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Sensitivity and Specificity of Subacute Computerized Neurocognitive Testing and Symptom Evaluation in Predicting Outcomes After Sports-Related Concussion

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Investigation performed at University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania

Background: Concussions affect an estimated 136 000 high school athletes yearly. Computerized neurocognitive testing has been shown to be appropriately sensitive and specific in diagnosing concussions, but no studies have assessed its utility to predict length of recovery. Determining prognosis during subacute recovery after sports concussion will help clinicians more confidently address return-to-play and academic decisions.

Purpose: To quantify the prognostic ability of computerized neurocognitive testing in combination with symptoms during the subacute recovery phase from sports-related concussion.

Study Design: Cohort study (prognosis); Level of evidence, 2.

Methods: In sum, 108 male high school football athletes completed a computer-based neurocognitive test battery within 2.23 days of injury and were followed until returned to play as set by international guidelines. Athletes were grouped into protracted recovery (>14 days; n = 50) or short-recovery (≤14 days; n = 58). Separate discriminant function analyses were performed using total symptom score on Post-Concussion Symptom Scale, symptom clusters (migraine, cognitive, sleep, neuropsychiatric), and Immediate Postconcussion Assessment and Cognitive Testing neurocognitive scores (verbal memory, visual memory, reaction time, processing speed).

Results: Multiple discriminant function analyses revealed that the combination of 4 symptom clusters and 4 neurocognitive composite scores had the highest sensitivity (65.22%), specificity (80.36%), positive predictive value (73.17%), and negative predictive value (73.80%) in predicting protracted recovery. Discriminant function analyses of total symptoms on the Post-Concussion Symptom Scale alone had a sensitivity of 40.81%; specificity, 79.31%; positive predictive value, 62.50%; and negative predictive value, 61.33%. The 4 symptom clusters alone discriminant function analyses had a sensitivity of 46.94%; specificity, 77.20%; positive predictive value, 63.90%; and negative predictive value, 62.86%. Discriminant function analyses of the 4 computerized neurocognitive scores alone had a sensitivity of 53.20%; specificity, 75.44%; positive predictive value, 64.10%; and negative predictive value, 66.15%.

Conclusion: The use of computerized neurocognitive testing in conjunction with symptom clusters results improves sensitivity, specificity, positive predictive value, and negative predictive value of predicting protracted recovery compared with each used alone. There is also a net increase in sensitivity of 24.41% when using neurocognitive testing and symptom clusters together compared with using total symptoms on Post-Concussion Symptom Scale alone.

Keywords: concussion; prognosis; symptoms; neurocognitive testing

In the United States, an estimated 1.6 to 3.8 million concussions[18] occur each year, and as we continue to understand more about the long-term effects of concussions, team physicians and athletic trainers at all levels of play are under increasing scrutiny to accurately diagnose and predict length of recovery to effectively manage sports concussions. On this front, computerized neurocognitive testing has been established to have 81.9% sensitivity and 89.4% specificity[2,3,9,10,15,27] in diagnoses of concussions, but little work has been done to determine the ability of neurocognitive testing to predict prognosis.

Such information would prove valuable, permitting important decisions to occur immediately after concussion regarding when the athlete may be able to return to physical exertion and the playing field. Perhaps most important to the student athlete, for whom longer recovery from concussions has been observed,[5,12,25] are decisions regarding return to the classroom and potential implications on

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academic function. Recent research has highlighted that recovery from concussion is a highly variable process, and more complicated recoveries have been shown to be related to the younger athlete,[12] those with a history of learning disability,[6] athletes exhibiting posttraumatic migraine symptoms,[23] female sex,[3,7] and those with a preexisting history of concussion.[4]

Although data are accumulating to show which constitutional factors may indicate those at risk for more protracted recovery after sports concussion, a paucity of data exist examining which subacute symptom and neurocognitive profiles may predict a more protracted recovery. Only 2 such studies exist. In one study, Iverson[14] used the Immediate Postconcussion Assessment and Cognitive Testing (ImPACT) test battery to evaluate recovery. Findings revealed that athletes who exhibited 3 of 4 reliable change deficits, relative to baseline levels of functioning, were 94.6% likely to require at least 10 days until recovery occurred, as defined by being asymptomatic at rest and with exertion and demonstrating intact neurocognitive functioning. Moreover, the study noted that the summed score on the Post-Concussion Symptom Scale (PCSS) was greater in the protracted recovery group, showing that athletes who have more symptoms take longer to recover.

A second study expanded Iverson's observations and sought to identify which types of symptoms were linked to recovery.[19] The study compared the change in the summative scores of the 4 symptom clusters (migraine, cognitive, sleep, neuropsychiatric; see Figure 1), as determined by a prior factor analysis, from each athlete's baseline testing with the first postinjury evaluation.[19,24] It found that athletes who took longer to recover showed significantly greater changes in migraine and cognitive symptom clusters. Put another way, patients who had more symptoms within the migraine and cognitive symptom clusters required more recovery time.[19]

In the literature, there is still debate whether the use of neurocognitive testing while a patient is symptomatic has clinical utility.[26] The argument posed is that if a patient has symptoms of concussive injury, limited clinical value exists in performing neurocognitive testing, given that a symptomatic patient should not return to play according to international consensus.[1,22] Within this context, many important clinical decisions need to occur during the subacute phase of recovery, including return to physical exertion, academic considerations, and informing clinicians, parents, coaches, and academic personnel about the effects of injury. Moreover, if neurocognitive testing could provide additional prognostic information in concert with symptoms in terms of length of recovery, the added value of neurocognitive testing while an athlete is symptomatic may prove beneficial.

Studies have been conducted revealing the added value of computerized neurocognitive testing in the diagnosis of sports-related concussion.[21,27,28] Van Kampen et al[28] compared neurocognitive and postconcussion symptom scores of concussed athletes with those of age- and education-matched nonconcussed high school and college athletes. Their study showed a net increase of 19% in the sensitivity of diagnosing concussions when computerized neurocognitive testing (ImPACT) was used with symptoms versus symptoms alone. A study by Fazio et al[11] demonstrated the ability of computerized neurocognitive testing as measured by ImPACT to diagnose subacute concussion when symptoms were not reported by athletes. The study revealed that concussed athletes who denied any symptoms within 4 days of concussion performed significantly worse across all 4 neurocognitive symptom scores when compared with a matched control group. Such findings highlight that asymptomatic athletes may continue to exhibit neurocognitive impairment, thereby indicating that neurocognitive assessment before return to play may be helpful.

Current large-population outcome studies using symptom- and neurocognitive-dependent measures after sports concussion highlight that typical recovery from sports concussion occurs within 10 to 14 days of injury.[5,10,12,15,21,25] However, these group studies fail to account for individual outliers and those who may exhibit more protracted recoveries. Thus, for our current study, we wanted to use a 14-day cutoff period as traditionally defining athletes who exhibit a "quick" recovery from sports concussion. The aim of this study was to quantify how well symptom and computerized neurocognitive profiles may predict more protracted recoveries—as defined by athletes exhibiting recoveries lasting longer than 14 days.

MATERIALS AND METHODS

The university's institutional research board conducted appropriate reviews of our research with human participants and approved this study.

Participants

The sample for this 5-year study (2002-2006 seasons) consisted entirely of male participants of Pennsylvania high school football programs governed by Pennsylvania Interscholastic Athletic Association, which strictly enforces all their rules regarding the number of preseason practices, scrimmages, and games each team may undertake every season. By rule, summer camp practices begin 2 weeks before regular season play, and each team is permitted 1 scrimmage at the end of both preseason weeks. Each team typically has 3 practices per day during the preseason and 3 contact practices per week throughout the regular season. All teams play a total of 9 regular season games during a season. This study included only athletes who had suffered concussions during preseason and regular season football activity; it did not include athletes who were injured in postseason playoffs. All athletes in participating schools who sustained a concussion were referred to the sports concussion clinic regardless of perceived severity. Under agreement with each school's athletic trainers, student athletes were not permitted to return to play unless cleared by the sports concussion program. Thus, student athletes injured in season when games were left to be played were highly motivated to return for follow-up. Data collection ended at the conclusion of the 2006 season. Over the course of the

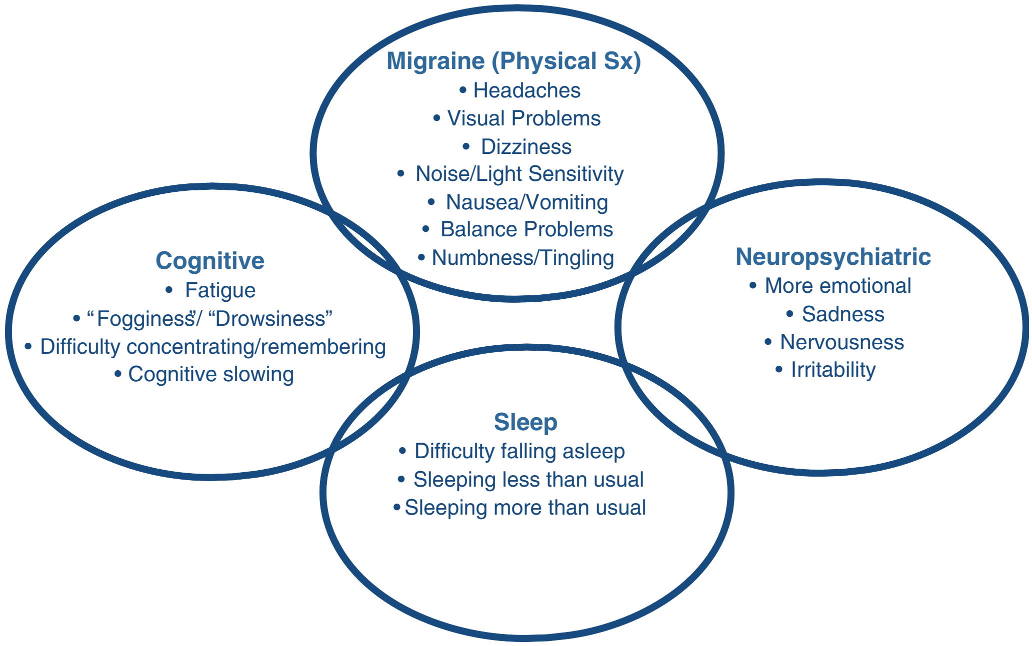

Figure 1. Post-Concussion Symptom Scale, grouped into 4 symptom clusters.

study, 177 athletes were evaluated for concussions, with 108 eventually being cleared to play: 58 as short recovery (≤14 days; mean, 6.90 days to recover) and 50 as protracted recovery (>14 days; mean, 33.04 days to recover). Regardless of group membership, the median time to first evaluation was 2 days. The remaining 69 athletes not cleared were either lost to follow-up or did not return to football by the end of the 2006 season. Of the 177 athletes evaluated, 137 had neurocognitive baseline testing—48 of 58 (82.75%) short-recovery athletes and 36 of 50 (72.00%) protracted-recovery athletes had baseline scores. Patient characteristics are listed in Table 1.

Identification of Concussion on the Field

Athletes must have been diagnosed with a concussion by athletic trainers and/or physicians present on the sidelines after on-field events. The basis for diagnosis was on-field presentation of 1 or more of the following signs or symptoms after impact to the head: (1) any noticeable change in mental status or consciousness; (2) loss of consciousness, disorientation, posttraumatic amnesia, or retrograde amnesia; or (3) any self-reported symptoms that appeared after a collision on the field. Typically, these symptoms were headache, dizziness, balance dysfunction, or visual changes (eg, visual blurring, diplopia, "seeing stars"). Next, all athletes must have completed both ImPACT neurocognitive testing and PCSS[20] assessment during follow-up until full recovery.

Clinical Management

Clinical management and care of participants followed international return-to-play standards.[1,22] Athletes were followed clinically, not according to a controlled research protocol, and no athlete was returned to play until he met standardized clinical criteria. The general course was to conduct the first evaluation with 72 hours, then approximately 1, 2, and 3 weeks after injury, if necessary. Athletes were evaluated by their schools' athletic trainers, and a single concussion specialist was consulted for each case throughout their recovery. International protocols require that an athlete must first report being completely symptom-free at rest before progression through a stepwise exertional program. The sequence involved guided activity with a trained athletic trainer, from light activity (eg, walking) to heavier exertion (eg, running wind sprints) without return of concussive symptoms. If any concussion-type symptoms returned during exercise, the athlete was instructed to go back to the prior level of exertion.

After satisfactory completion of the stepwise exertional program, 3 criteria had to be met by athletes before being cleared to return to play.

First, the athlete's total score on the PCSS[20] must have been less than 7. This was adopted as a cutoff based on prior studies.[16] The PCSS contains 22 symptoms that are not specific to concussion; even noninjured athletes may report symptoms at the time of baseline. A prior study noted that the mean symptom score for noninjured high school males was 5.8 despite never having suffered a concussion.[16] The same study found that 76% scored 6 or less, with a large portion scoring 0 (40.5%)—thus, the threshold of 7.

Regardless of his PCSS score, no athlete was returned to play if he was experiencing headache pain or other symptoms that were clearly linked to his diagnosed concussion, such as dizziness or balance dysfunction.

Second, in addition to the above criteria, the athlete must not have had more than 1 ImPACT neurocognitive

TABLE 1
Patient Characteristics: Pennsylvania High School Football Players

	Short Recovery[a]	Long Recovery[b]
Days to recover, mean	6.90	33.04
Days to first evaluation		
Mean	1.91	2.60
Median	2	2
Baseline testing, % (n)	82.75 (48 of 58)	72.00 (36 of 50)
Age, y (mean)	16.12	15.90
History		
Previous concussion	11	14
Headaches	8	7
Migraines	6	5
Attention-deficit/ hyperactivity disorder	2	2
Learning disability	1	1
Number of patients:		
Concussed	177	
Fully recovered	108	
Not fully recovered or lost to follow-up	69	

[a]≤14 days to recover; n = 58.
[b]>14 days to recover; n = 50.

composite score that was statistically worse than his baseline performance. Overall, 77% of the total sample, 82.75% of short recovery, and 72% of protracted recovery athletes, had baseline scores. When baseline performance was not available, the athlete's composite scores were compared with age-specific normative data. A prior study comparing concussed athletes with a noninjured sample of athletes showed that having 1 composite score below baseline was not uncommon but that only 3.6% of noninjured athletes had 2 scores below baseline.[16] Reliable change was determined on the basis of results of a previous study of high school and collegiate athletes. The values needed for a score to be significant at 80% confidence interval were as follows: 9 points for verbal memory composite, 14 points for visual memory composite, 0.06 seconds for the reaction time composite, and 3 points for the processing speed composite.[16]

Finally, the athlete must have had all his neurocognitive composite scores above the 10th percentile for his age, which broadly represents the normal range. The only exception was if a patient's baseline before injury was below the 10th percentile.

All physical activities were monitored by their athletic trainers or team physicians, and athletes were not returned to practice or game situations until they were evaluated by clinical staff and met specific return to play criteria.

Discriminative Measures

The current study used ImPACT software. ImPACT has been shown to have a high degree of sensitivity and specificity in diagnosing sports concussion, and it has been shown to be reliable[17,27] and valid in the measurement of sports concussion.[2,3,9,10,15] The entire test requires approximately 20 minutes with a computer screen and mouse.

First, the patient is asked demographic data, such as age, sex, relevant medical history, and concussion history. Next, the PCSS is administered, as based on a 7-point Likert-type scale with 22 concussion-related symptoms.[20] Athletes are asked to rank each symptom from 0 (complete absence) to 6 (most severe). A list of the 22 concussive symptoms and their separation into 4 separate symptom clusters—migraine, cognitive, neuropsychiatric, and sleep—are included in Figure 1. The summative scores for all symptoms within each cluster during the subacute period (2-3 days) evaluation were used for analysis. For example, the neuropsychiatric symptom cluster is the summative total from the individual symptoms during the subacute period of *more emotional*, *sadness*, *nervousness*, and *irritability*.

After completion of the demographic section and postconcussion symptom inventory, the neurocognitive modules of ImPACT are administered. There are 6 neurocognitive modules, each designed to evaluate different aspects of attention, memory, processing speed, and reaction time. Upon completion of the neurocognitive test module, 4 composite scores are generated: verbal memory, visual memory, processing speed, and reaction time. (For the individual tests and the construction of composite scores, see references 2, 9, 16, 17, 19, 26, 27.)

After referral to the sports concussion program, athletes continued to be evaluated using the ImPACT test battery and the PCSS throughout their recovery. Both preinjury baselines and all postconcussion evaluations were collected using the same version of the ImPACT test battery.

After their diagnosis and management, athletes were retrospectively divided into 2 groups: short recovery (≤14 days) or long recovery (>14 days). A series of t tests were evaluated to assess the potential differences between protracted-recovery and short-recovery groups regarding factors such as preconcussion history of migraine, headache, presence or absence of attention-deficit/hyperactivity disorder, and presence or absence of learning disability on recovery time. Multivariate analyses of variance were conducted and as were statistically significant were followed with univariate analysis to establish between and within group difference with the 4 symptom clusters and 4 neurocognitive scores. Stepwise discriminant analyses were then performed with the 4 symptom clusters (migraine, cognitive, neuropsychiatric, and sleep) and 4 neurocognitive scores (verbal memory, visual memory, processing speed, and reaction time) separately, then combined. Classification matrix, sensitivity, and specificity were then assessed for each of the 3 discriminant function analyses.

In this article, *sensitivity* and *specificity* refer to the ability of the variables to detect protracted recovery. Sensitivity is defined as the ability of the defined variables in the discriminant function analysis to identify an athlete who has protracted recovery when he actually has protracted recovery. Specificity is how well one can rely on the variables of the discriminant function to accurately say that an athlete will not suffer from a protracted recovery and will become asymptomatic within 14 days (ie, short recovery). Positive predictive value is the proportion of athletes classified as protracted recovery who indeed have protracted recovery. Negative predictive value is the proportion of athletes classified as not a protracted recovery that actually did not have protracted recovery (not protracted recovery = short recovery).

RESULTS

Of the 108 high school athletes eventually cleared to return to play based on published international criteria, 58 (53.7%) were classified as short recovery (≤14 days), and 50 (46.3%) were classified as protracted recovery (>14 days). All athletes were initially evaluated within the same time frame postinjury. The average times between injury and initial postinjury evaluation were 1.91 days for the short-recovery group (range, 0-5 days) and 2.6 days for the protracted-recovery group (range, 0-12 days). Regardless of eventual classification into long or short recovery, the median time to first evaluation was identical for both groups (2 days) (Table 1). Demographic variables were analyzed to establish between-group homogeneity, with no significant differences noted between short recovery or protracted recovery. Athletes who were classified in the short-recovery group returned to play in an average of 6.90 ± 3.30 days and protracted in 33.04 ± 47.22 days. The 2 groups did not differ significantly with regard to age (F = 0.88, P = .35) or education (F = 3.71, P = .061). The short-recovery group had an average age of 16.12 ± 1.2 and education of 9.81, compared with 15.9 years old and 9.44 years of education for the protracted-recovery group, respectively.

The potential significance of factors such as preconcussion history of migraine, headache, presence or absence of attention-deficit/hyperactivity disorder, and presence or absence of a learning disability on recovery time was evaluated through a series of t tests: headache (t = 0.623, P = .534), migraine (t = 0.589, P = .557), ADHD (t = 1.169, P = .244), and learning disability (t = 0.105, P = .917). There were 11 and 14 athletes who reported at least 1 previous concussion in the short and protracted groups, respectively. The short and protracted groups did not differ significantly with regard to any of these factors.

Means and standard deviations of all 8 variables are included in Table 2. Multivariate analysis of variance—with recovery groups as the dependent variables and with the 4 ImPACT scores and 4 symptom clusters as the independent variables—was significant (F = 3.435, P = .002). Univariate analyses of variance showed significant differences between long and short groups for visual memory (F = 9.843, P = .002), processing speed (F = 4.340, P = .040), migraine cluster (F = 9.333, P = .003), cognitive cluster (F = 4.328, P = .040), and sleep cluster (F = 4.945, P = .028). The other 3 variables were not significantly different: verbal memory (F = 0.756, P = .387), reaction time (F = 1.160, P = .284), and neuropsychiatric (F = 0.199, P = .656).

Discriminant function analysis of the 4 symptom clusters (migraine, cognitive, sleep, neuropsychiatric) was significant, $F(4, 101)$ = 3.319, $P \leq .013$. Statistics for each variable are included in Table 3. The analysis was able to correctly classify 63.21% of athletes into long or short recovery, with a sensitivity of 46.94% and a specificity of 77.20% in predicting prolonged recovery. The positive predictive value and negative predictive value were 63.90% and 62.86%, respectively.

Discriminant function analysis of the 4 ImPACT neurocognitive composite scores (verbal memory, visual memory, processing speed, reaction time) alone showed significance, $F(4, 99)$ = 3.946, $P < .005$. Statistics for each variable are included in Table 4. The analysis was able to correctly classify 65.38% of athletes into long or short recovery. It had a sensitivity of 53.20% and a specificity of 75.44% in predicting prolonged recovery. The positive predictive value and negative predictive value were 64.10% and 66.15%, respectively.

The combined discriminant function analysis with the 4 symptom clusters and 4 ImPACT neurocognitive composite scores was significant, $F(8, 93)$ = 3.435, $P < .002$. Statistics

TABLE 2
Means and Standard Deviations of Variables

Variables	Short Recovery	Protracted Recovery
Total symptom score	17.41 ± 16.72	26.61 ± 20.19
Verbal memory	72.38 ± 12.8	75.66 ± 14.30
Visual memory	69.89 ± 12.5	61.70 ± 15.89
Processing speed	35.53 ± 8.6	31.35 ± 8.87
Reaction time	0.636 ± 0.15	0.675 ± 0.178
Migraine symptom cluster	6.47 ± 6.63	10.90 ± 8.20
Cognitive symptom cluster	8.18 ± 8.23	11.63 ± 9.05
Sleep symptom cluster	0.982 ± 1.74	2.02 ± 3.30
Neuropsychiatric symptom cluster	1.61 ± 2.61	1.80 ± 2.63

TABLE 3
Discriminant Function Analysis: Symptom Cluster Scores Only

Symptom Cluster	Wilks Lambda	$F(1, 101)$	P	Canonical Coefficient
Migraine	0.936	5.957	.016	1.124
Neuropsychiatric	0.908	2.813	.097	−0.613
Sleep	0.892	0.960	.329	0.324
Cognitive	0.884	0.045	.833	−0.100

TABLE 4
Discriminant Function Analysis: Neurocognitive Scores Only

ImPACT Scores	Wilks Lambda	$F(1, 99)$	P	Canonical Coefficient
Visual memory	0.932	7.948	.006	0.921
Verbal memory	0.914	5.876	.017	−0.700
Processing speed	0.874	1.263	.264	0.450
Reaction time	0.872	1.070	.990	0.390

TABLE 5
Discriminant Function Analysis: Symptom Cluster and Neurocognitive Scores Combined

Variables	Wilks Lambda	*F*(1, 93)	*P*	Canonical Coefficient
Migraine cluster	0.828	6.774	.012	−0.990
Reaction time	0.807	4.233	.042	0.682
Visual memory	0.821	5.874	.017	0.654
Verbal memory	0.806	4.070	.047	−0.470
Neuropsychiatric cluster	0.792	2.420	.123	0.431
Processing speed	0.785	1.622	.206	0.416
Cognitive cluster	0.776	0.478	.491	0.253
Sleep cluster	0.780	0.942	.334	−0.242

for each variable are included in Table 5. It was able to correctly classify 73.53% of athletes into long or short recovery. It had a sensitivity of 65.22% and a specificity of 80.36% in predicting long recovery. The positive predictive value and negative predictive value were 73.17% and 73.8%, respectively (see Table 6).

A discriminant function analysis for the total symptom score on the 22-item PCSS alone, $F(1, 105) = 6.647$, $P < .011$, showed a sensitivity and specificity of 40.81% and 79.31%, respectively. The positive predictive value was 62.50% and the negative predictive value was 61.33%. In the symptom cluster discriminant function analysis, the migraine symptom cluster contributed the most, thus leading us to assess migraine cluster symptoms alone in a separate discriminant function analysis, $F(1, 104) = 9.429$, $P < .003$. The migraine symptom cluster alone had a sensitivity of 44.89% and specificity of 78.95% in predicting long recovery. The positive predictive value and negative predictive value were 64.71% and 62.50%, respectively.

DISCUSSION

Computerized neurocognitive testing has been proven sensitive and specific to diagnosing a concussion, and the primary objective of this study was to define how well self-reported symptom clusters and neuropsychological testing can together predict protracted recovery during the subacute stages of recovery, within 2 to 3 days of injury. Note that the short and protracted groups had significantly different outcomes, with a mean of 7 days and 33 days to recovery, respectively. Being able to predict, during the subacute stage of recovery (2-3 days postinjury), which athletes will take an average of 33 days to recover would be extremely beneficial to clinicians.

The results of this study lend support to the added value of using neurocognitive testing early in the recovery period. Individually, ImPACT neurocognitive testing and symptom cluster scores have similar sensitivity and specificity (Table 6). When ImPACT neurocognitive testing (verbal, visual, processing speed, reaction time) and symptom cluster scores (migraine, cognitive, processing speed, reaction time) were combined, there was an increase in the sensitivity to detect protracted recovery, compared with when each was used alone. When compared with total symptom score on the PCSS alone, there was a 24.41% increase in sensitivity for the combined group. Furthermore, the combined symptom clusters and ImPACT neurocognitive testing have a positive predictive value and a negative predictive value of 73.17% and 73.8%, respectively. In other words, a clinician who evaluated a patient within 2 to 3 days after a concussion could accurately predict 73.17% of the time whether the athlete will require a protracted recovery if neurocognitive testing and symptoms are used together. This suggests that there is “value added” in using neurocognitive testing early in recovery along with symptoms.

Also note that of the 4 variables contributing most to the classification power (Table 5), the migraine symptom cluster contributed the most. Given that headaches, dizziness, and nausea are prominent in concussions and play a major role in return-to-play decisions, their effect on length of recovery is not surprising.[23] However, the remaining 3 variables were ImPACT neurocognitive test scores: reaction time, visual memory, and verbal memory. This lends further support to the relative importance of computerized neurocognitive testing for identifying athletes who will have protracted recovery.

This study also begins to formulate a symptom and neurocognitive testing profile of athletes, which may be able to predict patients who will require protracted recovery. Using canonical analysis and the *P* values (Table 5) observed in the combined discriminant function analysis, 4 variables accounted for the majority of the classification power of the discriminant function analysis: migraine symptom cluster, ImPACT reaction time, ImPACT verbal memory, ImPACT visual memory. As such, for a patient who (1) primarily has migrainelike symptoms (headaches, vision problems, noise and light sensitivity, nausea, and dizziness) and (2) shows reliable change deficits as defined by Iverson et al[16] on ImPACT scores of reaction time (increase of 0.06), verbal memory (decrease of 9 points), and visual memory (decrease of 14 points) from one’s baseline or age-normative data, a clinician can say with 73.17% confidence that the athlete will have a protracted recovery.

This study also looks further into subcategorizing concussion symptoms into 4 separate symptom clusters. Because migraine symptom cluster was the largest contributor to classifying patients with protracted recovery, a simple discriminant function analysis of migraine cluster showed only comparable sensitivity and specificity when compared with total symptoms (Table 6), which suggests that when attempting to predict outcome, clinicians may focus on a smaller subset of symptoms (ie, headache, nausea, vomiting, balance problems, dizziness, sensitivity to light or noise, numbness, tingling, or visual problems). The value of such specific symptom profile distinctions may provide clinicians with the profile of athletes who may have protracted recovery, and it may offer potential insight into more effective treatment options.

Also of interest is that ImPACT reaction time scores were not found to be significantly different between short and protracted groups, as determined by univariate

TABLE 6
Comparison of Discriminant Function Analysis of Symptom Clusters and Neurocognitive Scores[a]

	Total Symptoms	Symptom Clusters Scores Only	Migraine Cluster Only	Neurocognitive Testing Scores Only	Symptom Cluster and Neurocognitive Scores
Wilks lambda	0.940	0.884	0.917	0.862	0.772
F	6.647	3.318	9.429	3.946	3.435
P	<.0113	<.0134	<.0027	<.0052	<.0017
Athletes correctly classified, long/short recovery, %	61.68	63.21	63.21	65.38	73.53
Sensitivity in predicting long recovery, %	40.81	46.94	44.90	53.20	65.22
Specificity in predicting long recovery, %	79.31	77.20	78.95	75.44	80.36
Predictive value of protracted recovery, %					
Positive	62.50	63.90	64.71	64.10	73.17
Negative	61.33	62.86	62.50	66.15	73.80

[a]Sensitivity, specificity, positive predictive value, and negative predictive value are given in relation to ability to differentiate protracted recovery.

analysis or as a significant contributor to the ImPACT neurocognitive scores–only discriminant function analysis. However, in the combined discriminant function analysis, it was the second-largest contributor, which is consistent with previous studies.[14,19] A possible explanation is that differences in reaction time are often subtle—only a few tenths of a second apart. One hypothesis is that large changes in reaction time may be more meaningful than smaller changes and, when large, may prove to be a key differentiating factor for protracted recovery.

This study is not without limitations. This database was selected because it used a homogeneous sample and all athletes received clinical on-field and postinjury management that required all athletes suffering any symptoms directly associated with a concussion to be referred to the sports concussion clinic. Moreover, athletes required clearance by the concussion specialists to return to play. Thus, clinical referral and management were consistent between schools. Yet, this study was observational, and this methodology did not allow experimental control factors, such as precise assessment intervals and the requirement that all athletes complete a specific number of assessments. Athletes were returned to play when they met international clinical criteria, not at a specific time after injury, thus leading to somewhat variable assessment intervals for the 2 groups. This clinical pathway, the conclusion of football season, and the graduation of students also resulted in natural attrition and a somewhat large number lost to follow-up. The retrospective classification of athletes into short or protracted groups creates the possibility that athletes classified as protracted recovery recovered in less than 14 days after injury but were not cleared until after this time. The subject pool did not include female athletes or sports other than football. Thus, findings cannot be generalized beyond male high school football players.

As we continue to better understand the pathophysiology of sports concussion and its potential long-term implications,[13,15] there is increasing scrutiny to better manage the injury. Prognostic consideration, determined acutely or subacutely, will provide clinicians reasonable and concrete information to share with the athlete, coaches, parents, and teachers about expectations of recovery. This study takes the first steps to show that concussion prognosis may be best predicted by evaluating symptom clusters and neurocognitive testing. However, we would like to caution that the positive predictive value was 73.17% and that a percentage of athletes were incorrectly classified. Prudence should be used in predicting recovery until more studies are conducted, and no athlete should be returned to play when symptomatic, even if neurocognitive testing yields normal findings.

REFERENCES

1. Aubry M, Cantu R, Dvorak J, et al. Summary and agreement statement of the First International Conference on Concussion in Sport. *Br J Sports Med*. 2002;36:6-10.
2. Barr WB, McCrea M. Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussions. *J Int Neuropsychol Soc*. 2001;7:693-702.
3. Collins MW, Grindel SH, Lovell MR, et al. Relationship between concussion and neuropsychological performance in college football players. *JAMA*. 1999;282:964-970.
4. Collins MW, Lovell MR, Iverson GL, Cantu RC, Maroon JC, Field M. Cumulative effects of concussion in high school athletes. *Neurosurgery*. 2002;51(5):1175-1179.
5. Collins MW, Lovell MR, Iverson GL, Ide T, Maroon J. Examining concussion rates and return to play in high school football players wearing newer helmet technology: a three year prospective cohort study. *Neurosurgery*. 2006;58:275-286.
6. Collins MW, Lovell MR, McKeag DB. Current issues in managing sports-related concussion. *JAMA*. 1999;282(24):2283-2285.
7. Colvin AC, Mullen J, Lovell MR, West RV, Collins MW, Groh M. The role of concussion history and gender in recovery from soccer-related concussions. *Am J Sports Med*. 2009;37(9):1699-1704.
8. Covassin T, Elbin R, Kontos A, Larson E. Investigating baseline neurocognitive performance between male and female athletes with a history of multiple concussion. *J Neurol Neurosurg Psychiatry*. 2010;81(6):597-601.
9. Erlanger D, Feldman D, Kutner K, et al. Development and validation of a web-based neuropsychological test protocol for sports-related return-to-play decision-making. *Arch Clin Neuropsychol*. 2003;18(3): 293-316.
10. Erlanger D, Saliba E, Barth J, Almquist J, Webright W, Freeman J. Monitoring resolution of postconcussion symptoms in athletes:

preliminary results of a web-based neuropsychological test protocol. *J Athl Train*. 2001;36:280-287.
11. Fazio V, Lovell MR, Pardini J, Collins MW. The relationship between postconcussion symptoms and neurocognitive performance in concussed athletes. *Neurorehabilitation*. 2007;22:207-216.
12. Field M, Collins MW, Lovell MR, Maroon J. Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *J Pediatr*. 2003;142:546-553.
13. Guskiewicz KM, Marshall SW, Bailes J, et al. Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery*. 2005;57:719-726.
14. Iverson G. Predicting slow recovery from sport-related concussion: the new simple-complex distinction. *Clin J Sport Med*. 2007;17:31-37.
15. Iverson GL, Brooks BL, Collins MW, Lovell MR. Tracking neuropsychological recovery following concussion in sport. *Brain Injury*. 2006;20:245-252.
16. Iverson GL, Lovell MR, Collins MW. Interpreting change on ImPACT following sport concussion. *Clin Neuropsychol*. 2003;17:460-467.
17. Iverson GL, Lovell MR, Collins MW. Validity of ImPACT for measuring processing speed following sports-related concussion. *J Clin Exp Neuropsychol*. 2005;27(6):683-689.
18. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil*. 2006;21:375-378.
19. Lau BC, Lovell MR, Collins MW, Pardini J. Neurocognitive and symptom predictors of recovery in high school athletes. *Clin J Sport Med*. 2009;19(3):216-221.
20. Lovell MR, Iverson GL, Collins MW, et al. Measurement of symptoms following sports-related concussion: reliability and normative data for the post-concussion scale. *Appl Neuropsychol*. 2006;13(3):166-174.
21. Makdissi M, Darby D, Maruff P, Ugoni A, Brukner P, McCrory PR. Natural history of concussion in sport: markers of severity and implications for management. *Am J Sports Med*. 2010;38(3):464-471.
22. McCrory P, Johnston K, Meeuwisse W, et al. Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. *Clin J Sport Med*. 2005;15(2):48-55.
23. Mihalik JP, Stump JE, Collins MW, Lovell MR, Field M, Maroon JC. Posttraumatic migraine characteristics in athletes following sports-related concussion. *J Neurosurg*. 2005;102:850-855.
24. Pardini J, Stump J, Lovell MR, Collins MW, Moritz K, Fu F. The Post Concussion Symptom Scale (PCSS): a factor analysis [abstract]. *Br J Sports Med*. 2004;38:661-662.
25. Pellman EJ, Lovell MR, Viano DC, Casson IR. Concussion in professional football: recovery of NFL and high school athletes assessed by computerized neuropsychological testing. Part 12. *Neurosurgery*. 2006;58:263-274.
26. Randolph C, McCrea M, Barr WB. Is neuropsychological testing useful in management of sport-related concussion? *J Athl Train*. 2005;30:139-152.
27. Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsychol*. 2006;21(1):91-99.
28. Van Kampen DA, Lovell MR, Pardini JE, Collins MW, Fu FH. The ''value added'' of neurocognitive testing after sports-related concussion. *Am J Sports Med*. 2006;34(10):1630-1635.