Examining Recovery Trajectories After Sport-Related Concussion With a Multimodal Clinical Assessment Approach

Luke C. Henry, PhD*
R.J. Elbin, PhD‡
Michael W. Collins, PhD*
Gregory Marchetti, PT, PhD§
Anthony P. Kontos, PhD*

*Department of Orthopaedic Surgery/UPMC Sports Medicine Concussion Program, University of Pittsburgh, Pittsburgh, Pennsylvania; ‡Department of Health, Human Performance and Recreation/Office for Sport Concussion Research, University of Arkansas, Fayetteville, Arkansas; §Department of Physical Therapy, Rangos School of Health Sciences, Duquesne University, Pittsburgh, Pennsylvania

Correspondence:
Luke C. Henry, PhD,
3200 S Water St,
Pittsburgh, PA 15203.
E-mail: lch32@pitt.edu

Received, April 7, 2015.
Accepted, August 20, 2015.
Published Online, October 6, 2015.

BACKGROUND: Previous research estimates that the majority of athletes with sport-related concussion (SRC) will recover between 7 and 10 days after injury. This short temporal window of recovery is based predominately on symptom resolution and cognitive improvement and does not accurately reflect recent advances in the clinical assessment model.

OBJECTIVE: To characterize SRC recovery at 1-week postinjury time intervals on symptom, neurocognitive, and vestibular-oculomotor outcomes and to examine sex differences in SRC recovery time.

METHODS: A prospective, repeated-measures design was used to examine the temporal resolution of neurocognitive, symptom, and vestibular-oculomotor impairment in 66 subjects (age, 16.5 ± 1.9 years; range, 14-23 years; 64% male) with SRC.

RESULTS: Recovery time across all outcomes was between 21 and 28 days after SRC for most athletes. Symptoms demonstrated the greatest improvement in the first 2 weeks, although neurocognitive impairment lingered across various domains up to 28 days after SRC. Vestibular-oculomotor decrements also resolved between 1 and 3 weeks after injury. There were no sex differences in neurocognitive recovery. Male subjects were more likely to be asymptomatic by the fourth week and reported less vestibular-oculomotor impairment than female subjects at weeks 1 and 2.

CONCLUSION: When the recommended "comprehensive" approach is used for concussion assessment, recovery time for SRC is approximately 3 to 4 weeks, which is longer than the commonly reported 7 to 14 days. Sports medicine clinicians should use a variety of complementing assessment tools to capture the heterogeneity of SRC.

KEY WORDS: Comprehensive assessment, Recovery time, Sport-related concussion

Neurosurgery 78:232–241, 2016 DOI: 10.1227/NEU.0000000000001041 www.neurosurgery-online.com

Sport-related concussions (SRCs) are purported to have a relatively short recovery time, with >90% of injured athletes returning to play within 7 to 14 days of injury.[1,2] However, a growing body of literature suggests that recovery may be longer for some athletes as a result of demographic differences (eg, younger subjects, female subjects, those with concussion history) or the heterogeneous nature of this injury.[3-6] The current literature is also wrought with methodological inconsistencies, including how symptom resolution and clinical recovery are defined.[7] The majority of studies examining SRC recovery included male football players and examined only symptom and cognitive recovery outcomes, for example,[8-11] limiting the generalizability of these findings. Additional research on SRC recovery trajectories across multiple domains, including assessments of symptoms, neurocognitive testing, balance, and vestibular and oculomotor outcomes in more diverse samples, is warranted.

ABBREVIATIONS: **BESS,** Balance Error Scoring System; **CI,** confidence interval; **DHI,** Dizziness Handicap Inventory; **ES,** effect size; **ImPACT,** Immediate Post-Concussion Assessment and Cognitive Test; **PCSS,** Post-Concussion Symptom Scale; **SAC,** Standard Assessment of Concussion; **SRC,** sport-related concussion

Postconcussion symptom reporting, although limited by self-report, remains an important clinical marker of recovery and readiness for return to play on successful completion of recommended return-to-play exertional protocols.[1,2,12] The literature documenting the time to symptom resolution is disparate; some studies report alleviation within 5 to 10 days,[10,11,13-16] whereas others have documented postconcussion symptoms beyond 7 to 14 days.[3,4,8,17] These inconsistencies in symptom recovery are attributable in part to how symptom resolution was determined. Some studies[10,11,14,16] defined symptom resolution (ie, asymptomatic status) by statistically comparing symptoms between concussed athletes and their baseline or nonconcussed control subjects, whereas other studies defined recovery as the date of medical clearance.[3,9] Symptom reporting is noted in the context of clinical examination, balance assessment, and neurocognitive testing and throughout physical exertion return-to-play protocols as a means of gauging overall symptom presentation but also specific to different assessments that may elicit symptoms within more specific parameters.

The subjectivity of self-reported symptoms underscores the importance of using more objective evaluations such as those afforded by neuropsychological assessment.[1,12] Some studies report that neurocognitive impairment resolves within 14 days of injury,[10,11,14,16,18] whereas other researchers have documented longer neurocognitive recovery trajectories lasting up to 21 days after injury.[8,19,20] Methodological differences such as the type of tests used (eg, paper-and-pencil vs computer-based tests) and when the tests are administered after SRC likely account for the wide range of reported recovery times for cognitive function.

Several studies examining recovery after SRC have used measures designed to assess the immediate (ie, sideline) and acute (ie, 1-3 days after injury) effects of SRC well past these time frames. McCrea et al[10,11] used the Standard Assessment of Concussion (SAC) to assess athletes within 2 days and up to 1 week after injury. At 1 to 2 days after injury, concussed athletes performed more poorly than their nonconcussed counterparts, but they were equivalent at 1 week after injury. Similar findings using the SAC have been reported in other studies,[10,11,14,16] and researchers have concluded that the SAC lacks sensitivity in detecting cognitive impairment beyond the acute time period after SRC.[7] In addition to the SAC, the Balance Error Scoring System (BESS) has been used to measure SRC recovery,[10,11,14,16] and researchers have reported that balance impairment resolves within 7 days of SRC in >90% of cases.[7,21] Similar to the SAC, researchers report that the BESS lacks sensitivity beyond the first 3 days[22-24] after SRC and that this measure is subject to practice and learning effects.[25,26]

Clinical balance measures such as the BESS focus on postural stability, which involves the vestibulospinal system. Recent clinical research findings support the use of vestibular and oculomotor measures as part of a comprehensive assessment of SRC.[27,28] However, little is known about the recovery trajectory of vestibular and oculomotor outcomes and how they compare with symptoms and neurocognitive outcomes because they have not yet been assessed with regard to SRC recovery.

Although recent consensus articles did not list sex as a modifying factor for SRC,[1] sex differences on the clinical presentation of SRC have been documented in several studies.[29,30] Specifically, concussed female patients have demonstrated greater symptoms and lower neurocognitive performance compared with concussed male patients.[31-33] Although these data provide clinical insight into the presentation of concussion between male and female patients, no study to date has directly compared the recovery rates among male and female patients across multiple clinical domains (eg, symptoms, neurocognitive, balance, vestibular, oculomotor).[14,30] Comparing and documenting the multimodal recovery from SRC between sexes are warranted and would further inform the clinical management of SRC for male and female athletes.

The primary purpose of the present study was to characterize recovery at 1-week postinjury time intervals during the first month after SRC using a comprehensive concussion assessment that included symptoms, neurocognitive, and vestibular-oculomotor outcomes. We expected that recovery curves would demonstrate significant improvement from the 1- to 2-week assessment and plateau (ie, recovery) around the 3- to 4-week postinjury time points. A secondary purpose of the study was to examine the effect of sex on recovery time. We expected that female patients would take longer to recover than male patients across each domain.

METHODS

Design and Participants

A prospective, repeated-measures design was used for this study. A total of 66 subjects met the inclusion/exclusion criteria and were initially enrolled in the protocol. All participants were between 14 and 22 years of age and had suffered an SRC within 7 days of initial assessment. Exclusion criteria included any 1 or more of the following: history of special education; history of neurological or psychiatric disorders; previous moderate to severe traumatic brain injury (Glasgow Coma Scale score <13); previous brain surgery; current use of central nervous system–affecting medications; history of ≥3 concussions; or previous concussion within the past 6 months. Participants with a history of migraine were eligible for participation. Only 3 male subjects reported a history of migraine and were included in the present analyses. After enrollment, 17% (n = 11) had incomplete data, missing the third- and/or fourth-week assessments. These subjects were included in analyses in which data were complete. In total, 55 of 66 subjects (83%) completed the study for all time points. There were a total of 42 male subjects (63.6%) and 24 female subjects (36.4%) in the study. Table 1 provides a summary of the demographic characteristics for the sample.

Measures

Neurocognitive Performance

The Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) is a computerized neurocognitive battery composed of 3 sections: a demographic/health history questionnaire, the 22-item Post-Concussion Symptom Scale (PCSS; see below), and 6 neurocognitive test modules covering memory, attention, learning, processing speed, and reaction time. The 6 neurocognitive modules comprise 4 composite scores for verbal and visual memory (percent correct), visual motor processing speed (with higher scores indicating better performance), and reaction time (seconds). Reliability data for the ImPACT are reported elsewhere.[34]

TABLE 1. Subject Characteristics at the Time of Injury by Sex With Comparisons (χ^2 Except When Indicated)

	Male (n = 42)	Female (n = 24)	*P* Value
Age, mean ± SD, y	16.5 ± 1.8	16.4 ± 2.1	.88[a]
Disorientation, n (%)	25 (60)	12 (50)	.39
Anterograde amnesia, n (%)	11 (26)	4 (17)	.37
Retrograde amnesia, n (%)	4 (10)	3 (13)	.70[b]
Loss of consciousness, n (%)	6 (14)	3 (13)	> .99[b]
Signs present, n (%)	31 (74)	12 (50)	.05

[a]Independent-samples *t* test.
[b]Fisher exact-probability test.

Postconcussion Symptoms

The PCSS is a 22-item symptom report covering physical (eg, headaches, dizziness), cognitive (eg, mental fogginess, memory problems), sleep-related (eg, fatigue, change in sleep patterns), and affective (eg, increased emotionality, irritability, anxiety) symptoms commonly reported after concussive injuries. Each symptom is rated on a 7-point Likert scale ranging from 0 (not experiencing this symptom) to 6 (severe). The PCSS, which is embedded at the beginning of the ImPACT battery, is a widely used and validated tool to assess postconcussion symptoms.[35-37]

Dizziness and Vestibular-Oculomotor Performance

A brief interview and clinical examination were used to assess vestibular symptoms and impairment, including dizziness, imbalance, and oculomotor components. The interview section contains 8 questions adapted from the Dizziness Handicap Inventory (DHI).[38] This measure is made up of items assessing general dizziness and specific items inquiring about when/where dizziness occurs (ie, dizziness when reading, dizziness in wide open spaces). The items are rated on a 7-point Likert scale (0 = none, 6 = severe). This modified DHI was used to calculate a total dizziness score reflected by participants' interview responses to the 8 DHI questions (Table 2). Researchers and clinicians specializing in vestibular disorders and concussion developed the clinical examination.[28] The vestibular-oculomotor score is made up of participants' responses to screening tests in a recently developed clinical tool used to screen concussion patients who might benefit from more thorough examination and subsequent referral for vestibular or oculomotor therapies.[28] This screening tool is described more thoroughly by Mucha et al.[28] The vestibular-oculomotor examination consists of assessments of symptoms after the performance of smooth pursuits, horizontal and vertical saccadic eye movements, vertical and horizontal gaze stability, near-point convergence, vestibular-ocular reflex, and visual-motion sensitivity (Table 3). All measures from the aforementioned screening test[28] were included in the present study except near-point convergence.

Procedures

The present study received Institutional Review Board Approval before any research activities. The researchers informed participants about the study, screened participants for inclusion/exclusion criteria, and obtained written informed consent (adult/parent) for all participants and assent from child participants when applicable. Participants completed the ImPACT and PCSS, followed by the DHI and vestibular-oculomotor measures. Researchers conducted the testing individually with each participant in a private laboratory testing room. The tests required approximately 1 hour total at each test session. Participants completed a total of 4 test sessions at 7- to 10-day postinjury time intervals.

Data Analysis

Subject demographic characteristics and outcome measures (neurocognitive composite scores, total symptom scores, dizziness, and vestibular-oculomotor responses) were described within 1 week of SRC and at subsequent 1-week postinjury intervals over 4 weeks. Sex group differences were estimated with contingency table analysis (χ^2 or Fisher exact test) and 2-sample *t* test for age. A series of 2 (sex) × 4 (time: 1, 2, 3, and 4 weeks after SRC) repeated-measures ANOVAs were conducted for neurocognitive composite scores (verbal and visual memory, visual processing speed, and reaction time), total symptom score, and dizziness and vestibular-oculomotor scores. In addition, the likelihood of becoming symptom free at each time point was estimated with a Cox proportional hazards model with sex as a between-group factor. Within-group changes between time points and between-group differences resulting from sex were determined to be significant at the $P < .05$ level with the use of a Bonferroni correction for multiple comparisons. All statistical analyses were conducted by a statistician (G.M.) who was blinded to all hypotheses.

TABLE 2. Modified Dizziness Handicap Inventory[a]

	During the Past Week Have You Experienced	None	Mild		Moderate		Severe	
1	Dizziness? (if no, mark 0 for all other questions)	0	1	2	3	4	5	6
2	Dizziness when looking up?	0	1	2	3	4	5	6
3	Dizziness when walking down aisles, hallways, etc?	0	1	2	3	4	5	6
4	Dizziness when turning over, getting out of bed, or when lying down?	0	1	2	3	4	5	6
5	Dizziness when reading?	0	1	2	3	4	5	6
6	Dizziness during quick head movements?	0	1	2	3	4	5	6
7	Dizziness when bending over?	0	1	2	3	4	5	6
8	Dizziness in open spaces?	0	1	2	3	4	5	6

[a]Participants responded verbally to each question and answers were recorded by the clinician. This Likert scale is identical to that used in the Post-Concussion Symptom Scale.

TABLE 3. Modified Vestibular-Ocular Motor Screening Description[a]

Component	Targeted Functional Ability
Smooth pursuits	Ability to follow a slowly moving target
Saccades-horizontal, saccades-vertical	Ability of the eyes to move between targets without head movement in each directional plane
Vestibular-ocular reflex, horizontal; vestibular-ocular reflex, vertical	Ability to stabilize vision during head movement in each directional plane
Visual motion sensitivity test	Ability to inhibit vestibular-induced eye movements using vision and motion sensitivity

[a]Before beginning the screening test, participants rate headache, dizziness, nausea, and mental fogginess on a 6-point Likert scale in a fashion similar to the Post-Concussion Symptom Scale. After each component, participants provide a rating for each of the 4 symptoms. The targeted function is described in the table for each component of the screening.

RESULTS

Demographics

Sixty-six postconcussive subjects (mean age, 16.5 ± 1.9 years; range, 14-22 years; 64% male) received evaluation at week 1 after concussion. Sixty and 55 subjects were subsequently evaluated at weeks 3 and 4 after concussion, respectively. Participants sustained SRCs across a variety of sports: basketball, n = 4; cheerleading, n = 4; skiing/snowboarding, n = 2; field hockey, n = 1; football, n = 16; hockey, n = 10; lacrosse, n = 5; rugby, n = 1; soccer, n = 13; softball, n = 6; volleyball, n = 3; and wrestling, n = 2. By 3 weeks after injury, six subjects were lost to follow-up, and an additional 5 were lost by week 4. Female and male subjects did not differ in age or in number of associated signs/symptoms at time of injury (Table 1). As a matter of clinical treatment, all subjects were given academic accommodations based on his/her level of symptom report and neurocognitive impairment, consistent with the protocol described by Sady et al.[39] Furthermore, return-to-activity recommendations followed a commonly used graded exertion protocol.[40,41] All repeated-measures analyses were tested for the proportionality of the error covariance matrix. Degrees of freedom were adjusted with the use of a Greenhouse-Geisser correction for any comparison not meeting the proportionality assumption.

Total Symptoms

Total symptom scores demonstrated the greatest change across the time period of the study ($F_{2,82}$ = 53.40; $P < .001$; effect size [ES] = 1.14). Thirty subjects (45.5% of the total sample, 54.4% of the sample remaining at week 4) were symptom free by 4 weeks after injury. Sex-adjusted mean total symptom scores were as follows: week 1 = 32.9 (95% confidence interval [CI], 27.3-38.5), week 2 = 17.2 (95% CI, 13.0-21.4), week 3 = 11.2 (95% CI, 7.6-14.7), and week 4 = 9.5 (95% CI, 5.7-13.2). Significant improvements in total symptom scores were supported between each postinjury time point ($P < .001$). A significant between-group effect of sex was evident for the total symptom score ($F_{1,53}$ = 14.03; $P < .001$; ES = 0.21). Mean total symptom scores by 4 weeks after injury were 2.8 ± 5.8 and 16.2 ± 21.2 for male and female subjects, respectively (Figure 1A). Male subjects had significantly lower total symptom scores than female subjects in weeks 2 (P = .002), 3 (P = .01), and 4 (P = .01) after concussion. Results from a Cox proportional hazard function model demonstrated that male subjects were more likely than female subjects to be symptom free within 4 weeks after injury (hazard ratio = 2.48; 95% CI, 1.29-4.75; $P < .006$; Figure 1B).

Neurocognitive

Descriptive statistics for neurocognitive and oculomotor symptom scores for all subjects across weeks 1 to 4 are presented in Table 4. Significant within-group improvement was seen between postconcussion weeks 1 and 4 in verbal memory scores ($F_{2,129}$ = 4.71; P = .007; ES = 0.42; Figure 2A). Verbal memory scores significantly improved between weeks 1 and 4 (Bonferroni P = .02) with all other between-week comparisons being nonsignificant. Visual memory scores improved across 4 weeks after injury ($F_{3,143}$ = 5.39; P = .002; ES = 0.38; Figure 2B). Significant changes were evident between weeks 1 and 3 (Bonferroni P = .04) and weeks 2 and 3 (Bonferroni P = .02), with no significant differences between weeks 3 and 4. Visual motor speed scores improved significantly ($F_{2,119}$ = 10.73; $P < .001$; ES = 0.58) across 4 weeks after injury, with significant changes found between weeks 1 and 3, weeks 1 and 4 (all Bonferroni $P < .004$), weeks 2 and 3, and weeks 2 and 4 (all Bonferroni $P < .02$), suggesting gradual improvement between weeks 1 and 3 and a plateau between weeks 3 and 4 (Figure 2C). Reaction time demonstrated significant improvement across post-injury weeks 1 to 4 ($F_{2,103}$ = 3.20; P = .046; ES = 0.28), with no significant individual time point differences (Figure 2D). There was no significant effect of sex across 4 weeks of follow-up on any of the neurocognitive scores.

Vestibular-Oculomotor

Mean modified dizziness scores decreased significantly after injury ($F_{2,73}$ = 29.26; $P < .001$; ES = 0.96), with significant post hoc changes observed between weeks 1 and 2, weeks 1 and 3, weeks 1 and 4 (all $P < .001$ with Bonferroni correction), and weeks 2 and 4 ($P < .01$; Figure 1C). A between-group effect of sex was observed ($F_{1,48}$ = 8.07; P = .007; ES = 0.56), with male subjects exhibiting lower overall mean dizziness scores by week 4. Post hoc individual time point comparisons demonstrated significantly lower mean dizziness scores in male subjects

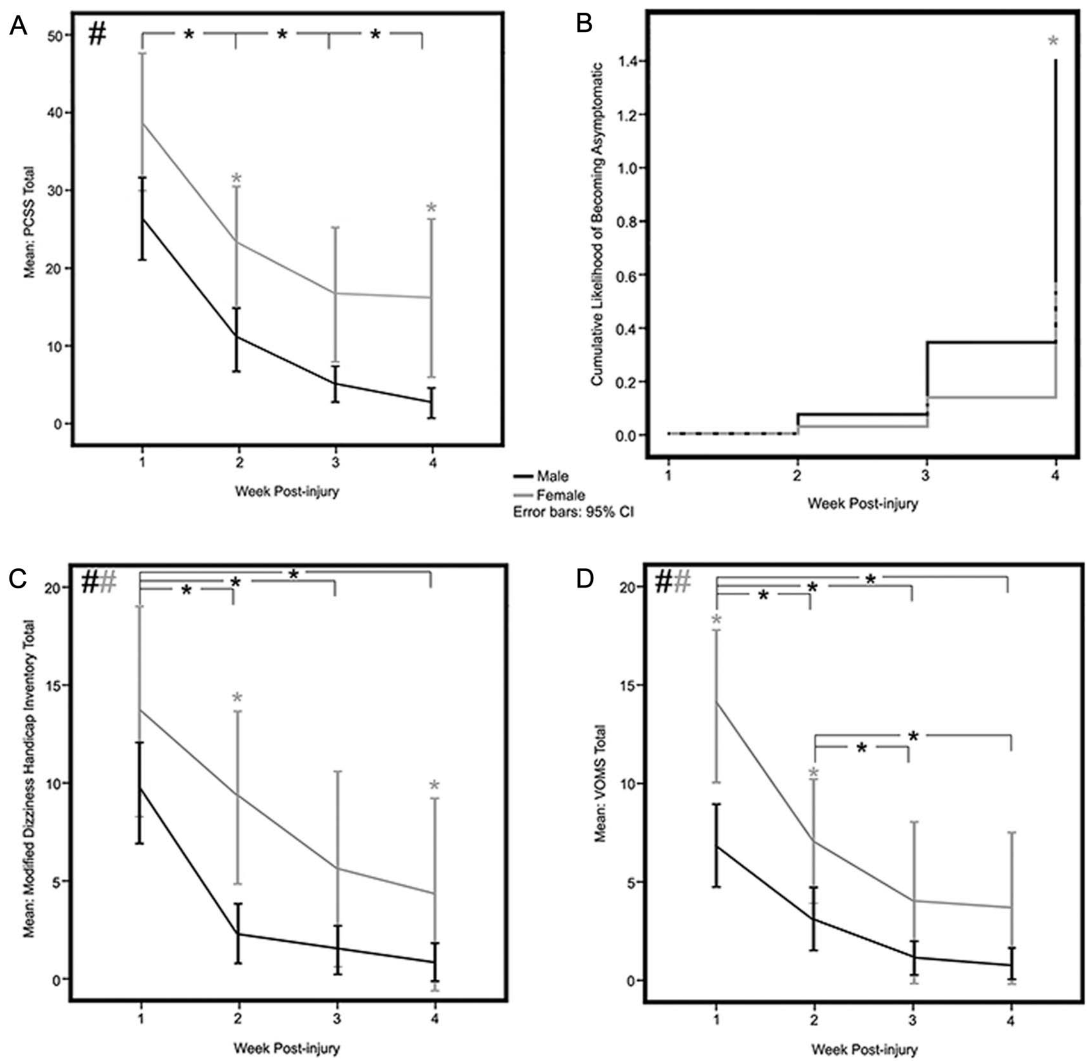

FIGURE 1. *Subjective symptom measures. Representation of mean Post-Concussion Symptom Scale (PCSS) over 4 weeks after injury (***A***); likelihood of becoming symptom free with the use of a Cox proportional hazard model (***B***); mean dizziness symptoms reported with the use of a modified Dizziness Handicap Inventory (DHI) over 4 weeks after injury (***C***); and mean reported symptom provocation using a vestibular-oculomotor screening (VOMS) examination (***D***). Self-reported symptoms diminished significantly over the 4 weeks, with individual week-to-week comparisons significant between weeks 1 and 2, 2 and 3, and 3 and 4 (***A***). The Cox proportional hazard model (***B***) shows that male patients are significantly more likely than female patients to report being symptom free by week 4 after injury. Reported dizziness also diminished significantly over the 4 weeks, with significant differences from weeks 1 to 2, 1 to 3, and 2 to 3 (***C***). There was also an overall significant effect of sex, with female patients reporting more dizziness, with significant differences at weeks 2 and 4 (***C***). Provoked reported symptoms on the VOMS showed a similar overall diminution over the 4 weeks, with significant differences from weeks 1 to 2, 1 to 3, and 1 to 4 and weeks 2 to 3 and 2 to 4 (***D***). There was also an overall significant effect of sex with female patients reporting greater symptom provocation, with significant differences at weeks 1 and 2 (***D***). Black # depicts an overall change across the 4 postinjury weeks; black * depicts significant effects between specified weeks; gray # represents an overall significant effect of sex; and gray * depicts significant sex differences at the specified time point. CI, confidence interval.*

(2.06; 95% CI, 0-4.48) than in female subjects (8.89; 95% CI, 5.66-12.12) at week 2 after injury (Figure 1C).

Vestibular-oculomotor symptom scores decreased by week 4 after injury ($F_{2,97}$ = 35.91; $P < .001$; ES = 0.98), with significant declines from week 1 to weeks 2 through 4 ($P < .001$) and from week 2 through weeks 3 and 4 ($P < .002$) after Bonferroni correction for multiple comparisons (Figure 1D). A between-group effect resulting from sex was observed in vestibular-oculomotor

TABLE 4. Outcome Measure Values at 1 to 4 Weeks After Concussion[a]

	Week 1 (n = 66)	Week 2 (n = 66)	Week 3 (n = 60)	Week 4 (n = 55)	Within-Group Effect Significance[b] (n = 55)
Verbal memory	78.7 ± 14.6	82.2 ± 13.4	84.7 ± 11.6	86.0 ± 13.0	$F_{2,129}$ = 4.71, P = .007
Visual memory	66.8 ± 13.9	68.7 ± 16.9	73.7 ± 13.9	73.5 ± 14.1	$F_{3,143}$ = 5.39, P = .002
Visual motor speed	36 ± 8.4	38.7 ± 8.0	40.7 ± 7.9	40.9 ± 8.0	$F_{2,119}$ = 10.73, $P < .001$
Reaction time	0.64 ± 0.15	0.60 ± 0.11	0.60 ± 0.11	0.59 ± 0.10	$F_{2,103}$ = 3.20, P = .046
Postconcussion symptom score	30.9 ± 19.3	15.1 ± 16.1	8.9 ± 13.2	7.4 ± 14.6	$F_{2,87}$ = 53.40, $P < .001$
Symptom free, n (%)[c]	1 (1.5)	10 (15.2)	22 (36.7)	30 (45.5)	N/A
Dizziness interview score	9.5 ± 8.2, n = 61	4.6 ± 6.3, n = 62	2.1 ± 5.5, n = 56	1.8 ± 5.4, n = 54	$F_{2,82}$ = 29.97, $P < .001$, n = 48
Vestibular-oculomotor symptom score	11.0 ± 9.9, n = 61	5.0 ± 8.1, n = 63	3.0 ± 7.4, n = 58	2.1 ± 6.9, n = 54	$F_{2,73}$ = 29.26, $P < .001$, n = 50

[a]Values are mean ± SD of all outcome measures at each time point except where indicated. Repeated-measures analysis of variance *F* and *P* values are reported for each.
[b]Repeated-measures analysis of variance.
[c]Impact Symptom Score = 0.

symptom scores ($F_{1,60}$ = 11.59; P = .001; ES = 0.75), with male subjects displaying lower overall mean scores compared with female subjects by 4 weeks. Post hoc comparisons showed that male subjects had lower mean vestibular-oculomotor symptom scores at week 1 (male subjects, 14.47; 95% CI, 9.41-19.54; female subjects, 27.0; 95% CI, 20.17-33.87) and week 2 (male subjects, 4.8; 95% CI, 0.82-8.78; female subjects, 16.1; 95% CI, 10.81-21.55). Differences at weeks 3 and 4 were not significant.

DISCUSSION

The present study reexamines SRC recovery trajectories in a mixed-sex cohort of adolescent and young adult athletes using multiple outcome recovery measures. Recovery outcomes for most athletes were between 21 and 28 days, which is longer than the purported time frame of 7 to 14 days.[11,14] Specifically, symptoms improved from week 1 to 2 but slowed thereafter. Sex does not play a role in initial symptom severity, but beginning in week 2, male subjects showed a sharper reduction in symptoms than female subjects. Neurocognitive recovery is highly heterogeneous, with different cognitive domains recovering at different rates, taking up to 28 days to show recovery across all domains. There were no sex differences in neurocognitive recovery. Showing steadier rates of recovery, both dizziness and vestibular-oculomotor function improved between weeks 1 and 3, plateauing thereafter. There was a clear sex difference in these measures, with male subjects recovering more quickly than female subjects. Overall, the results indicate a heterogeneous pattern of recovery across domains, underscoring the importance of multiple measures and assessments across time to ensure recovery.

Self-reported symptoms resolved in a linear recovery pattern, improving each week from 1 to 4 weeks after injury. Sex played a significant role in symptom reporting in general and across dizziness and vestibular-oculomotor measures. For both male and female subjects, symptoms decreased significantly from weeks 1 to 2, with marginal means from each sex not showing significant differences thereafter. However, male subjects reported significantly lower symptom totals relative to female subjects from weeks 2 to 4. Male subjects were also significantly more likely than female subjects to be asymptomatic by the fourth week. Despite the associated pitfalls, self-reported symptoms remain an important factor in monitoring and managing recovery from SRC. The results of the present study indicate steady symptom reduction in the first 3 weeks after injury, suggesting that nearly half (45.5%) of the athletes were recovered at this time point. By 4 weeks after injury, 56% were symptom free, with an even larger percentage (67%) being minimally symptomatic (ie, total symptom score ≤4). The present findings are considerably more conservative than many of the previously reported findings[10,14,16,18,42] in which a higher percentage of athletes were deemed recovered primarily on the basis of symptom reports. We chose a symptom total of zero to mean full resolution, whereas the aforementioned studies used a group-based statistical approach (either regression or comparison with a control group). The approach taken in the present study is statistical, but instead of using regression or comparison with a control group, we chose to look at the probability of being symptom free and thus have a more rigid definition of recovery (ie, PCSS total = 0), which better accounts for the trajectory of an individual subject within the group.

With regard to neurocognitive recovery in the present study, there was variability across cognitive domains. Athletes' recovery on visual memory, visual motor speed, and reaction time composites demonstrated significant linear recovery from week 1 through 3 but plateaued thereafter. In contrast, verbal memory recovery did not demonstrate significant improvement until week 4. The improvements in verbal memory performance from weeks 1 to 2 and weeks 2 to 3 were incremental and not significant, demonstrating a slower, more gradual recovery trajectory. The discrepancies in cognitive recovery reflect a domain-specific pattern of cognitive recovery, supporting the idea that any neurocognitive assessment for SRC must assess more than a single domain. Overall, in this sample, athletes required 4 weeks to demonstrate significant neurocognitive recovery as measured

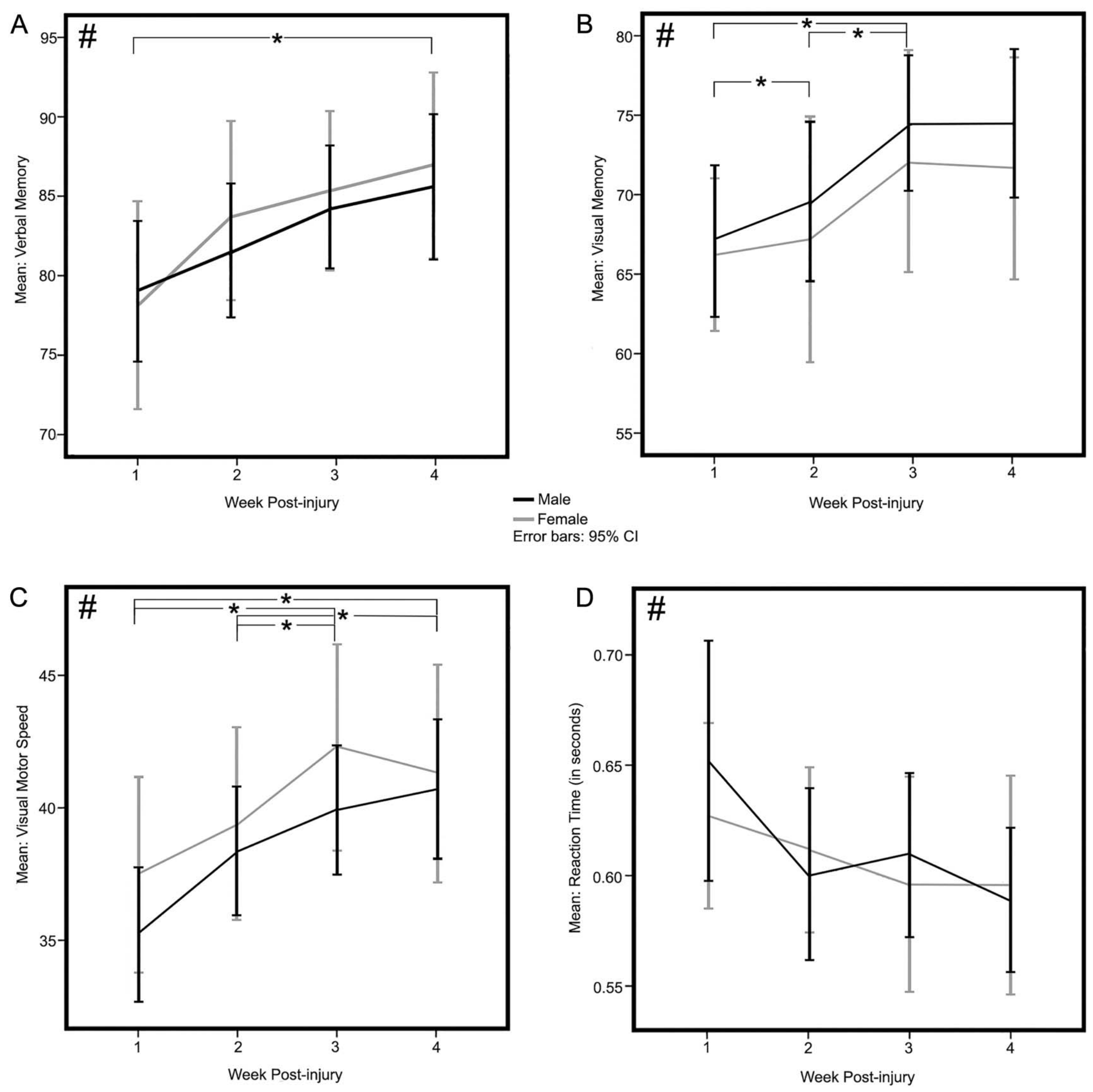

FIGURE 2. *Neurocognitive measures from the Immediate Post-Concussion and Cognitive Test (ImPACT). Representation of the mean performances across the 4 clinical composite scores including verbal memory (A), visual memory (B), visual motor speed (C), and reaction time (D). Verbal memory scores improve across the 4 postinjury weeks incrementally, with significant week-to-week differences apparent between weeks 1 and 4 only (A). Visual memory scores also improve across the 4 postinjury weeks, with significant week-to-week differences from weeks 1 to 2, 1 to 3, and 2 to 3 (B). Visual motor speed improves across the 4 postinjury weeks, with significant week-to-week differences apparent between weeks 1 and 3, 1 and 4, and 2 and 4 (C). Reaction time improves significantly over the 4 postinjury weeks, but no single week-to-week comparisons are significant (D). Black # depicts an overall change across the 4 postinjury weeks; black * depicts significant effects between specified weeks. CI, confidence interval.*

with ImPACT. There were no significant between-sex differences on neurocognitive measures. The present results are consistent with previous research that reported similar neurocognitive findings.[8,19,20] These studies share several features with the present study, including mixed-sex samples (with exception of the Lau et al[8] study, which used a male-only sample) and an average participant age of 16 years. The present findings are in contrast to studies showing shorter recovery times, which included older samples of primarily college athletes in mostly male[14] or exclusively male samples.[10,16] Furthermore, these previous studies used either sideline assessment measures (eg, SAC, BESS) along with paper-and-pencil–based neuropsychological or computerized neurocognitive tests that may have limited utility beyond 10 days after injury.[43] In contrast, the studies, including the current work, that demonstrated longer recovery trajectories after SRC all used computerized testing (ie, ImPACT). The longer recovery times for cognitive outcomes supported in the present and previous studies may reflect the more sensitive nature of computerized neurocognitive tests to detect the subtle effects of this injury. Although some researchers and clinicians are critical of computerized neurocognitive tests,[44-46] there is growing empirical evidence supporting the sensitivity of such tests.[47-49] Therefore, selecting measures that sensitively and reliably measure the effects of SRC on cognition is essential to clinical and research aspects of recovery.

Dizziness and vestibular-oculomotor symptoms demonstrated recovery trajectories similar to that of total symptoms. Specifically, dizziness demonstrated steady, significant decreases between weeks 1 and 2, weeks 2 and 3, and weeks 3 and 4; with female subjects reporting greater dizziness than male subjects at each time point. Although related, balance is a different construct[28] with different physiological underpinnings[50,51]; therefore, comparisons between them are not likely meaningful. This study is the first within the SRC literature to measure the recovery trajectory of dizziness as a separate construct rather than as 1 of many symptoms. Again, sex played a significant role, with female subjects reporting greater symptom provocation than male subjects at each time point. This finding is consistent with the sex differences in symptom reporting described above and elsewhere in the literature.[29,31,52-54] In contrast to total concussion symptom reports, which plateaued around 3 weeks after injury, both dizziness and reported symptoms after the vestibular-oculomotor examination were significantly different from weeks 3 to 4. This finding suggests that there is added value in assessing dizziness and vestibular-oculomotor symptoms at each clinical evaluation.

Limitations

In the present study, we assessed multiple outcomes to describe recovery after SRC in a sample that includes male and female athletes representing different sports. However, the present findings are not without limitations. Symptoms and vestibular-oculomotor outcomes were assessed with self-report data, which are limited by response bias. In addition, we assumed that athletes were honest and accurate in their responses. We used asymptomatic status to indicate recovery for symptoms because we did not have access to baseline data. However, many healthy athletes report some symptoms at baseline. Therefore, having access to baseline symptoms can provide valuable information in the assessment of recovery. Furthermore, the sample size of the present study is small; further work in larger samples is warranted. As a consequence of the smaller sample size, the age range is still relatively narrow. A similar study with a larger sample and age range should be conducted. The studies by Field et al[55] and Covassin et al[30] are the only 2 studies to compare high school and collegiate athletes. Both of these studies focused on clinical presentation rather than recovery, meaning that there are still several unanswered questions about the role of age/development on recovery. It is also worth noting that even though clinical recommendations are made, patient compliance cannot be known with certainty. It may well be the case that patients in the present sample did not or could not follow the clinical recommendations, thereby delaying recovery. Furthermore, the researchers in this study (with the exception of the statistician) were not blinded to the hypotheses. Although this is common in clinical research, it is important to note and acknowledge the role this might play in interpretation and therefore treatment ramifications. Finally, selection bias toward patients with longer recoveries is a limitation of this study, as it is in all concussion research.

CONCLUSION

The results of the present study reveal 2 important points in measuring recovery from SRC. First, athletes in the present sample demonstrated a more protracted recovery curve than has been reported in the literature. Specifically, our results indicate that recovery for most athletes approximates 3 to 4 weeks rather than the prevailing time frame of 7 to 14 days. Our results reinforce the importance of a comprehensive assessment of SRC that includes symptoms, neurocognitive testing, and vestibular-oculomotor outcomes because each component may have a different recovery trajectory that might be missed by focusing on only 1 or 2 assessments. Such an approach will provide clinicians with valuable information about an athlete's recovery and how the injury might be managed or treated.[56] The disparate recovery rate of symptoms, neurocognition, and equilibrium detailed here provides more evidence that concussions are not simple injuries with singular recovery trajectories but instead reflect an amalgamation of symptoms and dysfunctions that recovery differentially, not unitarily.

Disclosures

This research was supported in part by grants to the University of Pittsburgh from the National Institute on Deafness and Other Communication Disorders (1K01DC012332-01A1) to Dr Kontos and through a research contract between the University of Pittsburgh and ElMindA, Ltd (Israel) with Dr Kontos. Dr Collins is a codeveloper and board member of ImPACT Applications. The other authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES

1. McCrory P, Meeuwisse W, Aubry M, et al. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *J Sci Med Sport.* 2013;16(3):178-189.
2. Giza CC, Kutcher JS, Ashwal S, et al. Summary of evidence-based guideline update: evaluation and management of concussion in sports: report of the Guideline Development Subcommittee of the American Academy of Neurology. *Neurology.* 2013;80(24):2250-2257.
3. Lau BC, Collins MW, Lovell MR. Cutoff scores in neurocognitive testing and symptom clusters that predict protracted recovery from concussions in high school athletes. *Neurosurgery.* 2012;70(2):371-379; discussion 379.
4. Eisenberg MA, Meehan WP III, Mannix R. Duration and course of post-concussive symptoms. *Pediatrics.* 2014;133(6):999-1006.
5. Meehan WP III, Zhang J, Mannix R, Whalen MJ. Increasing recovery time between injuries improves cognitive outcome after repetitive mild concussive brain injuries in mice. *Neurosurgery.* 2012;71(4):885-891.

6. Covassin T, Bay E. Are there gender differences in cognitive function, chronic stress, and neurobehavioral symptoms after mild-to-moderate traumatic brain injury? *J Neurosci Nurs.* 2012;44(3):124-133.
7. Broglio SP, Puetz TW. The effect of sport concussion on neurocognitive function, self-report symptoms and postural control: a meta-analysis. *Sports Med.* 2008;38(1):53-67.
8. Lau B, 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.
9. Lau BC, Kontos AP, Collins MW, Mucha A, Lovell MR. Which on-field signs/symptoms predict protracted recovery from sport-related concussion among high school football players? *Am J Sports Med.* 2011;39(11):2311-2318.
10. McCrea M, Barr WB, Guskiewicz K, et al. Standard regression-based methods for measuring recovery after sport-related concussion. *J Int Neuropsychol Soc.* 2005;11(1):58-69.
11. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA.* 2003;290(19):2556-2563.
12. McCrory P, Meeuwisse W, Johnston K, et al. Consensus statement on concussion in sport: 3rd International Conference on Concussion in Sport held in Zurich, November 2008. *Clin J Sport Med.* 2009;19(5):185-200.
13. Fazio VC, Lovell MR, Pardini JE, Collins MW. The relation between post concussion symptoms and neurocognitive performance in concussed athletes. *NeuroRehabilitation*. 2007;22(3):207-216.
14. McCrea M, Guskiewicz K, Randolph C, et al. Incidence, clinical course, and predictors of prolonged recovery time following sport-related concussion in high school and college athletes. *J Int Neuropsychol Soc.* 2013;19(1):22-33.
15. Makdissi M, Cantu RC, Johnston KM, McCrory P, Meeuwisse WH. The difficult concussion patient: what is the best approach to investigation and management of persistent (>10 days) postconcussive symptoms? *Br J Sports Med.* 2013;47(5):308-313.
16. Prichep LS, McCrea M, Barr W, Powell M, Chabot RJ. Time course of clinical and electrophysiological recovery after sport-related concussion. *J Head Trauma Rehabil.* 2013;28(4):266-273.
17. Meehan WP III, Mannix RC, Stracciolini A, Elbin RJ, Collins MW. Symptom severity predicts prolonged recovery after sport-related concussion, but age and amnesia do not. *J Pediatr.* 2013;163(3):721-725.
18. Collins MW, Grindel SH, Lovell MR, et al. Relationship between concussion and neuropsychological performance in college football players. *JAMA.* 1999;282(10):964-970.
19. Covassin T, Elbin RJ, Nakayama Y. Tracking neurocognitive performance following concussion in high school athletes. *Phys Sportsmed.* 2010;38(4):87-93.
20. Iverson GL, Brooks BL, Collins MW, Lovell MR. Tracking neuropsychological recovery following concussion in sport. *Brain Inj.* 2006;20(3):245-252.
21. Quatman-Yates C, Hugentobler J, Ammon R, Mwase N, Kurowski B, Myer GD. The utility of the Balance Error Scoring System for mild brain injury assessments in children and adolescents. *Phys Sportsmed.* 2014;42(3):32-38.
22. King LA, Horak FB, Mancini M, et al. Instrumenting the Balance Error Scoring System for use with patients reporting persistent balance problems after mild traumatic brain injury. *Arch Phys Med Rehabil.* 2014;95(2):353-359.
23. Murray N, Salvatore A, Powell D, Reed-Jones R. Reliability and validity evidence of multiple balance assessments in athletes with a concussion. *J Athl Train.* 2014;49(4):540-549.
24. Finnoff JT, Peterson VJ, Hollman JH, Smith J. Intrarater and interrater reliability of the Balance Error Scoring System (BESS). *PM R.* 2009;1(1):50-54.
25. Mulligan IJ, Boland MA, McIlhenny CV. The Balance Error Scoring System learned response among young adults. *Sports Health.* 2013;5(1):22-26.
26. Burk JM, Munkasy BA, Joyner AB, Buckley TA. Balance Error Scoring System performance changes after a competitive athletic season. *Clin J Sport Med.* 2013;23(4):312-317.
27. Murray NG, Ambati VN, Contreras MM, Salvatore AP, Reed-Jones RJ. Assessment of oculomotor control and balance post-concussion: a preliminary study for a novel approach to concussion management. *Brain Inj.* 2014;28(4):496-503.
28. Mucha A, Collins MW, Elbin RJ, et al. A Brief Vestibular/Ocular Motor Screening (VOMS) assessment to evaluate concussions: preliminary findings. *Am J Sports Med.* 2014;42(10):2479-2486.
29. Covassin T, Elbin RJ. The female athlete: the role of gender in the assessment and management of sport-related concussion. *Clin Sports Med.* 2011;30(1):125-131, x.
30. Covassin T, Elbin RJ, Harris W, Parker T, Kontos A. The role of age and sex in symptoms, neurocognitive performance, and postural stability in athletes after concussion. *Am J Sports Med.* 2012;40(6):1303-1312.
31. Broshek DK, Kaushik T, Freeman JR, Erlanger D, Webbe F, Barth JT. Sex differences in outcome following sports-related concussion. *J Neurosurg.* 2005;102(5):856-863.
32. Colvin AC, Mullen J, Lovell MR, West RV, Collins MW, Groh M. The role of concussion history and gender in recovery from soccer-related concussion. *Am J Sports Med.* 2009;37(9):1699-1704.
33. Covassin T, Elbin RJ, Crutcher B, Burkhart S. The management of sport-related concussion: considerations for male and female athletes. *Transl Stroke Res.* 2013;4(4):420-424.
34. Iverson GL, Lovell MR, Collins MW. Interpreting change on ImPACT following sport concussion. *Clin Neuropsychol.* 2003;17(4):460-467.
35. Barlow M, Schlabach D, Peiffer J, Cook C. Differences in change scores and the predictive validity of three commonly used measures following concussion in the middle school and high school aged population. *Int J Sports Phys Ther.* 2011;6(3):150-157.
36. Kontos AP, Elbin RJ, Schatz P, et al. A revised factor structure for the post-concussion symptom scale: baseline and postconcussion factors. *Am J Sports Med.* 2012;40(10):2375-2384.
37. Stump JE, Lovell MR, Collins MW, Moritz K, Fu FH. The Post Concussion Symptom Scale (PCSS): a factor analysis. *Br J Sports Med.* 2004;38:661-662.
38. Jacobson GP, Newman CW. The development of the dizziness handicap inventory. *Arch Otolaryngol Head Neck Surg.* 1990;116(4):424-427.
39. Sady MD, Vaughan CG, Gioia GA. School and the concussed youth: recommendations for concussion education and management. *Phys Med Rehabil Clin N Am.* 2011;22(4):701-719, ix.
40. Baker JG, Freitas MS, Leddy JJ, Kozlowski KF, Willer BS. Return to full functioning after graded exercise assessment and progressive exercise treatment of postconcussion syndrome. *Rehabil Res Pract.* 2012;2012:705309.
41. Leddy JJ, Sandhu H, Sodhi V, Baker JG, Willer B. Rehabilitation of concussion and post-concussion syndrome. *Sports Health.* 2012;4(2):147-154.
42. Zuckerman SL, Lee YM, Odom MJ, Solomon GS, Forbes JA, Sills AK. Recovery from sports-related concussion: days to return to neurocognitive baseline in adolescents versus young adults. *Surg Neurol Int.* 2012;3:130.
43. Coldren RL, Russell ML, Parish RV, Dretsch M, Kelly MP. The ANAM lacks utility as a diagnostic or screening tool for concussion more than 10 days following injury. *Mil Med.* 2012;177(2):179-183.
44. Resch J, Driscoll A, McCaffrey N, et al. ImPACT test-retest reliability: reliably unreliable? *J Athl Train.* 2013;48(4):506-511.
45. Resch JE, Macciocchi S, Ferrara MS. Preliminary evidence of equivalence of alternate forms of the ImPACT. *Clin Neuropsychol.* 2013;27(8):1265-1280.
46. Bruce J, Echemendia R, Meeuwisse W, Comper P, Sisco A. 1 Year test-retest reliability of ImPACT in professional ice hockey players. *Clin Neuropsychol.* 2014;28(1):14-25.
47. Schatz P, Ferris CS. One-month test-retest reliability of the ImPACT test battery. *Arch Clin Neuropsychol.* 2013;28(5):499-504.
48. Schatz P, Sandel N. Sensitivity and specificity of the online version of ImPACT in high school and collegiate athletes. *Am J Sports Med.* 2013;41(2):321-326.
49. Elbin RJ, Schatz P, Covassin T. One-year test-retest reliability of the online version of ImPACT in high school athletes. *Am J Sports Med.* 2011;39(11):2319-2324.
50. Balaban CD, Jacob RG. Background and history of the interface between anxiety and vertigo. *J Anxiety Disord.* 2001;15(1-2):27-51.
51. Balaban CD, Thayer JF. Neurological bases for balance-anxiety links. *J Anxiety Disord.* 2001;15(1-2):53-79.
52. Asplund CA, McKeag DB, Olsen CH. Sport-related concussion: factors associated with prolonged return to play. *Clin J Sport Med.* 2004;14(6):339-343.
53. Delaney JS, Lacroix VJ, Leclerc S, Johnston KM. Concussions among university football and soccer players. *Clin J Sport Med.* 2002;12(6):331-338.
54. Dick RW. Is there a gender difference in concussion incidence and outcomes? *Br J Sports Med.* 2009;43(suppl 1):i46-i50.
55. 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(5):546-553.
56. Reynolds E, Collins MW. In-office management of sport-related concussion. *Prog Neurol Surg.* 2014;28:128-138.

COMMENTS

The authors report a series of 66 athletes with sports-related concussions. Specifically, they sought to determine the time course to recovery using a variety of tests. Consistent with other studies, female subjects were more likely than male subjects to have a protracted recovery. Unlike the majority of other studies, athletes were more likely to have a recovery period lasting up to 4 weeks. The authors conclude that assessment of athletes should include an analysis of symptoms, neurocognitive testing, and vestibular-oculomotor outcomes and that a battery of tests will likely provide better ability to determine return to play. This approach seems to be a rational one and may ultimately prove to be more universally adopted.

Craig H. Rabb
Oklahoma City, Oklahoma

The difficulties in the diagnosis and assessment of recovery in sports concussion continue to trouble clinicians in this field. The Holy Grail in concussion assessment is a simple sideline test that will diagnose the presence and severity of a concussion and determine the predicted recovery trajectory. Such a test continues to elude us. In an attempt to address this issue, the authors have examined a heterogeneous group of 66 athletes 14 to 23 years of age participating in 12 different sports who sustained a concussive injury within 7 days before initial assessment. Four modes of assessment were used: symptoms (Post-Concussion Symptom Scale [PCSS]), computerized neuropsychology (Immediate Post-Concussion Assessment and Cognitive Test [ImPACT]), dizziness symptoms (Dizziness Handicap Inventory [DHI]), and vestibular-oculomotor performance. The primary objective was to measure change within each modality over 4 weeks, and the secondary objective was to assess the effect of sex on recovery time. It is apparent that the authors' hypothesis is that the 4-tiered, multimodal assessment would be more informative than the more conventional assessment using symptom score and cognitive assessment. They found that the recovery time was prolonged (up to 4 weeks) according to PCSS, ImPACT, DHI, and vestibular-oculomotor, with sex demonstrating a significant difference using 3 modalities, in which prolonged symptoms were more frequent in female subjects. No sex difference was found in the use of ImPACT neurocognitive testing. The results of this study are not surprising. The recruitment process involved subjects presenting within 7 days of concussion, performing multiple 1-hour testing sessions over 4 weeks. Typically, the majority of concussed athletes, in whom symptoms usually resolve within 48 hours, will not voluntarily present at 5, 6, or 7 days for assessment. Thus, this paradigm is biased toward selection of subjects with prolonged symptoms, with the results reflecting this with the demonstration of prolonged symptoms in the cohort. This is a problem that we also encounter in our concussion research, especially in children and adolescents, in whom those with rapid recovery are less likely to volunteer to participate and those with other confounding variables such as anxiety (within the child and/or the parents) are more inclined to volunteer to participate in such studies.

The dropout rate of 17% is likely due to those whose symptoms had resolved and did not consider it worthwhile remaining in the study. The sex differences are consistent with the literature[1-3] in which it is well recognized that females are more inclined to volunteer symptoms than males. Therefore it is not surprising that the 3 symptom evaluations all demonstrated a sex difference, whereas there was no sex difference in the single modality, neurocognition, in which objective assessment was performed compared with the subjective nature of symptom reporting. It is worth emphasizing that the authors' selection of zero symptoms on PCSS will overestimate the number with persistent symptoms because normative data demonstrate that a significant number of normal (no-concussed) individuals endorse 3 to 6 symptoms at baseline, more so in females.[4]

An advantage of the 4-tiered multimodal assessment compared with conventional 2- or 3-tiered assessment is not borne out by the results of this study, and I encourage the authors to continue their research to explore this important issue further.

Gavin Davis
Victoria, Australia

1. Colvin AC, Mullen J, Lovell MR, West RV, Collins MW, Groh M. The role of concussion history and gender in recovery from soccer-related concussion. *Am J Sports Med.* 2009;37(9):1699-1704.
2. Covassin T, Swanik CB, Sachs M, et al. Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes. *Br J Sports Med.* 2006;40(11):923-927; discussion 927.
3. Kutcher JS, Eckner JT. At-risk populations in sports-related concussion. *Curr Sports Med Rep.* 2010;9(1):16-20.
4. Shehata N, Wiley JP, Richea S, Benson BW, Duits L, Meeuwisse WH. Sport concussion assessment tool: baseline values for varsity collision sport athletes. *Br J Sports Med.* 2009;43(10):730-734.