Advances in neuropsychological assessment of sport-related concussion

Ruben J Echemendia,[1,2] Grant L Iverson,[3] Michael McCrea,[4] Stephen N Macciocchi,[5] Gerard A Gioia,[6] Margot Putukian,[7] Paul Comper[8]

▸ Additional material is published online only. To view please visit the journal online (http://dx.doi.org/10.1136/bjsports-2013-092186)

For numbered affiliations see end of article.

Correspondence to
Dr Ruben J Echemendia, Psychological and Neurobehavioral Associates, Inc., 204 East Calder Way, Ste. 205, State College, PA 16801, USA; rechemendia@comcast.net

Received 14 January 2013
Accepted 19 January 2013

ABSTRACT

Objective To critically review the literature from the past 12 years regarding the following key issues in sports-related neuropsychological assessment: (1) the advantages and disadvantages of different neuropsychological assessment modalities; (2) the evidence for and against the current paradigm of baseline/postinjury testing; (3) the role of psychological factors in the evaluation and management of concussion; (4) advances in the neuropsychological assessment of children; (5) multi-modal assessment paradigms; (6) the role of the neuropsychologist as part of the sports healthcare team and (6) the appropriate administration and interpretation of neuropsychological tests.

Design Targeted computerised literature review (MEDLINE, PubMed, CINAHL and PsychInfo) from 2000 to the present using key words: neuropsychological, neurocognitive, assessment, testing, concussion and sports.

Results More than 2600 articles were identified using key word searches of the databases, including many duplicates. Several books were also reviewed. The articles were pared down for review if they specifically addressed the key areas noted above.

Conclusions Traditional and computerised neuropsychological tests are useful in the evaluation and management of concussion. Brief cognitive evaluation tools are not substitutes for formal neuropsychological assessment. At present, there is insufficient evidence to recommend the widespread routine use of baseline neuropsychological testing. Although scant, research suggests that psychological factors may complicate and prolong recovery from concussion in some athletes. Age-appropriate symptom scales for children have been developed but research into age-appropriate tests of cognitive functions lags behind. Neuropsychologists are uniquely qualified to interpret neuropsychological tests and can play an important role within the context of a multifaceted-multimodal approach to manage sports-related concussions.

INTRODUCTION

Sports-related concussions are frequently associated with one or more symptoms, impaired balance and cognitive deficits.[1–14] These problems can be measured using symptom scales,[15–19] balance testing[6 12–14] and neurocognitive testing. All three assessment modalities can identify significant changes in the first few days following injury, generally with normalisation over 1–3 weeks.[2 5–7 12 20] The presentation of symptoms and the rate of recovery can be variable, which reinforces the value of assessing all three areas as part of a comprehensive sport concussion programme.

Neuropsychological assessment has been described as an important 'cornerstone' of concussion management.[21] Concussion management programmes that use neuropsychological assessment to assist in clinical decision-making have been instituted in professional sports,[16 22] colleges[23 24] and high schools.[25]

In addition to neuropsychological measures, rapid cognitive screening tests have been developed (eg, Standardised Assessment of Concussion, SAC) that are sensitive to the immediate effects of concussion.[10 26] The SAC can be used on the sideline or later on the day of injury to identify cognitive deficits associated with concussion, and it is embedded in the Sport Concussion Assessment Tool—Second Edition (SCAT2[27]). Although useful on the day of injury and in the few days that follow, brief cognitive screening tests such as the SAC and SCAT2 are not substitutes for more comprehensive neuropsychological assessment.[27]

Numerous studies have found that both traditional and computerised cognitive tests are sensitive to the acute effects of concussion (eg[2 6–9 12 20 28–43]). Consequently, many position and consensus statements have recommended neuropsychological assessment as a component of concussion management programmes.[21 27 44 45]

The goal of this paper is to critically review clinical and research advances in neuropsychological assessment over the past 12 years. The seven key questions listed below were addressed.

1. What are the advantages and disadvantages of different neuropsychological testing modalities (eg, computerised batteries, traditional 'paper and pencil' tests or a combination of both)?
2. What is the evidence for or against the current paradigm of baseline/postinjury testing?
3. Is the assessment of 'psychological' factors important in the evaluation and management of concussion?
4. Have there been advances in the neuropsychological assessment of children?
5. What is the role of neuropsychological assessment within the context of multimodal assessment models?
6. What is the role of the neuropsychologist as part of the sports concussion healthcare team?
7. Who should administer and interpret neuropsychological tests?

To cite: Echemendia RJ, Iverson GL, McCrea M, *et al*. *Br J Sports Med* 2013;**47**:294–298.

METHODS

A targeted computerised literature search was conducted via Medline, PubMed, CINAHL and PsychInfo from 2000 to the present using the key words: neuropsychological, neurocognitive, assessment, testing, concussion and sports. This search identified more than 2600 articles including many duplicates. Several books were also reviewed. The articles were pared down for review if they specifically addressed the key areas noted above. Relevant articles were reviewed by the authors and included as appropriate.

NEUROPSYCHOLOGICAL TESTING MODELS

Baseline cognitive assessment using traditional neuropsychological tests was introduced in the 1980s.[46] Computerised tests were developed in the 1990s to provide an alternative to traditional tests and are now used almost exclusively in many sports settings. Traditional tests have been studied in combination with computerised batteries to assess construct validity.[47 48] The combined use of traditional and computerised neuropsychological tests in applied settings has been referred to as a 'hybrid' neuropsychological testing approach.[49] There is no scientific evidence that traditional testing, computerised testing or a hybrid approach is superior; each approach has its strengths and limitations.

Traditional tests are reasonably reliable, valid and sensitive to the effects of sports concussion.[7 50 51] They can be selected to fit the specific needs of the athlete and domains of neuropsychological importance. These tests have a much longer history of being applied in clinical settings, with some having large normative databases. However, traditional tests require face-to-face examination, which may introduce variance in test administration and scoring. These tests are also more labour-intensive, especially in sports settings, while conducting baseline testing in large numbers of athletes.

In contrast, computerised tests such as the Immediate Postconcussion Assessment and Cognitive Testing (ImPACT), Axon Sports, the Automated Neuropsychological Assessment Metrics (ANAM) and Headminder (ImPACT Applications, Inc; Axon Sports, LLC)[4 52] can be rapidly administered to individuals or groups. Computerised batteries are portable and efficient for the collection, synthesis and storage of large amounts of data. Clinical end-user reports are often immediately available.

Although computerised tests offer certain efficiencies, they also have limitations. First, they are brief and rely on a limited sample of cognitive functioning. Second, although a number of studies have shown that computerised batteries appear to have adequate psychometric properties,[29 53–59] other studies have raised questions about the reliability, form equivalence and validity of these instruments.[60–62] For instance, test–retest reliabilities have been reported to be quite low by some investigators, which increases reliable change (RC) metrics and limits the value of baseline examinations.[50 60–62] Third, alternate forms may not be equivalent.[62] Fourth, while one of the major purported advantages of computerised testing is the application to group testing, recent research indicates that group versus individual test administration may yield different results.[63] Based on the combined experience of the present authors, under most circumstances large group baseline testing should be avoided because of an inability to adequately control the testing environment. Fifth, although computers have provided a technological breakthrough in neurocognitive testing, the technology itself is subject to error. Significant variability exists in the accuracy of personal computers' measurement of response time,[64] although they claim to do so with millisecond accuracy. Variability has also been found in the use of computer mice or keyboards, and monitor refresh rates.[65] Sixth, computerised batteries have been marketed to clinicians from diverse disciplines, some of whom may have no education or training in cognitive assessment.[66] Finally, computerised batteries may be seen as a 'black box' approach to neuropsychological assessment, an approach that is partially encouraged by the immediate availability of a clinical report that contains simplified coding for whether a finding is reliable or significant. This may lead some clinicians astray by inaccurately providing a singular or 'cookbook' approach to assessment that is complicated by many of the factors discussed above.

Some authors have advocated the hybrid approach because traditional testing may be too labour intensive, and computerised testing may be too brief and may not sample all the domains affected by concussion. Typically, the hybrid approach uses a computerised battery at baseline and a combination of computerised and traditional tests following injury. Although the hybrid method is intuitively appealing, only a few studies to date have examined the clinical utility of this approach (eg[47 48]).

THE ROLE AND VALUE OF BASELINE TESTING

Baseline testing is conducted prior to an athlete's participation in a sport or a given season. In the event of a concussion, postinjury scores are compared to baseline scores to determine whether neurocognitive deficits exist.[67] Theoretically, baseline scores are thought to increase the diagnostic accuracy when compared to postinjury scores by limiting variance associated with pre-injury confounding variables.

The pre–post injury assessment model may introduce error because test interpretation must take into account test-retest reliability and the inherent error surrounding multiple testing sessions that often occur at intervals that are years apart.[49 61 68–70] Moreover, despite the methodological appeal of pre–post testing, the diagnostic accuracy of this paradigm has not been empirically tested in the sports domain. Consequently, whether this model has greater diagnostic accuracy than postconcussion assessment alone remains to be determined.[50 71] Recent research suggests that postinjury assessment alone may have promise, obviating the need for widespread and costly baseline assessments.

Echemendia *et al*[72] examined the utility of baseline testing among 266 concussed college athletes who had taken ImPACT at baseline and postinjury. RC from baseline was computed using two different RC methods. These RC methods were then compared to an interpretive method in which athletes scoring 1.5 SD units below expected normative performance were classified as showing a clinically significant change. Using postinjury data alone, a sensitivity of 86% and a specificity of 95% were found when predicting decline on the Verbal Memory Composite. The Visual Motor Speed Composite had a sensitivity of 80% with a specificity of 96%, and on the reaction time composite the sensitivity was 80% and the specificity was 97%. The Visual Memory Composite was not examined due to the differences in ImPACT versions (ie, the original version of the test did not include visual memory). These findings suggest that postinjury neuropsychological test data are robust and may not require baseline testing to identify clinically meaningful postconcussion cognitive decline as long as there exist appropriate, well-developed normative data.

Schmidt *et al*[73] employed similar methodology with 258 concussed college students who were tested with the ANAM battery at baseline and following injury. Two interpretive methods were used: (1) individualised baseline versus postinjury comparison and (2) normative data baseline comparison. The individual baseline method identified 2.6 times more athletes with impairment than the normative method on the Simple Reaction Time subtest, and the normative method identified athletes with impairment 7.6 times more often than the individual baseline method on the mathematic processing subtest. No differences occurred among the other ANAM measures, measures of postural control on the Sensory Organisation Test or a graded symptom checklist.

Although the data are preliminary and limited to a college-age population, these studies suggest that baseline testing may not be as necessary as once thought for identifying postinjury neurocognitive deficits in cognition or balance. Additional studies are needed to further evaluate the utility of baseline testing with different age groups, different neuropsychological test batteries, different instruments used to assess baseline functioning across multiple domains and using different methodologies for examining the clinical usefulness of baseline versus normative comparisons. It is also important to identify those groups of individuals for whom the use of baseline data may be superior to the use of normative data (eg, those athletes who have cognitive abilities in the upper or lower 20% of the normative sample, or those with LD or ADHD), and which normative data should be used with which individuals (eg, mean scores by gender, sport, age and ethnicity).

If baseline data are not used, it is important that robust local normative data are available for comparison to postinjury data. If baseline neurocognitive testing is employed, the integrity of those baselines must be maximised through the use of appropriately trained examiners and well-supervised test administrations in individual or small group settings ($\leq 5:1$ athlete: proctor ratio), creating a proper motivational set and screening for invalid baseline data (eg, sandbagging or purposefully poor performance).

PSYCHOLOGICAL FACTORS ASSOCIATED WITH CONCUSSION

Athletes with concussion may suffer a broad spectrum of physical and cognitive symptoms. They are also at risk for psychological and emotional disturbance following injury,[74–77] including but not limited to depression, anxiety, social isolation and loneliness, frustration, anger and guilt.[78] Whether co-occurring psychological symptoms reflect a response to being injured and/or the pathophysiological consequences of concussion is not clear.[79]

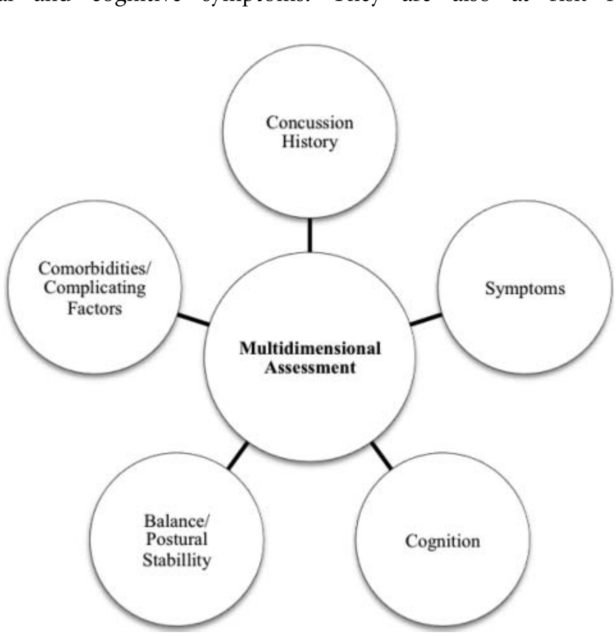

Figure 1 Multidimensional Model of Concussion Assessment.

Some of the research related to psychological functioning in athletes has been conducted in the context of establishing a valid cognitive baseline.[80 81] Screening for psychological disturbance during baseline and postinjury assessments is an important element of concussion management, not only because of the prevalence of psychological difficulties, but also because the early identification and treatment of pre-existing or comorbid psychological issues associated with concussion may prevent the development of persistent postconcussive symptoms in vulnerable individuals.[82]

For instance, some athletes who have atypical, protracted and perplexing recovery following concussion may also have co-occurring depression or other psychological disorders.[74] Many factors may be operative following concussion that can complicate recovery in some individuals. First, removing athletes from participation prevents the athlete from interacting with teammates and disrupts normal social networks. Second, teammates, coaches and friends may view concussed athletes as vulnerable and fragile, a perception that runs counter to the culture of invulnerability of most competitive athletes. Finally, there is usually no outward evidence of injury in concussed athletes, which may lead others to wonder whether the athlete is truly injured.

CONCUSSION ASSESSMENT OF CHILDREN

The evaluation and management of concussion in children presents a number of unique challenges. There are no published studies that have examined postconcussive impairments in children below the high school level, largely due to the fewer age-appropriate neurocognitive tests to study concussion in this age group.[83 84] The key assessment domains in children are generally similar to those in adolescents and young adults with concussion (ie, postconcussion symptoms, specific neuropsychological functions and balance), but important differences must be accounted for, including children's cognitive, physical and emotional development as well as their capacity to serve as the primary reporter of their symptoms.[85]

Three of the computerised batteries in use today for the management of sport concussion have been used with children under the age of 12. A preliminary normative study of children aged 8 and older using CogSport found clear cognitive developmental changes that must be taken into account when evaluating children.[86] The Pediatric ImPACT is a developmentally appropriate, computer-administered assessment battery for children in the age range 5–12, adapted from the format of ImPACT. The measure combines both standardised age-specific symptom ratings and six subtests measuring neurocognitive performance (learning and memory, response speed) to assist in multidimensional assessment of concussion.[87] Finally, CNS Vital Signs[88] has normative data across the lifespan, starting at age 8.

Computerised batteries for preadolescent athletes show early promise but currently lack the necessary evidence to draw any firm conclusions regarding their clinical utility. Similarly, traditional neurocognitive tests have not been applied to children who have sustained sport-related concussions.

In contrast, symptom measures that have been used with children included the Health and Behavior Inventory (HBI[89]), Acute Concussion Evaluation (ACE[90]), Postconcussion Symptom Inventory (PCSI[91]) and Rivermead Postconcussion Symptoms

Questionnaire.[92] The literature is growing for children aged 8 and older employing both child-report and parent-report measures.[90 93] Two measures (ACE and PCSI) have been used with children aged 7 and younger. Some of the studies employing these symptom measures document sensitivity to concussion effects through group change (eg[94]) but few report RC metrics applicable to individual cases. In addition, normative data are not available for most of these measures.

THE ROLE OF NEUROPSYCHOLOGICAL TESTING IN A MULTIDIMENSIONAL ASSESSMENT MODEL

The symptoms of concussion are complex and vary widely across individuals. An athlete might experience prominent symptoms in one domain, but subtle problems in another. The heterogeneity of concussion supports the movement towards multimodal concussion assessment, which is premised on the view that single domain-specific outcome measures (eg, cognition or balance) are insufficient for detecting the full spectrum of concussion sequelae. As depicted in figure 1, the multidimensional assessment approach recognises this complexity and integrates outcome measures across multiple domains of functioning.[39 95 96]

ROLE OF THE NEUROPSYCHOLOGIST

The biopsychosocial model of concussion,[97–100] the value of neurocognitive testing and the efficacy of psychoeducational interventions to improve outcome[101 102] all underscore the important roles that neuropsychologists can play as members of a multidisciplinary sports medicine team. Neuropsychologists provide expertise not only in cognitive evaluation and management of the injury, but they also identify and address potential psychological issues and problems.[102] These psychological interventions need not be intensive and are most effective when introduced early during the acute or subacute recovery phase.[100]

ADMINISTRATION AND INTERPRETATION OF NEUROPSYCHOLOGICAL TESTS

While the use of neuropsychological tests for evaluating sport-related concussion has increased exponentially over the past 15 years, little attention has been paid to who should administer and interpret these tests.[103 104] Differentiating between administering and interpreting neuropsychological tests is important. Although most healthcare professionals can learn to administer tests, significantly more expertise is required when interpreting neuropsychological test data. Interpretation of test scores in injured athletes is complex and requires advanced knowledge in psychometrics (eg, reliability, validity, normative classification, base rates and RC), standardised assessment procedures, the effects of situational factors on test performance, the impact of culture and linguistic differences on test scores and the influence of pre-existing (eg, ADHD or learning disability) or co-occurring conditions (eg, depression or anxiety) on test performance.[103] These interpretive issues apply to computerised tests, which may erroneously give the appearance of being easy to interpret because they provide a nearly instantaneous printout of the results[105] with scores estimated to be reliably changed from baseline highlighted in different colours. Neuropsychologists are the professionals best trained to interpret neuropsychological tests.[103 106]

CONCLUSIONS

- The role and value of neuropsychological testing as part of a comprehensive concussion evaluation and management programme has been well established. Traditional measures, computerised batteries and hybrid approaches have been studied, each with corresponding strengths and weaknesses. There is no conclusive evidence supporting one approach over another.
- Brief cognitive screening tests such as the SAC and SCAT2 are not substitutes for more comprehensive neuropsychological assessment.
- Recent studies have demonstrated the utility of computerised neuropsychological testing in the absence of baseline data. Although popular, there is insufficient published evidence to recommend the widespread universal use of baseline neuropsychological testing within a sport concussion management programme. Additional research is needed to determine the utility of baseline data with different age groups, across different test instruments, among different cultures and languages and those with pre-existing psychological, educational and medical difficulties.
- Psychological factors can have an important and pervasive impact on an athlete's recovery after concussion. Research examining psychological functioning in athletes and how psychological factors affect postconcussion recovery is imperative.
- Although advances have been made in symptom scales that are appropriate and useful with children, researches related to psychometrically sound, age-appropriate tests

What are the new findings?

- Neuropsychological testing remains a key element of a comprehensive concussion evaluation and management programme but should not be used in a stand-alone manner to make return-to-play decisions.
- Brief cognitive screening tests such as the Standardised Assessment of Concussion (SAC) and Sport Concussion Assessment Tool—Second Edition (SCAT2) are not substitutes for comprehensive neuropsychological assessment.
- Neuropsychological testing is useful in the absence of baseline data as long as adequate normative data are available. There is insufficient published evidence to recommend the widespread universal use of baseline neuropsychological testing within a sport concussion management programme.
- Research related to psychometrically sound, age-appropriate tests that are sensitive to the effects of concussion in children is needed.

How might it impact clinical practice in the near future?

- Appropriate use of neuropsychological test data can be very useful in the evaluation and management of athletes diagnosed with concussion. Although neuropsychological testing should be a central element of concussion management programmes, widespread universal baseline testing may not be necessary when appropriate local norms exist.

that are sensitive to the effects of concussion in children are needed.

- Neuropsychological instruments should not be used in a stand-alone manner to make return-to-play decisions.
- Neuropsychological tests can be administered by properly trained paraprofessionals, but the interpretation of neuropsychological test data is complex and ideally performed by a trained neuropsychologist.

Author affiliations
[1]Psychological and Neurobehavioral Associates, Inc., State College, Pennsylvania, USA
[2]Department of Psychology, University of Missouri-Kansas City, State College, Pennsylvania, USA
[3]Department of Psychiatry, University of British Columbia, Vancouver, British Columbia, Canada
[4]Department of Neurosurgery and Neurology, Medical College of Wisconsin, Milwaukee, Wisconsin, USA
[5]Rehabilitation Psychology and Neuropsychology, Shepherd Center, Atlanta, Georgia, USA
[6]Division of Pediatric Neuropsychology, Children's National Medical Center & Department of Pediatrics and Psychiatry, George Washington University School of Medicine, Rockville, Maryland, USA
[7]Department of Athletic Medicine, Princeton University, University Health Services, Princeton, New Jersey, USA
[8]Kinesiology and Physical Education & Graduate Department of Rehabilitation Science, University of Toronto, Ontario, Canada

Contributors GLI, MM, SAM, GAG, MP and PC all contributed to the design, planning, literature review, manuscript preparation and manuscript review. RJE also contributed to the design, planning, literature review, manuscript preparation and manuscript review. He was also responsible for the overall content as a guarantor.

Competing interests See the supplementary online data for competing interests (http://dx.doi.org/10.1136/bjsports-2013-092186).

Provenance and peer review Commissioned; internally peer reviewed.

REFERENCES

1 Barr WB, McCrea M. Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion. *J Int Neuropsychol Soc* 2001;7:693–702.
2 Collins MW, Grindel SH, Lovell MR, *et al*. Relationship between concussion and neuropsychological performance in college football players. *J Am Med Assoc* 1999;282:964–70.
3 Delaney JS, Lacroix VJ, Gagne C, *et al*. Concussions among university football and soccer players: a pilot study. *Clin J Sport Med* 2001;11:234–40.
4 Erlanger D, Feldman D, Kutner K, *et al*. Development and validation of a web-based neuropsychological test protocol for sports-related return-to-play decision-making. *Arch Clin Neuropsychol* 2003;18:293–316.
5 Erlanger D, Saliba E, Barth J, *et al*. Monitoring resolution of postconcussion symptoms in athletes: preliminary results of a web-based neuropsychological test protocol. *J Athl Train* 2001;36:280–7.
6 Guskiewicz KM, Ross SE, Marshall SW. Postural stability and neuropsychological deficits after concussion in collegiate athletes. *J Athl Train* 2001;36:263–73.
7 Macciocchi SN, Barth JT, Alves W, *et al*. Neuropsychological functioning and recovery after mild head injury in collegiate athletes. *Neurosurgery* 1996;39:510–14.
8 Makdissi M, Collie A, Maruff P, *et al*. Computerised cognitive assessment of concussed Australian Rules footballers. *Br J Sports Med* 2001;35:354–60.
9 Matser JT, Kessels AG, Lezak MD, *et al*. A dose-response relation of headers and concussions with cognitive impairment in professional soccer players. *J Clin Exp Neuropsychol* 2001;23:770–4.
10 McCrea M, Kelly JP, Randolph C, *et al*. Immediate neurocognitive effects of concussion. *Neurosurgery* 2002;50:1032–40.
11 Warden DL, Bleiberg J, Cameron KL, *et al*. Persistent prolongation of simple reaction time in sports concussion. *Neurology* 2001;57:524–6.
12 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;290:2556–63.
13 Peterson CL, Ferrara MS, Mrazik M, *et al*. Evaluation of neuropsychological domain scores and postural stability following cerebral concussion in sports. *Clin J Sport Med* 2003;13:230–7.
14 Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *J Athl Train* 2000;35:19–25.
15 Lovell MR. Evaluation of the professional athlete. Poster presented at the annual conference of the New Developments in Sports-Related Concussion Conference, 1996, Pittsburgh, PA, 1996.
16 Lovell MR. Evaluation of the professional athlete. In: Bailes JE, Lovell MR, Maroon JC, eds. *Sports-related concussion*. St. Louis: Quality Medical Publishing, 1999 200–14.
17 Lovell MR, Collins MW. Neuropsychological assessment of the college football player. *J Head Trauma Rehabil* 1998;13:9–26.
18 Lovell MR, Iverson GL, Collins MW, *et al*. Measurement of symptoms following sports-related concussion: reliability and normative data for the post-concussion scale. *Appl Neuropsychol* 2006;13:166–74.
19 Randolph C, Millis S, Barr WB, *et al*. Concussion symptom inventory: an empirically derived scale for monitoring resolution of symptoms following sport-related concussion. *Arch Clin Neuropsychol* 2009;24:219–29.
20 Lovell MR, Collins MW, Iverson GL, *et al*. Recovery from mild concussion in high school athletes. *J Neurosurg* 2003;98:296–301.
21 Aubry M, Cantu R, Dvorak J, *et al*. Summary and agreement statement of the First International Conference on Concussion in Sport, Vienna 2001. Recommendations for the improvement of safety and health of athletes who may suffer concussive injuries. *Br J Sports Med* 2002;36:6–10.
22 Lovell M, Echemendia R, Burke C. Models of neuropsychological assessment—professional ice hockey. In: Lovell M, Echemendia R, Barth J, Collins M, eds. *Traumatic brain injury in sports: an international neuropsychological perspective*. Lisse: Swets & Zeitlinger, 2004:221––31.
23 Schatz P, Covassin T. Neuropsychological testing programs for college athletes. In: Echemendia R, ed. *Sports neuropsychology: assessment and management of traumatic brain injury*. New York: Guilford Press, 2006:36–42.
24 Collins M, Lovell M, Echemendia R. Models of neuropsychological assessment—collegiate and high school sports. In: Lovell M, Echemendia R, Barth J, Collins M, eds. *Traumatic brain injury in sports: an international neuropsychological perspective*. Lisse: Swets & Zeitlinger, 2004:435–43.
25 Pardini J, Collins M. Creating a successful concussion management program at the high school level. In: Echemendia RJ, ed. *Sports neuropsychology: assessment and management of traumatic brain injury*. New York: Guilford Press, 2006:36–42.
26 McCrea M. Standardized mental status testing on the sideline after sport-related concussion. *J Athl Train* 2001;36:274–9.
27 McCrory P, Meeuwisse W, Johnston K, *et al*. Consensus statement on concussion in sport: the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. *Br J Sports Med* 2009;43(Suppl 1):i76–90.
28 Iverson GL, Gaetz M, Lovell MR, *et al*. Relation between fogginess and outcome following concussion. *Arch Clin Neuropsychol* 2002;17:769–70.
29 Collins MW, Iverson GL, Lovell MR, *et al*. On-field predictors of neuropsychological and symptom deficit following sports-related concussion. *Clin J Sport Med* 2003;13:222–9.
30 Lovell MR, Collins MW, Iverson GL, *et al*. Grade 1 or "ding" concussions in high school athletes. *Am J Sports Med* 2004;32:47–54.
31 Iverson GL, Lovell MR, Collins MW. Interpreting change on ImPACT following sport concussion. *Clin Neuropsychol* 2003;17:460–7.
32 Fazio VC, Lovell MR, Pardini JE, *et al*. The relation between post concussion symptoms and neurocognitive performance in concussed athletes. *NeuroRehabilitation* 2007;22:207–16.
33 Iverson GL. Predicting slow recovery from sport-related concussion: the new simple-complex distinction. *Clin J Sport Med* 2007;17:31–7.
34 Covassin T, Schatz P, Swanik CB. Sex differences in neuropsychological function and post-concussion symptoms of concussed collegiate athletes. *Neurosurgery* 2007;61:345–50; discussion 350–1.
35 McClincy MP, Lovell MR, Pardini J, *et al*. Recovery from sports concussion in high school and collegiate athletes. *Brain Inj* 2006;20:33–9.
36 Iverson GL, Brooks BL, Collins MW, *et al*. Tracking neuropsychological recovery following concussion in sport. *Brain Inj* 2006;20:245–52.
37 Van Kampen DA, Lovell MR, Pardini JE, *et al*. The "value added" of neurocognitive testing after sports-related concussion. *Am J Sports Med* 2006;34:1630–5.
38 Collins MW, Lovell MR, Iverson GL, *et al*. Examining concussion rates and return to play in high school football players wearing newer helmet technology: a three year prospective cohort study. *Neurosurgery* 2006;58:275–86.
39 Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the concussion assessment battery. *Neurosurgery* 2007;60:1050–7; discussion 1057–8.
40 Sosnoff JJ, Broglio SP, Hillman CH, *et al*. Concussion does not impact intraindividual response time variability. *Neuropsychology* 2007;21:796–802.
41 Broshek DK, Kaushik T, Freeman JR, *et al*. Sex differences in outcome following sports-related concussion. *J Neurosurg* 2005;102:856–63.
42 Erlanger D, Kaushik T, Cantu R, *et al*. Symptom-based assessment of the severity of a concussion. *J Neurosurg* 2003;98:477–84.
43 Collie A, Makdissi M, Maruff P, *et al*. Cognition in the days following concussion: comparison of symptomatic versus asymptomatic athletes. *J Neurol Neurosurg Psychiatry* 2006;77:241–5.

44 McCrory P, Johnston K, Meeuwisse W, *et al*. Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. *Br J Sports Med* 2005;39:196–204.
45 Moser RS, Iverson GL, Echemendia RJ, *et al*. Neuropsychological evaluation in the diagnosis and management of sports-related concussion. *Arch Clin Neuropsychol* 2007;22:909–16.
46 Barth JT, Alves W, Ryan T, *et al*. Mild head injury in sports: neuropsychological sequelae and recovery of function. In: Levin H, Eisenberg J, Benton A, eds. *Mild head injury*. New York: Oxford University Press, 1989:257–75.
47 Maerlender A, Flashman L, Kessler A, *et al*. Examination of the construct validity of ImPACT computerized test, traditional, and experimental neuropsychological measures. *Clin Neuropsychol* 2010;24:1309–25.
48 Maruff P, Thomas E, Cysique L, *et al*. Validity of the CogState brief battery: relationship to standardized tests and sensitivity to cognitive impairment in mild traumatic brain injury, schizophrenia, and AIDS dementia complex. *Arch Clin Neuropsychol* 2009;24:165–78.
49 Comper P, Hutchison M, Magrys S, *et al*. Evaluating the methodological quality of sports neuropsychology concussion research: a systematic review. *Brain Inj* 2010;24:1257–71.
50 Randolph C, McCrea M, Barr WB. Is neuropsychological testing useful in the management of sport-related concussion? *J Athl Train* 2005;40:139–52.
51 Echemendia RJ, Putukian M, Mackin RS, *et al*. Neuropsychological test performance prior to and following sports-related mild traumatic brain injury. *Clin J Sport Med* 2001;11:23–31.
52 Reeves DL, Winter KP, Bleiberg J, *et al*. ANAM genogram: historical perspectives, description, and current endeavors. *Arch Clin Neuropsychol* 2007;22(Suppl 1):S15–37.
53 Bleiberg J, Cernich AN, Cameron K, *et al*. Duration of cognitive impairment after sports concussion. *Neurosurgery* 2004;54:1073–8; discussion 1078–80.
54 Broglio SP, Puetz TW. The effect of sport concussion on neurocognitive function, self-report symptoms and postural control: a meta-analysis. *Sports Med* 2008;38:53–67.
55 Collie A, Darby D, Maruff P. Computerised cognitive assessment of athletes with sports related head injury. *Br J Sports Med* 2001;35:297–302.
56 Collie A, Maruff P, Makdissi M, *et al*. CogSport: reliability and correlation with conventional cognitive tests used in postconcussion medical evaluations. *Clin J Sport Med* 2003;13:28–32.
57 Iverson GL, Lovell MR, Collins MW. Validity of ImPACT for measuring processing speed following sports-related concussion. *J Clin Exp Neuropsychol* 2005;27:683–9.
58 Iverson GL, Lovell M, Podell K, *et al*. Reliability and validity of ImPACT. Poster presented at the annual conference of the International Neuropsychological Society, 2003, Honolulu, Hawaii, 2003.
59 Schatz P, Pardini JE, Lovell MR, *et al*. Sensitivity and specificity of the ImPACT test battery for concussion in athletes. *Arch Clin Neuropsychol* 2006;21:91–9.
60 Mayers LB, Redick TS. Clinical utility of ImPACT assessment for postconcussion return-to-play counseling: psychometric issues. *J Clin Exp Neuropsychol* 2012;34:235–42.
61 Broglio SP, Ferrara MS, Macciocchi SN, *et al*. Test-retest reliability of computerized concussion assessment programs. *J Athl Train* 2007;42:509–14.
62 Resch JE, Macciocchi SN, Ferrara MS. Equivalence of alternative forms of computerized neuropsychological test. Paper presented at the annual conference of the National Athletic Trainers' Association, 2012, St. Louis, MI, 2012.
63 Moser RS, Schatz P, Neidzwski K, *et al*. Group versus individual administration affects baseline neurocognitive test performance. *Am J Sports Med* 2011;39:2325–30.
64 Schatz P, Gibney B, Leitner D. Validation of millisecond timing accuracy in microcomputers (abstract). *Arch Clin Neuropsychol* 2009;24:538.
65 Cernich AN, Brennana DM, Barker LM, *et al*. Sources of error in computerized neuropsychological assessment. *Arch Clin Neuropsychol* 2007;22(Suppl 1):S39–48.
66 Bauer RM, Iverson GL, Cernich AN, *et al*. Computerized neuropsychological assessment devices: joint position paper of the American Academy of Clinical Neuropsychology and the National Academy of Neuropsychology. *Arch Clin Neuropsychol* 2012;27:362–73.
67 Echemendia RJ, Julian LJ. Mild traumatic brain injury in sports: neuropsychology's contribution to a developing field. *Neuropsychol Rev* 2001;11:69–88.
68 Echemendia RJ. Measurement issues in sports neuropsychology. *Bull Natl Acad Neuropsychol* 2010;25:5–9.
69 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;39:2319–24.
70 Schatz P. Long-term test-retest reliability of baseline cognitive assessments using ImPACT. *Am J Sports Med* 2010;38:47–53.
71 Randolph C, Kirkwood MW. What are the real risks of sport-related concussion, and are they modifiable? *J Int Neuropsychol Soc* 2009;15:512–20.
72 Echemendia RJ, Bruce JM, Bailey CM, *et al*. The utility of post-concussion neuropsychological data in identifying cognitive change following sports-related MTBI in the absence of baseline data. *Clin Neuropsychol* 2012;26:1077–91.
73 Schmidt JD, Register-Mihalik JK, Mihalik JP, *et al*. Identifying impairments after concussion: normative data versus individualized baselines. *Med Sci Sports Exerc* 2012;44:1621–8.
74 Putukian M, Echemendia RJ. Psychological aspects of serious head injury in the competitive athlete. *Clin Sports Med* 2003;22:617–30, xi.
75 Guskiewicz KM, Marshall SW, Bailes J, *et al*. Recurrent concussion and risk of depression in retired professional football players. *Med Sci Sports Exerc* 2007;39:903–9.
76 Mainwaring LM, Hutchison M, Bisschop SM, *et al*. Emotional response to sport concussion compared to ACL injury. *Brain Inj* 2010;24:589–97.
77 Mainwaring L, Bisschop S, Comper P, *et al*. Emotional reaction of varsity athletes to sports-related concussion. *J Exerc Sport Psychol* 2004;26:119–35.
78 Bloom GA, Horton AS, McCrory P, *et al*. Sport psychology and concussion: new impacts to explore. *Br J Sports Med* 2004;38:519–21.
79 Chen JK, Johnston KM, Petrides M, *et al*. Recovery from mild head injury in sports: evidence from serial functional magnetic resonance imaging studies in male athletes. *Clin J Sport Med* 2008;18:241–7.
80 Bailey CM, Samples HL, Broshek DK, *et al*. The relationship between psychological distress and baseline sports-related concussion testing. *Clin J Sport Med* 2010;20:272–7.
81 Kontos AP, Covassin T, Elbin RJ, *et al*. Depression and neurocognitive performance after concussion among male and female high school and collegiate athletes. *Arch Phys Med Rehabil* 2012;93:1751–6.
82 Ponsford J, Cameron P, Fitzgerald M, *et al*. Predictors of postconcussive symptoms 3 months after mild traumatic brain injury. *Neuropsychology* 2012;26:304–13.
83 Kirkwood MW, Yeates KO, Wilson PE. Pediatric sport-related concussion: a review of the clinical management of an oft-neglected population. *Pediatrics* 2006;117:1359–71.
84 Lovell MR, Fazio V. Concussion management in the child and adolescent athlete. *Curr Sports Med Rep* 2008;7:12–15.
85 Gioia GA, Vaughan CG, Sady MS. Developmental considerations in pediatric concussion evaluation and management. In: Apps JN, Walter KD, eds. *Pediatric and adolescent concussions: diagnosis, management, and outcomes*. New York: Springer Press, 2012:151–76.
86 McCrory P, Collie A, Anderson V, *et al*. Can we manage sport related concussion in children the same as in adults? *Br J Sports Med* 2004;38:516–19.
87 Gioia GA, Vaughan CG, Isquith PK. *Professional manual for pediatric immediate post-concussion assessment & cognitive testing (Pediatric ImPACT)*. Pittsburgh, PA: ImPACT Applications, Inc., 2012.
88 Gualtieri CT, Johnson LG. Reliability and validity of a computerized neurocognitive test battery, CNS Vital Signs. *Arch Clin Neuropsychol* 2006;21:623–43.
89 Yeates KO. Mild traumatic brain injury and postconcussive symptoms in children and adolescents. *J Int Neuropsychol Soc* 2010;16:953–60.
90 Gioia GA, Collins M, Isquith PK. Improving identification and diagnosis of mild traumatic brain injury with evidence: psychometric support for the acute concussion evaluation. *J Head Trauma Rehabil* 2008;23:230–42.
91 Gioia GA. Post-concussion symptom inventory, parent version and child version; National Institute of Neurological Disorders and Stroke (NINDS) common data elements 2012. http://www.commondataelements.ninds.nih.gov (accessed 10 Nov 2012).
92 King NS, Crawford S, Wenden FJ, *et al*. The Rivermead Post Concussion Symptoms Questionnaire: a measure of symptoms commonly experienced after head injury and its reliability. *J Neurol* 1995;242:587–92.
93 Janusz JA, Sady MD, Gioia GA. Post-concussion symptom assessment. In: Kirkwood M, Yeates KO, eds. *Mild traumatic brain injury in children and adolescents*. New York: Guilford Press, 2012:241–63.
94 Gioia GA, Schneider JC, Vaughan CG, *et al*. Which symptom assessments and approaches are uniquely appropriate for paediatric concussion? *Br J Sports Med* 2009;43(Suppl 1):i13–22.
95 Ayr LK, Yeates KO, Taylor HG, *et al*. Dimensions of postconcussive symptoms in children with mild traumatic brain injuries. *J Int Neuropsychol Soc* 2009;15:19–30.
96 Echemendia RJ, Cantu RC. Return to play following sports-related mild traumatic brain injury: the role for neuropsychology. *Appl Neuropsychol* 2003;10:48–55.
97 Register-Mihalik JK, Guskiewicz KM, Mihalik JP, *et al*. Reliable change, sensitivity, and specificity of a multidimensional concussion assessment battery: implications for caution in clinical practice. *J Head Trauma Rehabil*, 2012.
98 Iverson GL. Outcome from mild traumatic brain injury. *Curr Opin Psychiat* 2005;18:301–17.
99 Iverson GL, Zasler ND, Lange RT. Post-concussive disorder. In: Zasler ND, Katz HT, Zafonte RD, eds. *Brain injury medicine: principles and practice*. New York: Demos Medical Publishing, 2007:373–405.
100 Iverson GL. A biopsychosocial conceptualization of poor outcome from mild traumatic brain injury. In: Bryant R, Keane T, eds. *PTSD and mild traumatic brain injury*. New York: Guilford Press, 2012:37–60.

101 Borg J, Holm L, Peloso PM, *et al*. Non-surgical intervention and cost for mild traumatic brain injury: results of the WHO Collaborating Centre Task Force on mild traumatic brain injury. *J Rehabil Med* 2004:76–83.

102 Mittenberg W, Tremont G, Zielinski RE, *et al*. Cognitive-behavioral prevention of postconcussion syndrome. *Arch Clin Neuropsychol* 1996;11:139–45.

103 Echemendia RJ, Herring S, Bailes J. Who should conduct and interpret the neuropsychological assessment in sports-related concussion? *Br J Sports Med* 2009;43(Suppl 1):i32–5.

104 McCrea M. *Mild traumatic brain injury and postconcussion syndrome: the new evidence base for diagnosis and treatment*. New York, NY: Oxford University Press, 2007.

105 American Academy of Clinical Neuropsychology. American Academy of Clinical Neuropsychology (AACN) practice guidelines for neuropsychological assessment and consultation. *Clin Neuropsychol* 2007;21:209–31.

106 Herring SA, Cantu RC, Guskiewicz KM, *et al*. Concussion (mild traumatic brain injury) and the team physician: a consensus statement—2011 update. *Med Sci Sports Exerc* 2011;43:2412–22.

Advances in neuropsychological assessment of sport-related concussion

Ruben J Echemendia, Grant L Iverson, Michael McCrea, et al.

Br J Sports Med 2013 47: 294-298
doi: 10.1136/bjsports-2013-092186