Sensitivity of the Concussion Assessment Battery

OBJECTIVE: Sports medicine clinicians commonly use multiple tests when evaluating patients with concussion. The specific tests vary but often include symptom inventories, posturography, and neurocognitive examinations. The sensitivity of these tests to concussion is vital in reducing the risk for additional injury by prematurely returning an athlete to play. Our study investigated the sensitivity of concussion-related symptoms, a postural control evaluation, and neurocognitive functioning in concussed collegiate athletes.

METHODS: From 1998 to 2005, all high-risk athletes completed a baseline concussion-assessment battery that consisted of a self-reported symptom inventory, a postural control evaluation, and a neurocognitive assessment. Postconcussion assessments were administered within 24 hours of injury to 75 athletes who had physician-diagnosed concussion. Individual tests and the complete battery were evaluated for sensitivity to concussion.

RESULTS: The computerized Immediate Post-Concussion Assessment and Cognitive Testing and HeadMinder Concussion Resolution Index (neurocognitive tests) were the most sensitive to concussion (79.2 and 78.6%, respectively). These tests were followed by self-reported symptoms (68.0%), the postural control evaluation (61.9%), and a brief pencil-and-paper assessment of neurocognitive function (43.5%). When the complete battery was assessed, sensitivity exceeded 90%.

CONCLUSION: Currently recommended concussion-assessment batteries accurately identified decrements in one or more areas in most of the athletes with concussion. These findings support previous recommendations that sports-related concussion should be approached through a multifaceted assessment with components focusing on distinct aspects of the athlete’s function.

KEY WORDS: HeadMinder Concussion Resolution Index, Immediate Post-Concussion Assessment and Cognitive Testing, Neurocognitive assessment, Postural control

Between 1.6 and 3.8 million concussions occur in the United States annually (19a) with a total cost of nearly $17 billion (36). In athletics, large-scale investigations have found that 5 to 6% of collegiate football athletes sustain a concussion during the competitive season, and the rate of concussion incidence is on the rise (14, 17). The National Collegiate Athletic Association Injury Surveillance System (26) reports a steady increase in the concussion injury rate between 1987 and 2003. In addition, more than 50% of interscholastic athletes may not report a concussive injury to medical personnel (24).

Evaluation of concussion is particularly difficult for the clinician because no definitive diagnostic tool is available. A recent sport-concussion meeting summary statement recommended a battery of tests be used for evaluation of patients with concussion (25). Administration of the assessment battery should occur in the preseason to establish a baseline level of functioning on each athlete which can then be compared to postinjury performance. Postconcussion assessments are commonly administered within 24 hours of injury and continue in various sequences until the athlete performs at or above the baseline level (6, 16, 21, 23, 29). Components of the assessment battery vary but commonly include an evaluation of self-reported concussion-related symptoms, postural control, and neurocognitive functioning. When used in conjunction with a clinical examination, the sensitivity of the assessment battery to concussion must be high to minimize the risk of a false-negative finding. Athletes with concussion who are identified to be functioning normally by the assessment battery while still recovering from injury may be at risk for additional injury and a potentially catastrophic outcome if returned to play before injury resolution (5).
Approximately 85% of certified athletic trainers use self-reported symptoms as part of their concussion-assessment battery (28). Symptoms listed on a self-reported inventory have been amended over the years but typically include items such as headache, fatigue, and difficulty concentrating. The Post-Concussion Symptom Checklist includes an extensive list of concussion-related symptoms and has been suggested as a standardized symptom-assessment tool (20). A nine-item list of concussion-related symptoms, however, was shown to have factorial and content validity (30) and was later reported to demonstrate excellent fit to a three-factor model (31). The investigators suggested these nine items may provide the best description of concussion symptomology without introducing confounding symptoms that are unrelated to concussion.

Postural control assessments obtained from patients after concussion revealed deficits in the sensory integration process used for maintaining optimal balance (15, 16, 29). When patients were evaluated within 24 hours of injury, Guskiewicz et al. (16) reported decrements in 36 concussed athletes compared with 36 matched controls. Their evaluation used the Neuropres Sensory Organization Test (SOT; NeuroCom International, Inc., Clackamas, OR) with notable deficits in the composite balance score and the vestibular and visual ratios. The injured athletes’ deficits resolved within 3 days after injury. Although posturography is now recommended as a postconcussion assessment tool (12, 25), no data are available that evaluate the sensitivity of the SOT to concussion in collegiate athletes.

The neurocognitive assessment has been suggested as the most important element of the concussion-assessment battery because it provides the greatest amount of information to the clinician during the evaluation process (11). The neurocognitive assessment has traditionally been completed using a series of pencil-and-paper tests that evaluate the domains of processing, planning, memory, and switching mental set (2). A thorough battery may take hours to administer, but brief batteries of less than 45 minutes are common to sports medicine (6, 13, 15, 16, 29). Several different combinations of pencil-and-paper test batteries exist; however, a test battery that included the Hopkins Verbal Learning Test, Trail Making Test Part B, the Symbol Digit Modalities Test, the Stroop Color Word Test, and the Controlled Oral Word Association Test was reported to be 23% sensitive to concussion when administered 2 days after injury. In the same study, a brief neurostatus assessment (Standardized Assessment of Concussion) administered on the sideline immediately after injury was sensitive to 80% of the injuries, but sensitivity decreased to 31% when the assessment was administered at Day 1 postinjury (22).

Recent advances in computer technology and accessibility have resulted in a shift away from traditional testing methods and toward computerized assessments. Since 2001, use of computer-based assessments has increased, and now these assessments are more widely applied than pencil-and-paper tests (9, 28). Computer programs are purported to decrease the clinician’s administration time through mass testing, improve test accuracy, and allow the sports medicine clinician to interpret test results without consulting a licensed neuropsychologist. The sensitivity of computer tests is reported to be higher than that of pencil-and-paper assessments, and the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT; ImPACT Applications, Pittsburgh, PA) program demonstrated 82% sensitivity when administered within 72 hours of injury (34). Similarly, the HeadMinder Concussion Resolution Index (CRI; HeadMinder, Inc., New York, NY) was described as being 88% sensitive to concussion in 26 high school and adult athletes with concussion who were evaluated 1 to 2 days after concussion (8).

Although the sensitivity of individual tests has been examined previously, only one study has evaluated the sensitivity of an assessment battery. The investigators, however, did not examine all methods using the same interval, and they failed to include computerized assessment techniques (22). The sensitivity of assessment tests to concussion is likely to change rapidly with regard to the expeditious recovery from injury that is often observed. Therefore, the purpose of this study was to compare the sensitivity of different concussion-assessment batteries when these tests are administered within 24 hours of an injury diagnosis.

METHODS

As part of an ongoing study on the effects of sports-related concussion, we administered preseason (baseline) concussion assessments to all university athletes who were at high risk for concussion between 1998 and 2005. In the event an athlete sustained a concussion as diagnosed by the team physician, a follow-up assessment using the same tests was administered within 24 hours (Day 1). All concussions were graded for severity based on American Academy of Neurology guidelines (1). The assessment battery included an evaluation of self-reported, concussion-related symptoms, an assessment of postural control on the NeuroCom Smart Balance Master SOT (NeuroCom International, Inc.), and a neurocognitive assessment. Each athlete signed an Institutional Review Board–approved informed consent before completing the baseline assessment.

To evaluate the sensitivity of concussion-related symptoms, we recorded the severity and/or duration of the nine items recommended by Piland et al. (30, 31): headache, nausea, balance problems, fatigue, trouble falling asleep, drowsiness, feeling “slowed down,” feeling “in a fog,” and difficulty concentrating. During the baseline and Day 1 assessments, each item was ranked from zero to six on a Likert scale, and summative scores served as representation of self-reported, concussion-related symptoms. The severity scale was anchored with “not severe at all” and “as severe as possible” statements. The duration scale was anchored with “briefly,” “sometimes,” and “always” options.

The postural control assessment was completed using the NeuroCom SOT. The SOT uses a force platform to track an athlete’s center of pressure in six different testing conditions. Test conditions include combinations of the athlete having his/her...
eyes open and closed, referencing a fixed or sway support surface, and referencing a fixed or sway visual surrounding. Sway referencing occurs in direct relation to the anterior and posterior motion of an athlete’s center of pressure. Three 20-second trials were completed for each condition to yield a total of 18 trials. A composite balance score and ratio scores (vestibular, visual, and somatosensory) correlating to each of the components of the balance mechanism were calculated from the different test conditions (27). A complete postural control assessment took approximately 15 minutes.

Three neurocognitive assessment methods were used in the study. From the fall of 1998 through spring of 2001, a trained clinician administered a neuropsychological assessment battery that included the Hopkins Verbal Learning Test (4), the Trail Making Test (33), the Symbol Digit Modalities Test (35), the Digit Span (37), and the Controlled Oral Word Association Test (3). In the fall of 2001, the pencil-and-paper assessment battery was replaced with the HeadMinder CRI. Beginning in the fall of 2004, we replaced the HeadMinder CRI with ImPACT concussion management software. During the 2004 to 2005 season, we used ImPACT version 2.1a, and in 2005 we upgraded and implemented ImPACT version 4.5.729 software.

Each of the computer-based tests consisted of multiple subtests or modules that are used to calculate output scores for clinical interpretation. The HeadMinder CRI has six tests that produce five index scores including processing speed, simple reaction time, complex reaction time, and simple and complex reaction time errors. The components of the HeadMinder CRI have been described in detail previously (8). The ImPACT system uses six modules to produce five index scores including verbal memory, visual memory, processing speed, reaction time, and impulse control. The ImPACT test has been described in detail by Iverson et al. (19). Both the HeadMinder CRI and the ImPACT system also include symptom inventories.

All baseline test administrations occurred in controlled areas free from noise and distraction and were provided under the supervision of a test administrator. Pencil-and-paper tests were given by a test administrator to a single athlete. Baseline computerized testing took place in small groups, and athletes were positioned away from others to allow them to maximize their concentration. All postconcussion assessments were completed individually in the presence of a test administrator.

Data Analysis

All symptomology, postural control, and neurocognitive functioning data were reviewed to evaluate the sensitivity of each assessment component. A significant change in concussion-related symptoms was indicated if the Day 1 summative score was 1 standard deviation greater than the baseline score. Standard deviations for symptom reports were acquired from previously reported baseline data (31). Clinically meaningful changes in postural control were indicated when any variable declined by more than 1 standard deviation from the baseline assessment. Data for the postural control calculations were obtained from baseline SOT assessments of varsity athletes at our university. A licensed neuropsychologist (SNM) interpreted any significant changes in the Day 1 pencil-and-paper assessments compared with the baseline evaluations. The criterion for cognitive impairment on the pencil-and-paper assessment battery was whether the concussed athlete showed clinically meaningful declines (more than 1 standard deviation) on two or more tests. Similar guidelines for determining impairment have been used previously (22). Significant declines in the HeadMinder CRI and ImPACT scores were interpreted based on the reliable change index score calculations embedded within the computer programs. Clinically meaningful declines were indicated on the clinical report and occurred if an athlete exceeded the 85% confidence interval on the HeadMinder CRI (7) or the 80% confidence interval on the ImPACT assessment (18). To evaluate the distribution of concussion severity by neurocognitive assessment technique (i.e., pencil and paper, HeadMinder CRI, or ImPACT test), a $\chi^2$ analysis was performed. Statistical analyses were completed using SPSS version 14.0 software (SPSS, Chicago, IL), and statistical significance was set at $P < 0.05$.

RESULTS

Seventy-five athletes who sustained a physician-diagnosed concussion between 1998 and 2005 were included in the data analysis. The dates of baseline and Day 1 testing indicate a median follow-up of 129 days. All athletes competed at the Division I varsity level, and the study included 62 men (83%) and 13 women (17%). Figure 1 shows the distribution of concussion incidence with respect to the American Academy of Neurology grading system, sport, and academic year of occurrence. The $\chi^2$ analysis indicates an equal distribution of Grade 1, 2, and 3 concussions across the neurocognitive assessment measures [$\chi^2 (4) = 3.981; P = 0.409$]. Football accounted for the greatest number of concussions during the 8 years with 59 diagnosed injuries. Women’s soccer followed with eight injuries, and then men’s basketball and cheerleading were next with three injuries each. Equestrian and softball had one injury each. The mean performance values for each of the assessment techniques are presented in Tables 1, 2, and 3.

All athletes were evaluated using a nine-item duration and/or severity symptom inventory. Twenty-one athletes were evaluated on duration only, 28 were evaluated on severity only, and 26 athletes were evaluated on both severity and duration of symptoms. A meaningful change in Day 1 summative symptom scores was noted when the duration and/or severity total exceeded the baseline total by 1 standard deviation (i.e., 5.79 and 5.15, respectfully). For duration, mean summative scores for our sample were 3.67 (±5.01) at baseline and 20.32 (±13.97) on Day 1. Mean total severity scores at baseline were 3.02 (±4.00) and 15.93 (±10.98) on Day 1. A total of 51 athletes (68.0%) showed a clinically significant increase in duration or severity on the nine-item concussion-related symptom inventory at Day 1. Twenty-four athletes (32%) did not show a clinically significant increase in either severity or duration when evaluated within 24 hours of concussion.
The NeuroCom SOT calculates a composite balance score and three ratios (somatosensory, visual, and vestibular) that correspond to the components of the balance mechanism. Using a 1-standard deviation cutoff, a change in a postural control measure was deemed clinically significant for an athlete with concussion when the score decreased by 3.71 below the baseline composite balance score, by 2.35 below the baseline somatosensory ratio score, by 3.47 below the baseline visual ratio score, or by 6.95 below the baseline vestibular ratio score. Baseline or Day 1 postural control data were missing on 12 athletes, which left us with data from 63 athletes for assessment. The numbers of athletes with concussion that were identified as impaired on each of the SOT scores are provided in Table 4. When we considered all output scores, 39 athletes (61.9%) were identified as having impaired postural control on at least one SOT variable within 24 hours of sustaining a concussion as compared with their baseline assessments. Twenty-four athletes (38.1%) showed no impairment on any postural control variables at the same time point.

Twenty-three athletes were evaluated using the pencil-and-paper battery described above, and 28 and 24 athletes were evaluated using the CRI and ImPACT tests, respectively. A review of the postconcussion neurocognitive pencil-and-paper assessments by a neuropsychologist (SNM) found the Trail Making Tests and the Symbol Digit Modalities Tests to be the most sensitive to the effects of concussion. Slightly over half of the athletes with concussion (52.2%) showed decrements on at least one of these two tests. The Digit Span Test was the least sensitive to concussion; it failed to show decrements in performance in nearly 70% of the cohort. Sensitivity results of the pencil-and-paper assessment battery are presented in Table 5.

The pencil-and-paper assessment battery as a whole revealed cognitive decrements in 10 athletes (43.5%) but failed to identify 13 athletes (56.5%) as impaired.

The incidence of impairment for each of the ImPACT test variables is presented in Table 6. The ImPACT test identified 15 athletes (62.5%) as impaired on at least one cognitive variable at the Day 1 time point. An additional four athletes (16.7%) showed a significant increase over their baseline assessments on the ImPACT symptom inventory but showed no decline on the cognitive portions of the ImPACT assessment. Overall, the ImPACT test identified significant changes in cognitive and/or symptomatic variables in 19 of the 24 athletes (79.2%). Five athletes (20.8%) showed no significant change in either cognitive variables or reported symptoms.

The HeadMinder CRI identified 22 athletes with concussion (78.6%) as cognitively impaired on one or more variables when assessed within 24 hours of injury (Table 6). An

<table>
<thead>
<tr>
<th>TABLE 1. NeuroCom Sensory Organization Test component values measured at baseline and Day 1 postinjury.</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite balance, mean (SD)</td>
<td>Somatosensory ratio, mean (SD)</td>
<td>Visual ratio, mean (SD)</td>
<td>Vestibular ratio, mean (SD)</td>
</tr>
<tr>
<td>Baseline</td>
<td>82.39 (5.70)</td>
<td>96.39 (2.96)</td>
<td>93.41 (5.13)</td>
</tr>
<tr>
<td>Day 1 postinjury</td>
<td>80.06 (8.76)</td>
<td>94.80 (4.87)</td>
<td>91.61 (8.58)</td>
</tr>
</tbody>
</table>

*SD, standard deviation.

\[N = 63\] athletes.
**TABLE 2. Values for ImPACT and Concussion Resolution Index computerized neurocognitive assessments measured at baseline and Day 1 postinjury**

<table>
<thead>
<tr>
<th></th>
<th>ImPACT componentsb</th>
<th>HeadMinder Concussion Resolution indexc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Memory composite, verbal</td>
<td>Memory composite, visual</td>
</tr>
<tr>
<td>Baseline</td>
<td>0.84 (0.11)</td>
<td>0.74 (0.16)</td>
</tr>
<tr>
<td>Day 1 postinjury</td>
<td>0.77 (0.17)</td>
<td>0.67 (0.16)</td>
</tr>
</tbody>
</table>

a ImPACT, Immediate Post-Concussion Assessment and Cognitive Testing. Values are means (standard deviations).
b N = 24 athletes.
c N = 28 athletes.

**TABLE 3. Athlete scoring on components of the pencil-and-paper test battery**

<table>
<thead>
<tr>
<th>Athlete with concussion, status</th>
<th>Hopkins Verbal Memory, Trial 1</th>
<th>Hopkins Verbal Memory, Trial 2</th>
<th>Hopkins Verbal Memory, Trial 3</th>
<th>Trail Making Test A, total time</th>
<th>Trail Making Test B, total time</th>
<th>Symbol Digit Modalities Test, total correct</th>
<th>Symbol Digit Modalities Test, total incorrect</th>
<th>Digit Span Forward Test, correct</th>
<th>Digit Span Backward Test, correct</th>
<th>Controlled Oral Word Association Test, total number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>7.65 (1.5)</td>
<td>9.74 (1.32)</td>
<td>11.04 (0.93)</td>
<td>20.20 (4.70)</td>
<td>46.15 (14.59)</td>
<td>61.78 (7.80)</td>
<td>1.90 (1.83)</td>
<td>9.26 (1.84)</td>
<td>7.13 (2.32)</td>
<td>40.35 (7.24)</td>
</tr>
<tr>
<td>Day 1 postinjury</td>
<td>7.00 (1.81)</td>
<td>9.61 (1.75)</td>
<td>10.17 (1.37)</td>
<td>23.27 (6.14)</td>
<td>50.27 (16.42)</td>
<td>57.78 (7.78)</td>
<td>0.27 (0.88)</td>
<td>8.47 (2.21)</td>
<td>7.57 (2.06)</td>
<td>40.48 (6.50)</td>
</tr>
</tbody>
</table>

Values are means (standard deviations). N = 23 athletes.

**TABLE 4. Incidence of concussion in athletes who were identified as impaired at Day 1 postinjury on the basis of the NeuroCom Sensory Organization Test**

<table>
<thead>
<tr>
<th>Athlete with concussion, status</th>
<th>Composite balance, no. (%)</th>
<th>Somatosensory ratio, no. (%)</th>
<th>Visual ratio, no. (%)</th>
<th>Vestibular ratio, no. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impaired</td>
<td>23 (36.5%)</td>
<td>23 (36.5%)</td>
<td>20 (31.7%)</td>
<td>15 (23.8%)</td>
</tr>
<tr>
<td>Not impaired</td>
<td>40 (63.5%)</td>
<td>40 (63.5%)</td>
<td>43 (68.3%)</td>
<td>48 (76.2%)</td>
</tr>
</tbody>
</table>

The total number of athletes was 63.

**TABLE 5. Incidence of concussion in athletes identified as impaired at Day 1 postinjury on each of the tests administered as part of the pencil-and-paper assessment battery**

<table>
<thead>
<tr>
<th>Athlete with concussion, status</th>
<th>Hopkins Verbal Learning Test, no. (%)</th>
<th>Trail Making Tests A and B, no. (%)</th>
<th>Symbol Digit Modalities Test, no. (%)</th>
<th>Digit Span Test, no. (%)</th>
<th>Controlled Oral Word Association Test, no. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impaired</td>
<td>9 (39.1%)</td>
<td>12 (52.2%)</td>
<td>12 (52.2%)</td>
<td>7 (30.4%)</td>
<td>8 (34.8%)</td>
</tr>
<tr>
<td>Not impaired</td>
<td>14 (60.9%)</td>
<td>11 (47.8%)</td>
<td>11 (47.8%)</td>
<td>16 (69.4%)</td>
<td>15 (65.2%)</td>
</tr>
</tbody>
</table>

The total number of athletes was 23.

Impairment was determined by a neuropsychologist making a clinical interpretation of scores.
evaluation of symptoms reported on Day 1 did not reveal any additional athletes who were not already identified as being impaired with respect to at least one cognitive variable. Six athletes (21.4%) showed no impairment on any HeadMinder CRI cognitive variable and reported no increase in symptoms beyond their baseline inventories at the Day 1 assessment.

When the athletes with concussion were evaluated on the entire battery, which included the pencil-and-paper tests, postural control assessment, and the self-reported symptom inventory, 95.7% were identified as impaired on the basis of at least one evaluative measure. When the computerized neuropsychological tests were coupled with the postural control and symptom assessments, the battery that included the ImPACT test was 91.7% sensitive to concussion. The battery that included the HeadMinder CRI was 89.3% sensitive to the effects of concussion.

**DISCUSSION**

The aim of this study is to examine the sensitivity of concussion-assessment instrumentation in three distinct cohorts. Athletes with diagnosed concussions were evaluated between 1998 and 2005 using self-reported symptoms, postural control assessment, and one of three cognitive assessment methodologies. The Day 1 postconcussion assessments show that the ImPACT (79.2%) and HeadMinder CRI (78.6%) tests are the most sensitive to the effects of concussion when we combined cognitive test performance and symptom reports. These were followed in sensitivity by concussion-related symptoms (68.0%), the postural control evaluation (61.9%), and the pencil-and-paper neurocognitive assessment (43.5%). When the complete concussion assessment battery of self-reported symptoms, postural control, and neurocognitive functioning was administered, the sensitivity ranged from 89 to 96%. The remaining 4 to 11% of the athletes showed no sign of impairment on any variable contained within the battery when it was administered within 24 hours of injury.

The ability of the ImPACT and HeadMinder CRI tests to detect decrements after concussive injury has been evaluated previously. Schatz et al. (34) reported that the ImPACT test was 81.9% sensitive to the effects of concussion when both cognitive and symptom scores were used in a study of 72 high school athletes who were evaluated within 3 days of their injuries. Our sensitivity rate was slightly lower (79.2%) when both cognitive and symptom scores were evaluated within 24 hours of injury. The cognitive assessment alone was 62.5% sensitive to concussion, and concussion-related symptoms accounted for an additional 16.7% of the cases. Higher sensitivity was expected at the Day 1 time point because the greatest cognitive decrements and highest symptom reports are typically reported closest to the time of injury (16, 23, 29). Our results suggest that the sensitivity of the ImPACT test is bolstered by the inclusion of self-reported symptoms.

The HeadMinder CRI test also uses concussion-related symptoms to establish impairment, but symptom scores on the HeadMinder CRI failed to identify any additional athletes relative to those who demonstrated impaired cognitive functioning on the test. A previous assessment of the HeadMinder CRI sensitivity by Erlanger et al. (8) showed differing results in a sample of 26 high school and adult athletes with concussion. In their sample, only 12% of the athletes were identified as impaired with the use of solely cognitive markers, but 88% were identified as impaired when self-reported symptoms and/or cognitive markers were used at the first follow-up examination. This contrasts with our findings, where 78.6% of the athletes were shown to have some cognitive impairment at the first follow-up examination.

### Table 6. Incidence of concussion in athletes identified as impaired at Day 1 postinjury by the ImPACT and HeadMinder Concussion Resolution Index

<table>
<thead>
<tr>
<th>ImPACT components</th>
<th>Memory composite verbal, n (%)</th>
<th>Memory composite, visual, n (%)</th>
<th>Visual motor speed composite, n (%)</th>
<th>Reaction time composite, n (%)</th>
<th>Impulse control composite, n (%)</th>
<th>Symptom inventory, n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impaired</td>
<td>10 (41.7%)</td>
<td>5 (20.8%)</td>
<td>5 (20.8%)</td>
<td>10 (41.7%)</td>
<td>1 (4.2%)</td>
<td>15 (62.5%)</td>
</tr>
<tr>
<td>Not impaired</td>
<td>14 (58.3%)</td>
<td>19 (79.2%)</td>
<td>19 (79.2%)</td>
<td>14 (58.3%)</td>
<td>23 (95.8%)</td>
<td>9 (37.5%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HeadMinder Concussion Resolution Index</th>
<th>Simple reaction time, n (%)</th>
<th>Complex reaction time, n (%)</th>
<th>Processing speed index, n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impaired</td>
<td>20 (71.4%)</td>
<td>20 (71.4%)</td>
<td>14 (50.0%)</td>
</tr>
<tr>
<td>Not impaired</td>
<td>8 (28.6%)</td>
<td>8 (28.6%)</td>
<td>14 (50.0%)</td>
</tr>
</tbody>
</table>

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**TABLE 6. Incidence of concussion in athletes identified as impaired at Day 1 postinjury by the ImPACT and HeadMinder Concussion Resolution Index**

(a) ImPACT, Immediate Post-Concussion Assessment and Cognitive Testing; n, number of athletes; (%), percentage of N, total number of athletes.

(b) For ImPACT study components, N = 24 athletes.

(c) Impairment was established using reliable change index calculations imbedded within the programs.

(d) For HeadMinder Concussion Resolution Index, N = 28 athletes.
The pencil-and-paper neurocognitive battery demonstrated poorer sensitivity when compared with the computerized tests (i.e., ImPACT and HeadMinder CRI tests). Less than half (43.5%) of the athletes with concussion who were evaluated in this study were considered clinically impaired based on the neuropsychologist’s interpretation of the results. Our sensitivity rate was higher than that reported by McCrea et al. (22), who identified a similar pencil-and-paper assessment battery to be 23% sensitive to concussion when administered 2 days postinjury. A differing assessment battery and an additional day of rest after the injuries may account for differences in the sensitivity. In addition, some of our athletes may have exhibited impairment on a single pencil-and-paper test, but were not considered clinically impaired unless they showed impairment on two or more tests at Day 1 postinjury. This is evidenced by higher levels of sensitivity for the Trail Making and Symbol Digit Modalities Tests compared with the overall sensitivity of the pencil-and-paper battery.

Our evaluation of concussion-related symptoms revealed that 68.0% of our athletes reported more than a 1-standard deviation increase in symptoms at Day 1 over their baseline assessments. Sensitivity of our 9-item scale was greater than that reported by McCrea et al. (22) in a sample of 34 athletes with concussion who were evaluated at the same time point. Differences in symptom inventories and techniques used to determine clinically significant change may account for the discrepancy in sensitivity findings. Unlike other concussion measurements, considerable variability exists in the items included in the self-reported concussion assessment scale. Using confirmatory factor analysis, Piland et al. (30) demonstrated that nine items fell directly into three concussion-related categories: somatic, neurobehavioral, and cognitive symptoms. The investigators found a good fit for the nine-item symptom inventory with athletes who had concussion, but they failed to report the sensitivity of the new inventory. Our results indicated greater sensitivity exists with the nine-item inventory than with the more extensive symptom scales.

The instrumented postural control assessment identified 61.9% of the sample (athletes with concussion) as impaired at the Day 1 time point. More than one-third of our sample did not show a detectable change in postural control on the basis of our cut-off values. We were unable to find any literature that identifies the sensitivity of the SOT in a similar cohort, but previous studies have used the NeuroCom SOT in evaluating postconcussion postural control. These analyses reported a significant overall decline in group mean scores when compared with the baseline assessment and a matched control group (15, 16, 29). A composite balance score change of greater than 6.83 has been suggested to represent a significant difference between individuals with concussion and normal, healthy subjects (15). Our 1 standard deviation cut-off score for a clinically meaningful change in composite balance was more liberal than this recommendation. The postural control assessment used in this study did prove to be more sensitive than the less sophisticated balance assessment that was implemented at a similar time point (22).

Our study has limitations that warrant discussion. First, considerable variability exists in the time from baseline administration to postconcussion assessment. As is common in clinical practice, our athletes were administered a single baseline assessment as an incoming athlete and up to 2.5 years may have passed before a follow-up assessment was performed. The effects of large time intervals on test sensitivity necessitate research attention. Second, the time interval between the injury and the postinjury assessment may have also influenced our findings. Presumably, some recovery may have occurred during this time, which makes it likely that sensitivity will increase if assessment is administered closer to the time of injury (22). Third, our criteria of a 1 standard deviation change from baseline-level functioning is a conservative and arbitrary cutoff that may not have identified all athletes with persisting deficits and symptoms (32). Future investigations should consider other statistical methods, such as reliable change index or standardized regression-based techniques, for the interpretation of clinical data. Finally, little is known about what influence other factors such as learning disabilities, concussion history (6), or age have on sensitivity outcomes. Some research has indicated that younger athletes recover at differing rates (10), which may influence the sensitivity of the instruments incorporated here. An extensive investigation of the sensitivity of the assessment battery among youth athletes is warranted.

When administered 1 day postinjury, the sensitivity of the self-report concussion-assessment instruments evaluated here ranged from 43 to 80%. No single test had a sensitivity sufficiently high to warrant its use in isolation. The use of multiple assessment techniques, however, increased the sensitivity to a clinically acceptable level. These findings support previous recommendations that sport-related concussion should be approached through a multifaceted assessment, and each component of the assessment process should focus on distinct aspects of an athletes’ function (12, 25). Although specific tests may vary between clinical sites, our data suggest that when measures of neurocognitive functioning, postural control, and self-reported symptoms are completed for an athlete in the postmorbid state, these values can be integrated with clinical examinations to make a diagnosis of concussion and a decision regarding the individual’s return to play (12).

REFERENCES


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COMMENTS

The authors have conducted a germane study examining the sensitivity of varying concussion assessment procedures to a relatively small sample of concussed collegiate athletes. This is the first study of its kind to generally assess the sensitivities of these assessment strategies to a cohort of concussed athletes. Thus, the authors’ findings are certainly of importance.

With this stated, there are certain weaknesses in the methodology used by the authors. First, because of the methodology of the study, the authors were not able to evaluate each athlete with all tools. In other words, the authors assessed cohorts of athletes rather than use the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), HeadMinder Concussion Resolution Index, paper-and-pencil testing, and postural stability testing with each individual athlete. Although the authors stated that there were no significant differences in grades of concussion between groups, this carries little merit in determining whether one injury is more severe than another. As has been shown by many researchers, the grading systems have little prognostic significance and are arbitrary in nature; thus, using that scale to determine severity of injury may be misguided. In short, within the context of a small sample size, it is entirely possible that more severe concussions may have occurred for one testing methodology versus another. Such results could sway findings to make one test battery look far less sensitive than another. Again, with a small sample size and a lack of methodological control, replication of these findings are certainly indicated.

SENSITIVITY OF THE CONCUSSION ASSESSMENT BATTERY
As the authors state, prospective research using all tools with a much larger sample size could help circumvent these methodological concerns.

Furthermore, the authors failed to use a control group; thus, the issue of specificity of the test batteries cannot be properly assessed. It should be noted that sensitivity and specificity of both the ImPACT and HeadMinder computerized testing programs have been delineated in previous studies.

Within the context of the methodological weaknesses that occur in analysis, it is not surprising to see the increased sensitivity of the computerized testing versus the pencil-and-paper test batteries. Not only does computerized testing seem much more sensitive because it can measure processing speed and reaction time; it also offers relative ease in administration, repeatability, convenience, standardization of test administration, and the ability to easily communicate test results. These aspects add value to computerized assessment and evaluation of athletes. It is clear that progress has been made in the development of objective, census-specific, reliable, and valid tools for properly assessing and quantifying recovery from sports-related concussion. Considerable data have been published recently revealing the need for objective assessment tools that augment clinical evaluation. Computerized neurocognitive testing should be considered as a tool that helps to augment a careful symptom evaluation that occurs when the subject is at rest and undergoing physical exertion. As the field of concussion management rapidly evolves, there seems to be a burgeoning consensus that three specific criteria must be met before an athlete can be allowed to return to play after a diagnosed cerebral concussion. That is, the athlete should be 1) symptom free at rest, 2) symptom free with exertion, and 3) demonstrating tight neurocognitive function. With the results of the current study, it would seem there are likely differences in how one defines intact neurocognitive function, and computerized neurocognitive test batteries seem to be the most appropriate tool to confidently determine this issue.

Michael Collins
Neuropsychologist
Joseph C. Maroon
Pittsburgh, Pennsylvania

This paper nicely illustrates several developments in the diagnosis of sports-related concussion. Computerized testing of athletes with concussion is here to stay, and ongoing investigations continue to fine-tune the usefulness of these computerized assessment programs. In addition, as the authors indicate in the Discussion, use of grading scales for concussion is being questioned because of the lack of evidence to support those scales. Such recommendations are a direct result of high-quality research into concussion.

Alex B. Valadka
Houston, Texas

In an effort to analyze the sensitivities of different methods of concussion assessment, Broglio et al. measured the commonly used testing modalities and their performance in sports concussion. In 75 collegiate athletes studied within 24 hours of their concussions, the authors compared computerized neuropsychological tests to self-reported symptom lists, postural control evaluations, and brief pencil-and-paper neurocognitive evaluations. Their findings showed that in the above order, the sensitivity of these concussion-measurement techniques accurately identified the injured athletes. The complete assessment battery yielded a sensitivity of nearly 90%.

Although this study does have limitations, which the authors have noted, their results indicate that a multifaceted approach using different measures of brain functionality is advantageous for making correct diagnosis and management decisions. At present, notwithstanding the importance of neuroimaging studies, the documentation of symptomatic athletes usually relies on neurocognitive testing, postural assessment, and self-reported symptoms and their correlation with the physical and neurological examinations. This research analyzes the sensitivity of these separate neurocognitive assessment instruments. Given the importance of accurate detection of the concussed athlete, we continue to realize that a multimodality appraisal is necessary.

Julian E. Bailes
Morgantown, West Virginia

This paper addresses several extremely important and timely issues. The results and conclusions of this study are preliminary and need to be replicated, but in the interim, they serve to highlight factors fundamental to concussion-management programs.

First, the study includes a comparison of two computerized neuropsychological assessment batteries purported to be useful for concussion management. That both batteries performed well is an important finding. However, when combined with the relatively poor performance of the pencil-and-paper measures, a more interesting possibility is suggested: Are well-designed computerized reaction-time-based neurocognitive batteries substantially different from one another? Stated alternately, are computerized batteries superior because they use “special” paradigms, or are they superior because computerization permits measurement of reaction time at the millisecond level far better than is possible with pencil-and-paper tests and a stopwatch?

Second, not surprisingly, a multifactorial approach to concussion management surpassed even the high sensitivity of the computerized measures. We all know that there is more to concussion than cognitive impairment, but it is helpful to have a study quantify the additional contributions of these factors.

Although more studies of this type clearly are needed, I applaud the authors for raising the “heresy” that different well-designed computerized cognitive batteries are more alike than they are different.

Joseph Bleiberg
Neuropsychologist
Washington, DC