. The literature is sparse regarding the effect of age on recovery after concussion in adolescents, with the exception of one study[29] demonstrating that high school athletes have slower cognitive recovery than collegiate athletes. Our results are consistent with this work, in part, by showing worse performance on verbal and visual memory tests in the younger student-athletes in our sample. Our findings warrant further study into the role age-specific mechanisms of TBI pathophysiology may have in mediating this association.[30–34]

Sex

Although several researchers[35–39] have suggested neuroprotection for females after TBI, other studies[40–42] suggest poorer outcomes for females after TBI. Additionally, high school and collegiate female athletes have a higher incidence of concussion than their male counterparts[3,43] and may be at greater risk for postconcussive syndrome after mild TBI.[44] Our data indicate that females were followed clinically for a longer period of time than males and were more impaired on visual motor speed testing than their male counterparts; no differences were observed for their performance in other domains of neurocognitive function. Although previous authors have demonstrated baseline sex differences on neurocognitive tests, with females generally scoring lower on visuospatial tests than males,[45,46] our data account for these baseline differences by using standardized Z-scores. Although the number of females in our sample was small, these findings are consistent with other data suggesting that females may perform worse after TBI.

As a whole, athletes who returned to play in the same contest in which the injury was sustained were less impaired on visual memory testing, likely indicating less severe signs and symptoms of injury on the field and a higher probability of appropriate decision making by coaches and athletic trainers regarding return to play. In fact, as a group, athletes returning to play scored above average on visual memory over the time course studied. Interestingly, postconcussion management (return to play), sex, and neurocognitive performance were related in that females who returned to play in the same contest in which the concussion occurred performed significantly better on visual memory tasks than those who were removed from the contest. Conversely, males performed the same, whether or not they returned to play. This may indicate differences in early management based on sex, possibly related to sex differences in immediate symptom reporting[47] or other factors not evaluated. However, the lack of differences in neurocognitive performance for males in this composite score and return-to-play status suggests that perhaps some male athletes require more vigilant monitoring to determine the appropriateness of being returned to play after concussion.

Concussion Grade

Numerous concussion grading scales have been presented in the literature. Unfortunately, return-to-play guideline systems have been predicated on anecdotal experience and tend to rely heavily on loss of consciousness as a measure of severity. Previous investigators[48] have demonstrated that amnesia, not loss of consciousness, predicts cognitive deficits after concussion. Although the retrospective assignment of CCS grade has not been previously reported, the CCS lends itself well to the identification and extraction of injury-related factors (presence or absence of confusion, amnesia, and loss of consciousness) needed to assign a score. The clinical charts for this study were provided by 2 investigators who routinely provide detailed information regarding symptoms and events surrounding concussions. The choice of concussion scale, along with the complete and detailed histories consistently provided for athletes, likely contributed to the high interrater reliabilities noted for the CCS in this study.

Limitations

This study represents an initial analysis relating activity levels after concussion in student-athletes and their longitudinal neurocognitive performance and symptom reporting. The retrospective nature of the study means that it is subject to a number of considerations and limitations when we interpret the results. Athletes in this study were students seeking treatment for sport-related concussion and, therefore, may not represent all athletes who sustain concussion. Because they were evaluated in the clinical setting, they may have had more initial symptoms, more or less motivation, or more social support, all of which could affect symptom reporting and performance on neurocognitive tests. Data were collected in a clinical setting, so the time for each follow-up visit varied among athletes. However, we attempted to address this issue by categorizing the data into discrete and clinically relevant time intervals. Even when we used this approach, a significant number of athletes had fewer than 5 observations for the data set. Reasons for this are varied and include time to referral and scheduling of appointments, as well as limited need for follow-up at the time intervals defined for analysis. Additionally, baseline testing was not available for all athletes, precluding use of this factor in analysis. However, the use of Z-scores derived from a normative data set available on the ImPACT developers' Web site, along with published normative symptom data,[20] helped us differentiate between inherent and TBI-related differences in age and sex on performance.

The level of activity was self-reported and recorded clinically, which could introduce recall bias into activity reporting. The AIS has not yet been prospectively validated to evaluate how well AIS scores correspond with a specific measurable level of exertion; however, the interrater reliability data presented in this study suggest that the measure can be consistently obtained from chart review. Further, AIS levels for each individual at each time point were captured through our mixed-effects regression analysis and allowed us to assess specifically how activity levels over time affected longitudinal outcomes. However, authors of future prospective studies should quantify and manipulate cognitive and exercise load after concussion for a more accurate measure of exertion levels and use this information comparatively with the AIS. The AIS level 1 may have been too broad, and levels 2 to 4 may have shared commonalities. Within AIS level 1, we acknowledge differences among representative activities within each category (eg, mowing the lawn, slow jogging). With this type of retrospective analysis, we could not control for or quantify the speed of slow jogging, duration of running, and what was considered school activity. We did not demarcate the difference between regular school class activity and participation in physical education class. This is a general limitation to self-reporting in retrospective studies in the area of sport-related concussion, a factor that all researchers in this area acknowledge needs improvement. The AIS is an initial scale, and we anticipate that further refinements may help to increase its sensitivity and further strengthen the interrater reliability of the instrument.

This study was limited to student-athletes, and further work is required to generalize these results to larger, more diverse populations over longer time periods. However, the longitudinal nature of this study—up to 33 days postconcussion—and the potential importance of activity intensity for recovery in all persons with mild TBI strengthen the conclusions and management implications raised. Importantly, our AIS scale was not designed as a guide for return-to-play progression but rather as a categorization strategy of the student-athlete's activity level (whether it be academics or athletics) after injury.

Conclusions and Management Recommendations

This study provides support for an individualized, graded return-to-play protocol but also highlights the notion that concussion management may need to include recommendations regarding return to all activities, including school, work, and daily chores, and not just return to sport-specific activity. Additionally, our data indicate differences in recovery based on age and sex, which suggest that different strategies for postconcussion activities may be needed in males and younger student-athletes. Future prospective studies should quantify both cognitive and physical exertion after concussion. At first glance, it appears that a moderate level of exertion (AIS = 2) may be relatively beneficial in recovery from concussion. These findings may lead to rehabilitation strategies, for which we will need to consider the roles of both cognitive and physical exertion on outcomes of student-athletes recovering from sport-related concussion.

ACKNOWLEDGMENTS

Support for this project was contributed in part by NIHK08HD40833. We thank Jamie Pardini, PhD, for her assistance in preparing the human subjects approval for this study. We also thank Kevin M. Guskiewicz, PhD, ATC, FACSM, for his critical review of the manuscript.

FINANCIAL DISCLOSURES

Michael W. Collins, PhD, and Mark R. Lovell, PhD, are stockholders in ImPACT Applications, Inc, the company that develops and sells ImPACT software. None of the other authors have any financial or other conflicts of interests to disclose.

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Cynthia W. Majerske, MD, MS, contributed to conception and design; acquisition and analysis and interpretation of the data; and drafting, critical revision, and final approval of the article. Jason P. Mihalik, MS, CAT(C), ATC, contributed to conception and design; analysis and interpretation of the data; and drafting, critical revision, and final approval of the article. Dianxu Ren, PhD, contributed to analysis and interpretation of the data and drafting and final approval of the article. Michael W. Collins, PhD, contributed to conception and design and critical revision and final approval of the article. Cara Camiolo Reddy, MD, contributed to acquisition and analysis and interpretation of the data and critical revision and final approval of the article. Mark R. Lovell, PhD, contributed to conception and design, analysis and interpretation of the data, and critical revision and final approval of the article. Amy K. Wagner, MD, contributed to conception and design; acquisition and analysis and interpretation of the data; and drafting, critical revision, and final approval of the article.

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