Day of injury assessment of sport-related concussion

Michael McCrea,[1] Grant L Iverson,[2] Ruben J Echemendia,[3] Michael Makdissi,[4] Martin Raftery[5]

▸ Additional material is published online only. To view please visit the journal online (http://dx.doi.org/10.1136/bjsports-2013-092145)

[1]Departments of Neurosurgery and Neurology, Medical College of Wisconsin, Milwaukee, Wisconsin, USA
[2]Department of Psychiatry, University of British Columbia, Vancouver, British Columbia, Canada
[3]University of Missouri-Kansas City, Psychological and Neurobehavioral Associates, Inc., State College, Pennsylvania, USA
[4]The Florey Institute of Neuroscience and Mental Health, Melbourne Brain Centre, Melbourne, Australia
[5]International Rugby Board, New South Wales, Australia

Correspondence to
Dr Michael McCrea, Departments of Neurosurgery and Neurology, Medical College of Wisconsin, Milwaukee, WI 53226, USA; mmccrea@mcw.edu

Received 3 January 2013
Accepted 19 January 2013

To cite: McCrea M, Iverson GL, Echemendia RJ, *et al. Br J Sports Med* 2013;**47**:272–284.

ABSTRACT

Objective To conduct a critical review of the literature on instruments currently used in the assessment of sport-related concussion on the day of injury.

Data sources Computerised searches of the literature posted to MEDLINE, PubMed, CINAHL, PsychInfo and Cochrane Library from 1 January 1982 through 21 August 2012. Key words and medical embedded subheadings (MeSH) terms relevant to sport-related concussion were applied, which identified 577 articles.

Study selection In addition to MeSH term and key word criteria, a study was included in the analysis if the article: (1) was published in English, (2) represented original research, (3) pertained to sport-related concussion (ie, not non-sports traumatic brain injury), (4) included assessment or diagnostic data collected within 24 h of the injury event and (5) involved human research. A total of 41 studies qualified for review.

Data extraction All articles were examined to determine if the study met the additional requirements for inclusion. A standardised method was used to document critical elements of the study design, population, tests employed and key findings.

Data synthesis A large number of studies were analysed that reported data from testing conducted within 24 h of injury. These studies collectively demonstrated that a number of instruments are capable of measuring the acute effects of concussion across several domains, such as symptoms, cognition and balance.

Results Relating to specific assessment domains are compiled in separate tables and an interpretive summary of the findings is provided.

Conclusions Several well-validated tests are appropriate for use in the assessment of acute concussion in the competitive sporting environment. These tests provide important data on the symptoms and functional impairments that clinicians can incorporate into their diagnostic formulation, but they should not solely be used to diagnose concussion.

INTRODUCTION

Concussion is often considered by clinicians to be among the most complex injuries in sports medicine to diagnose, assess and manage. There is no perfect diagnostic test or marker for an immediate diagnosis of concussion in the sporting environment. Rather, it is a clinical diagnosis based largely on the observed injury mechanism, signs and symptoms. A vast majority of sport-related concussions (hereafter referred to as *concussion*) occur without loss of consciousness or frank neurological signs.[1–4] In milder forms of concussion, the athlete might be slightly confused, without clearly identifiable retrograde or post-traumatic amnesia. In addition, most concussions cannot be identified or diagnosed by neuroimaging techniques (eg, CT orMRI).

Over the past two decades, there has been a concentrated, international effort towards improved methods for diagnosing concussion. Subject matter experts have attempted to build consensus on the key signs and symptoms critical to the diagnosis, particularly during the acute postinjury period.[5 6] Sport governing bodies have sponsored global educational campaigns to make athletes, parents, clinicians and other key stakeholders better able to recognise the signs and symptoms that indicate possible concussion.

At the same time, a 'standardisation movement' has facilitated the development of several tests designed to aid in concussion assessment and diagnosis. A basic premise of this movement has been that performance-based assessment measures may be superior to an athlete's reporting of symptoms, which might be unreliable due to the athlete's tendency to under-report or fail to recognise their symptoms. Standardised tests are intended to provide a more objective, performance-based method of measuring postinjury recovery and determining an athlete's fitness to return to play. In most cases, these tests assess single domains of concussion effects (eg, postconcussion symptoms, neurocognitive functioning and postural stability). The recently developed Sports Concussion Assessment Tool—Second Edition (SCAT2)[7] involves an integrated, multimodal assessment model. In addition to brief screening tests, there has been a proliferation in recent years of computerised neurocognitive tests proposed for concussion assessment.

Standardised tests and measures can be used on the day of injury to assess the acute effects of injury. The purpose of this article is to describe the methods and results of a critical review intended to specifically address whether the existing tests and measures currently in use are sensitive and reliable enough on the day of injury to assist clinicians in accurately evaluating sport-related concussion.

METHODS

Literature search

We conducted a systematic survey of the published literature in several computerised databases, including: MEDLINE, PubMed, CINAHL, PsychInfo and Cochrane Library. Based on the focus of this critical review, we limited our search to the published literature over a 30-year period from 1 January 1982 through 21 August 2012. We used a combination of the following key words and medical embedded subheadings (MeSH) terms as parameters for our search:

1. *Concuss** (concussion, concussed, concussive, etc), *Brain Inj** (brain injury, injuries, injured, etc), *Head Inj** (head injury, injuries, injured, etc);

2. *Sport*, athlete*, football, soccer, ice hockey, field hockey, boxing, rugby, lacrosse, wrestling*;
3. *Diagnos*, assess*, test**.

Terms within each group were combined using the Boolean operator 'OR'; then the two groups were combined using the Boolean 'AND' operator. Search statistics were documented with respect to the number of articles generated by the MeSH term and key word search. In addition, the reference lists of acquired articles of relevance were reviewed for other articles not found in the electronic databases.

Study selection criteria

In addition to meeting the MeSH term and key word search criteria, the basic requirements for a study to be included were that the article: (1) was published in English, (2) represented original research, (3) pertained to sport-related concussion (ie, not non-sports traumatic brain injury), (4) included assessment or diagnostic data collected on the day of injury (eg, within 24 h of the injury event) and (5) involved human research (no animal studies). Duplicate articles from more than one electronic database were eliminated.

Data extraction and analysis

Each article identified by the electronic literature search was reviewed to determine if it met the inclusion criteria described above. In some instances, this determination could be made from a review of the abstract. In other cases, it required a review of the full-text article. For the included studies, a standardised data extraction method was used to document the study design, population and assessment techniques (see Tables 1–6). For each study, the reviewer provided a summary of the key findings, statistics and a critical assessment of the evidence relevant to the day of injury assessment. We did not conduct a detailed or systematic analysis of the psychometric properties of the instruments included in this review.

RESULTS

In total, the electronic literature database search identified 577 articles. After applying additional requirements and eliminating duplicate articles, a total of 44 qualified for further review. A majority of articles were rejected because data were not collected within 24 h of the injury. Several studies included assessments across multiple domains (eg, symptoms, cognition and balance) and were included in those individual domains accordingly. Tables 1–6 below provide a summary of key findings from studies in each assessment domain.

Symptom rating scales

Several studies have documented symptoms of concussion immediately following, or over the first 24 h after, injury. These studies usually use a symptom rating scale completed by the athlete. The most commonly and consistently reported acute symptoms, across studies, are headaches, dizziness and some form of mental status disturbance, such as mental clouding, confusion or a slowing down of feelings.[8–14] Other commonly reported acute symptoms include visual problems, fatigue and nausea.[8 11 13 14] Some observable signs of concussion include a dazed facial expression and unsteady gait.[13]

Data from 18 studies that reported results from symptom rating scales in the first 24 h following injury were extracted and included in table 1. The time interval following injury varied considerably, from minutes to the following day. Research groups used many variations of concussion rating scales, which varied considerably in the number of symptoms being assessed.

The Post-Concussion Scale[15–17] has evolved over the years, and slightly different versions have been used in published studies.[18–24] The internal consistency of the scale ranges from 0.88 to 0.94 in high school and college students, and from 0.92 to 0.93 in concussed athletes.[25] Normative data for the scale are available for 1391 young men and 355 young women in high school or university.[25]

SCAT2 is an outcome measure that includes symptom ratings, balance testing and cognitive screening.[7] Two scores are derived from the SCAT2 symptom scale: total number of symptoms and symptom severity score. The symptom severity score is intuitive in that it is the sum of the Likert ratings for the entire scale. This score, however, is not included in the SCAT2 total score. The total number of symptoms score is included in the SCAT2 total score. This score is reverse scored in that the total number of symptoms endorsed as mild or greater are subtracted from 22 (thus, if a person endorses 8 symptoms, his score would be 14). A number of concerns have been expressed about the design and scoring of SCAT2, and recommendations have been offered for improving it for clinical use.[26] Normative reference values are available for high school students. Data are not available on large samples of concussed athletes.

The Concussion Symptom Inventory (CSI[27]) is a 12-item scale that was developed using samples of more than 16 000 uninjured athletes and more than 600 concussed athletes. It can be derived from the Post-Concussion Scale and SCAT2. A comparison of the three concussion rating scales is provided in table 2.

One of the most salient findings from this review is that these rating scales are sensitive to the acute effects of concussion in high school, university and professional athletes. Acutely concussed athletes, on average, obtain high scores on symptom rating scales, which is consistent with a meta-analytic review of the literature. Broglio and Puetz[28] extracted data from 14 studies involving 1796 injured athletes. Across the 14 studies, the mean overall effect size an average of 1.2 days after injury was large (ie, –3.31). In 10 studies that included both symptom ratings and cognitive assessment (N=913 injured athletes), the average effect sizes for symptom ratings (–1.21) and cognition (–0.95) were more similar. Symptom checklist scores and the corresponding sensitivity of the scales typically diminish with the passage of time due to natural recovery.

Neurocognitive tests

A total of 31 studies using cognitive testing on the day of injury qualified for review (see table 3). Data were available from several competitive levels across a broad array of sports. Most of these studies used brief cognitive screening tests intended for rapid assessment in the sporting environment (eg, sideline and rink side). Fewer studies utilised conventional ('paper and pencil') neuropsychological testing within 24 h of injury, and 11 studies involved the use of computerised neuropsychological testing. The most widely studied instrument has been the Standardised Assessment of Concussion (SAC; 12 studies). ANAM (n=5), CogSport/Axon (n=3) and ImPACT (3 studies) were the most commonly studied computerised tests.

The array of studies reviewed illustrates the ability to measure or quantify the nature and magnitude of cognitive impairment within the first 24 h of concussion. These studies document that neuropsychological tests can detect changes across multiple domains of cognitive functioning that are susceptible to the acute effects of concussion, such as cognitive processing speed, working memory, attention and concentration, new learning

 McCrea M, *et al*. *Br J Sports Med* 2013;**47**:272–284. doi:10.1136/bjsports-2013-092145

Table 1 Studies using symptom checklists on the day of injury

Reference		Study design		Sample					
First author	Year	Study type	Measure	Sports	Age/ level	M/F	Concussed N	Controls N	Findings
Prichep[43]	2012	PHC	CSI	FB	HS/C	M	65	0	Athletes with concussions were classified as having a mild concussion (n=51) or a moderate concussion (n=14) based on clinical characteristics. Those with moderate concussions had significantly greater CSI total scores (ie, 31.5) than those with mild concussions (ie, 17.1)
Barr[42]	2012	PHC	CSI	FB	HS/C	M	59	31	Concussed athletes (M=20.1; SD=13.6) had significantly greater total scores than controls (M=2.1; SD=3.4)
McCrea[41]	2010	CCS	CSI	FB	HS/C	M	28	28	Immediately following injury, the concussed group had a significantly greater CSI score than controls. 18.8 (15.1) vs 2.1 (3.4) p<0.05. Also, significantly greater CSI scores at days 1 and 3
McCrea[46]	2009	PHC	Graded Symptom Checklist (GSC)	FB, SCR, LX, IH	HS/C	M/F	562 (223 With no symptom-free waiting period (SFWP) and 339 with an SFWP of any duration)	0	The average GSC scores for the SFWP and No SFWP groups were 20.6 and 21.4, respectively, immediately following injury and 16.0 and 18.0 following the game
Randolph[27]	2009	CR	12-Item Concussion Symptom Inventory (CSI)	FB, SCR, LX, IH	HS/C	M/F	641	0	Average baseline CSI scores were M=2.4 (SD=4.7). Postconcussion scores were: immediate/sideline M=11.1 (SD=12.5), postgame M=8.9 (SD=11.5), day 1 M=8.3 (SD=10.3), day 3 M=4.6 (SD=8.1) and day 5 M=2.9 (SD=6.6)
Broglio[29]	2007	CR	9-Item Self-report Symptom Scale	FB, SCR, OT	C	M/F	75	0	Postinjury evaluation done within 24 h of injury. 51 of 75 athletes showed a clinically significant increase in duration or severity on the nine-item concussion-related symptom inventory at day 1. Mean total severity scores were 3.0 (SD=4.0) at baseline and 15.9 (SD=11.0) on day 1
Register-Mihalik[47]	2007	PHC	GSC	FB, LX, SCR, OT	HS/C	NA	247	0	On the 20-item GSC, total severity scores were as follows: baseline M=2.7 (SD=4.8), day 1 M=11.7 (SD=13.0), day 3 M=5.8 (SD=10.2) and day 7 M=1.9 (SD=6.0)
Hynes[48]	2006	PHC	University of Guelph Hockey Neck Injury Questionnaire	IH	HS/C/O	M	13	0	Whiplash injuries and direct head trauma-related concussions both result in symptoms in the first 24h following injury
Bruce[49]	2004	PHC	PCSS	FB, IH, SCR, LX RB, OT	C	M	57	29	Athletes with a previous history of ≥1 concussion (n=30) reported significantly more symptoms at baseline than participants without a previous concussion history (n=27). However, previously injured athletes reported significantly fewer PCS symptoms at 2 h postinjury than non-previously injured athletes (counter to expectations). There were no differences in symptom reporting at 48 h. Compared with controls, both groups reported more symptoms at 2 and 48 h postinjury
Field[50]	2003	CCS	PCS	FB, SCR	HS/C	M/F	54	38	Concussed athletes (high school and college) had significantly more postconcussive symptoms 24 h after injury than controls (high school concussed M=19.8 (SD=16.0) and control M=3.8 (SD=5.7); college concussed M=28.3 (SD=24.5), control M=7.9 (SD=12.8)
Guskiewicz[12]	2003	CR	GSC	FB	C	M	184	0	Immediately following injury, headache (85.2%) was the most commonly reported symptom, followed by dizziness/balance difficulties (77%) and feeling cognitively 'slowed down' (69.4). Among individuals with headache immediately following injury, 89.2% still reported headache at 3 h, 65.9% at 24 h after injury, 24.5% at day 5 and 13.8% at day 7
Lovell[21]	2003	CCS	PCS	FB, SCR, OT	HS	M/F	64	24	Preseason PCS total scores were 9.9 (SD=12.9) for the concussed sample and 3.4 (SD=7.1) for the controls. At approximately 36 h postinjury, PCS total scores were 25.3 (SD=23.8) and 1.4 (SD=3.4) in the concussed sample and controls, respectively

Continued

Table 1 Continued

Reference		Study design		Sample					
First author	Year	Study type	Measure	Sports	Age/level	M/F	Concussed N	Controls N	Findings
McCrea[2]	2003	CCS	GSC	FB	C	M	94	56	There was a large difference in total scores between concussed athletes and controls immediately following injury (ie, 20.9 points) The mean difference between groups following the game was 17 points, and at 24 h, it was 11.5 points
Peterson[31]	2003	CCS	16-Item Self-report Symptom Scale	FB, SCR, OT	C	M/F	24	18	There were significantly more symptoms for the concussion group at day 1 (p<.001). On day 1 postinjury, the most prominent symptoms were headache and difficulty in concentrating. Other very commonly reported symptoms were feeling in a fog, balance problems and feeling slowed down
Piland[51]	2003	CCS	Head Injury Scale (HIS) (16-Item Post-Concussion Scale)	FB/S	C	M/F	17	16	On days 1 and 2 postinjury, the concussion group had significantly greater HIS scores than controls
Johnson[52]	2002	CCS	18-Item Post-Concussion Scale	RB, IH	C	M/F	9	9	Injured individuals reported significantly more postconcussion symptoms than controls on day 1 postinjury
Echemendia[53]	2001	CCS	Post-Concussion Symptom Checklist	FB, IH, SCR, OT	C	M/F	29	20	Injured athletes reported a significantly greater number of postconcussion symptoms 2 h following injury 8.5 (8.9) vs 1.50 (3.2) p=0.044
Macciocchi[3]	1996	CCS	Symptom Checklist	FB	C	M	183	48	Concussed players had significantly increased symptoms (headache, dizziness, memory problems) at 24 h relative to baseline and compared with controls

Author, the last name of the first author; No., reference number; year, the year of publication.
Study type is coded as follows (per the Oxford Centre for Evidence based Medicine): CCS, case control studies (retrospective); CR, case reports; CrS, cross-sectional studies; CS, clinical series (some kind of control, including historical controls); PHC, prospective and historical cohort studies; RCT, randomised clinical trials.
Measures refer to specific tests (eg, SCAT2, BESS, etc).
Sports coded as follows: BX, boxing; FB, football; FH, field hockey; IH, ice hockey; LX, lacrosse; OT, other; RB, rugby; SCR, soccer; WR, wrestling.
Age/level is coded as follows: C, college; HS, high school; O, other; P, professional; Y, youth.
F/M indicates gender: F, female and M, male; list both if it applies.

Table 2 Comparing three concussion symptom rating scales

Post-Concussion Scale	Concussion Symptom Inventory	Sport Concussion Assessment Tool (SCAT2)
Items=22	Items=12	Items=22
Likert rating scale: 0–6	Likert rating scale: 0–6	Likert rating scale: 0–6
Baseline Normative Scores	Baseline Normative Scores	Baseline Normative Scores
Total score: 1391 high school & college males* Mean=4.6, median=2.0, SD=7.7 Cronbach's α (males)=0.88 Total score: 355 high school & college females* Mean=7.9, median=4.0, SD=11.5 Cronbach's α (females)=0.91	Total score: 641 high school and university students† Mean=2.4 (SD=4.7)	Total symptom score: 1134 high school athletes Mean=16.9 (SD=5.3)‡ Total symptom score: 214 high school athletes Mean=19.75 (SD=3.28)§
Acutely concussed	Acutely concussed	Acutely concussed
Total score: 217 concussed young men* Mean=23.3, median=19.0, SD=7.7 Cronbach's α (males)=0.93 Total score: 43 concussed young women* Mean=27.9, median=23.0, SD=22.4 Cronbach's α (females)=0.92	641 Concussed high school & university students† Immediate/sideline mean=11.1 (SD=12.5) Postgame mean=8.9 (SD=11.5) Day 1 mean=8.3 (SD=10.3) Day 3 mean=4.6 (SD=8.1) Day 5 mean=2.9 (SD=6.6)	Not available
Individual items	Individual items	Individual items
Headache	Headache	Headache
Nausea	Nausea	Nausea or vomiting
Vomiting	–	–
Balance problems	Balance problems/dizziness	Balance problems
Dizziness	–	Dizziness
Fatigue	Fatigue	Fatigue or low energy
Trouble falling asleep	–	Trouble falling asleep (if applicable)
Sleeping more than usual	–	–
Sleeping less than usual	–	–
Drowsiness	Drowsiness	Drowsiness
Sensitivity to light	Sensitivity to light	Sensitivity to light
Sensitivity to noise	Sensitivity to noise	Sensitivity to noise
Irritability	–	Irritability
Sadness	–	Sadness
Nervousness	–	Nervousness or anxiety
Feeling more emotional	–	More emotional
Numbness or tingling	–	–
Feeling slowed down	Feeling slowed down	Feeling slowed down
Feeling mentally 'Foggy'	Feeling like 'in a fog'	Feeling like 'in a fog'
Difficulty concentrating	Difficulty concentrating	Difficulty concentrating
Difficulty remembering	Difficulty remembering	Difficulty remembering
Visual problems	Blurred vision	Blurred vision
–	–	'Pressure in Head'
–	–	Neck Pain
–	–	'Don't feel right'
–	–	Confusion

*Lovell *et al*.[25]
†Randolph *et al*.[27]
‡Valovich McLeod *et a.l*[54]
§Jinguji *et al*.[55]
Author, the last name of the first author; No., reference number; year, the year of publication.
Study type is coded as follows (per the Oxford Centre for Evidence based Medicine): CCS, case control studies (retrospective); CR, case reports; CrS, cross-sectional studies; CS, clinical series (some kind of control, including historical controls); PHC, prospective and historical cohort studies; RCT, randomised clinical trials.
Measures refer to specific tests (eg, SCAT2, BESS, etc).
Sports coded as follows: BX, boxing; FB, football; FH, field hockey; IH, ice hockey; LX, lacrosse; OT, other; RB, rugby; SCR, soccer; WR, wrestling.
Age/level is coded as follows: C, college; HS, high school; O, other; P, professional; Y, youth.
F/M indicates gender: F, female and M, male; list both if it applies.

and memory and executive functioning. Measures of orientation appear less sensitive, but might be a marker of a more severe gradient of injury when impaired.

The study by Broglio *et al*[29] was the most extensive comparison of conventional and computerised neurocognitive testing approaches within 24 h of injury. This study revealed different levels of detecting cognitive abnormalities across ImPACT, Headminder CRI and a conventional test battery. A high percentage of symptomatic athletes exhibited a significant decline on both computerised and conventional neuropsychological testing on the day of injury. Approximately 15–30% of athletes were also impaired on testing after reporting a full symptom recovery. It should be noted, however, that 10–25% of athletes who were still symptomatic showed no significant decline on cognitive testing.

Overall, the studies reviewed illustrated a significant decline in cognitive functioning compared with an athlete's individual preinjury baseline performance, relative to the performance of

Table 3 Studies using cognitive tests on the day of injury

Reference		Study design		Sample					
First author	Year	Study type	Measure	Sport	Age/level	M/F	Concussed N	Controls N	Findings
Prichep[43]	2012	PHC	Standardised Assessment of Concussion (SAC), Automated Neuropsychological Assessment Metric (ANAM)*	FB	HS/C	M	65 (51 mild, 14 moderate)	NA	873 Players seasons involved in baseline testing. At the time of injury, players with moderate concussion (defined by presence of LOC, amnesia, more severe symptoms) had worse cognitive performance on the SAC than those with mild concussion (M=23.8 vs 26.3; F=9.1, p=0.0038) At the time of injury, athletes with moderate concussion performed significantly worse than athletes with mild concussion on ANAM CDD, CDS, M2S, SRT and SR2 subtests (p<0.05) Mean SAC and ANAM scores at the time of injury were not statistically significantly different between two groups of athletes who returned to play in less than or greater than 14 days after injury, although data trended towards poorer performance in those who returned after 14 days
Barr[42]	2012	CCS	SAC, ANAM	FB	HS/C	M	59	31	Concussed athletes obtained lower scores than matched controls on the SAC on the day of injury (25.6 (3.3) vs 27.9 (1.60); p<.05) Concussed athletes obtained lower scores than matched controls in 5 of 6 ANAM subtests (ie, CDS, M2S, MTH, SRT, SR2) on day of injury
Moriarity[56]	2011	PHC	SCAT2, Axon Sports	BX	Am	M	160	NA	10.6% of boxers failed postbout computerised testing on the Axon Sports battery, evidenced by impaired reaction time that was not evident on routine ringside examination
Echlin[57]	2010	CR	Sports Concussion Assessment Tool—2nd Edition (SCAT2) (SAC cognitive subtest), Immediate Postconcussion Assessment and Cognitive Testing (ImPACT)	IH	O (Jr. ice hockey)	M	17 (5 sustained a second concussion, but 1 concussion was excluded due to study criteria. 21 total concussions evaluated in the study)	NA	SCAT2 (SAC) and ImPACT were administered in a limited number of cases. Individual recovery curves indicate a decline from baseline to time of injury on the SCAT2 SAC in several cases, but no statistical analyses were reported. In 8 (38%) of 21 cases of concussions diagnosed and sequentially followed, the athletes scored either in the normal range or within their baseline ImPACT score but were clearly still symptomatic. In 2 (10%) of 21 concussions evaluated, the player was symptom-free and exhibited cognitive deficits on SCAT2 or ImPACT
Makdissi[58]	2010	CCS	Digit Symbol Substitution Test (DSST), Trail Making B, CogSport	FB (Aus)	O (elite)	M	78	NA	Deficits on DSST and Trail Making B recovered concurrently with symptoms, but impairments on computerised testing recovered 2–3 days later and were evident in 35% of concussed athletes after symptom resolution
McCrea[41]	2010	CCS	SAC, ANAM	FB	HS/C	M	28	28	At the time of injury, concussed athletes obtained significantly lower scores than matched controls on the SAC (25.5 (3.3) vs 27.9 (1.6); p<0.05) and on ANAM MTH, SRT, SR2 subtests (all p<0.05). There were no significant group differences on ANAM CDD, CDS and M2S subtests
McCrea[46]	2009	PHC	SAC	FB, SCR, LX, IH	HS/C	M/F	562 (223 with SFWP, 339 with no SFWP)	0	Concussed athletes scored significantly lower than baseline on the SAC immediately and 2–3 h after injury. At those two acute time points, there were no statistically significant differences between concussed athletes who eventually did or did not observe a symptom-free waiting period (SFWP)
Covassin[59]	2008	PHC	ImPACT	SCR, LX, FB, WR, OT	C	M/F	57 (36 with no prior concussion, 21 with 2 +prior)	NA	At day 1 postinjury (mean 1.2 days), there were no differences between the no prior concussion group and 2+ prior concussions group on the ImPACT cognitive measures (verbal memory, reaction time, visual memory, processing speed). At day 1, athletes with and without a history of concussion had lower performance on ImPACT verbal memory (p=0.002), visual memory (p<0.001), visual processing speed (p=0.001) and reaction time (p<0.001) compared to preinjury baseline

Continued

Table 3 Continued

Reference		Study design		Sample					
First author	Year	Study type	Measure	Sport	Age/level	M/F	Concussed N	Controls N	Findings
Broglio[29]	2007	CR	ImPACT, Headminder Concussion Resolution Index (CRI), HVLT, Digit Span, SDMT, COWAT	FB, SCR, OT	C	M/F	75	0	Within 24 h of injury, ImPACT was 79.2% sensitive (using 1+impaired cognitive test or symptoms). 62.5% of concussed athletes were impaired on at least one cognitive subtest on ImPACT; 16.7% of concussed athletes showed a significant increase from baseline on the ImPACT symptom inventory, but no decline on cognitive subtests; 4.2–41.7% of concussed athletes were impaired on the various ImPACT subtests; 62.5% were impaired on the ImPACT symptom inventory Headminder CRI was 78.6% sensitive (using 1+impaired cognitive test). 78.6% of concussed athletes were impaired on at least one of the Headminder subtests; 50–71.4% of individuals were impaired on the various Headminder CRI subtestsA paper-and-pencil assessment battery was 43.5% sensitive (using 2+ impaired tests). 30.4–52.2% of concussed athletes were impaired on the various paper and pencil measures. Trail Making Tests and Symbol Digit Modalities Tests were most sensitive When combined with postural control testing and symptom assessment, the following sensitivity values were observed: paper and pencil: 95.7, ImPACT: 91.7, Headminder CRI: 89.3. No specificity data were reported because there were no controls
Moriarity[60]	2004	CCS	CogSport	BX	C (college amat. boxers)	M	7	30	Boxers whose bouts were stopped by the referee (but not clinically diagnosed with concussion) had significantly slower simple reaction times and choice reaction time on CogSport<2 h postmatch compared to baseline
Bleiberg[61]	2004	CCS	ANAM	BX	O (military cadets)	M	68	18	From 0–23 h postinjury, concussed athletes scored significantly lower than control subjects on ANAM SPD and MTH subtests. They remained worse for SPD on 1–2 day interval. SRT and CPT deteriorated for both groups from baseline to 0–23 h postinjury. The other four ANAM subtests showed no difference from baseline to 0–23 h postinjury
Field[50]	2003	CCS/ PHC	HVLT, Digit Span, SDMT, Trail Making Tests, COWAT, Brief Visual Spatial Memory Test-Revised (BVMT-R)	FB, SCR	HS/C	M/F	54	38	At 24 h after injury, there were significant differences between concussed athletes and controls on select cognitive measures, stratified by the level of competition High school: HVLT learning, BVMT-R learning and BVMT-R delayed recall College: HVLT learning and delayed recall
Bruce[62]	2003	CCS	HVLT	FB, IH, SCR, OT	C	M	19	19	At 2 h postinjury, concussed athletes performed significantly slower than controls on the Stroop Color Word test. There were no differences between the concussed group and the controls in semantic clustering strategies on the HVLT
McCrea[2]	2003	CCS	SAC	FB	C	M	94	56	Concussed college athletes obtained significantly lower scores than matched controls on the SAC immediately and again within 2–3 h after concussion
Peterson[31]	2003	CCS	Hopkins Verbal Learning Test (HVLT), Trail Making Tests A & B, Symbol Digit Modalities test (SDMT), Digit Span, Forward/Backward, Controlled Oral Word Association Test (COWAT)	FB, SCR, OT	C	M/F	24	18	Concussed athletes scored lower than controls on a composite index of information processing speed (Trail Making B, SDMT) on day 1 (p<0.003)
Daniel[63]	2002	CR	SAC	FB	C	M	21	NA	Concussed individuals showed a significant drop in mean SAC total score from baseline to immediately following injury

Continued

Table 3 Continued

Reference		Study design		Sample					
First author	Year	Study type	Measure	Sport	Age/level	M/F	Concussed N	Controls N	Findings
McCrea[64]	2002	CR	SAC	FB	HS/C	M	91	NA	Mean SAC total scores (and all 4 subtests) for concussed athletes were significantly lower than preinjury baseline performance immediately after injury (p<0.0001) and at 15 min postinjury (p=0.035). Athletes with LOC scored lowest on the SAC, followed by athletes with PTA but no LOC, and athletes with no LOC/ no PTA immediately following injury and 15 min postinjury
Barr[65]	2001	CCS	SAC	FB	HS/C	M	50	68	Concussed athletes exhibited an approximate 4-point drop in SAC scores (27.1–22.9) from baseline to the time of injury, compared to an increase of 0.2 in the control group from baseline to retest (p 0.001). Reliable change index and receiver operator characteristic curve analyses indicated that a change score of −1 (baseline to postinjury) resulted in maximum sensitivity and specificity in classifying concussed and non-concussed athletes. Specificity increased with larger change scores, and sensitivity decreased
Echemendia[53]	2001	CCS	Digit span, HVLT, Stroop Test	FB, IH, SCR, OT (basket-ball)	C	M/F	29	20	Concussed athletes performed significantly worse than athlete controls 2 h after injury on Digit Span Backward, HVLT Learning, HVLT Delayed, HVLT percent retained and Stroop (all p<0.04). No group differences were found on other neurocognitive measures
Macciocchi[66]	2001	PHC	Paced Auditory Serial Addition Task (PASAT), Trail Making Tests, Halstead Reitan Neuropsychological Test Battery (HRNTB), SDMT	FB	C	M	24 (12 who sustained 1 concussion, 12 who sustained 2 concussions)	NA	No difference between athletes with 1 vs 2 concussions in test performance on Trail Making A & B, SDMT, or PASAT within 24 h of concussion. Statistics comparing baseline to within 24 h postinjury on cognitive measures were not reported, but referenced as improved performance over serial testing
Guskiewicz[35]	2001	CCS	Trail Making Tests, Digit Span, Stroop Test, HVLT	NA	C	NA	36	36	Significant group differences between concussed athletes and controls on Trail Making Test B and digit span within 1 day of injury. No difference in cognitive performance by athletes who experienced LOC and/or amnesia vs injured athletes without LOC or PTA
McCrea[67]	2001	CCS	SAC	FB	HS/C	M	63	55	SAC total score for concussed athletes at the time of injury was significantly lower than preinjury baseline and lower than uninjured controls. A decline of one point on the SAC provided maximum sensitivity and specificity (95% sensitive, 76% specific) in differentiating concussed and non-concussed athletes. Specificity increased with larger change scores, and sensitivity decreased
Warden[68]	2001	CR	ANAM	BX	O (military cadets)	M	14	0	Within 1 h postinjury, concussed boxers were significantly slower than baseline on ANAM simple reaction time test. Figure presented, but no statistics for 1 h data
Matser	2000	CCS	Categorization Task Text, Digit Symbol Test, Logical Memory: Short Term Memory and Long Term Memory subtests; and Visual Reproduction: Short Term Memory subtest and Long Term Memory subtest	BX	O (Amat. boxers)	M	38	28	After a boxing match, boxers who competed exhibited a pattern of impaired performance on all of the assessments listed (all p<0.05)
McCrory[14]	2000	CCS	Digit Symbol Substitution Test (DSST)	OT (Aus. FB)	O (elite)	M	23	0	Within 15 min of injury, concussed athletes had significantly lower scores on the DSST compared to baseline (in all groups stratified by symptom duration). DSST scores were significantly lower for concussed athletes with symptoms lasting >15 min compared to those with symptoms <5 min. DSST total score correlated with the number of reported symptoms

Continued

Review

Table 3 Continued

Reference		Study design		Sample					
First author	Year	Study type	Measure	Sport	Age/level	M/F	Concussed N	Controls N	Findings
Collins[69]	1999	CCS	HVLT, Trail Making Tests, Digit Span, SDMT, Grooved pegboard, COWAT	FB	C	M	16	10	Performance of the concussed group was ∼ 1 SD worse than controls on HVLT total learning (trials 1–3) and HVLT delayed memory within 24 h of injury. No statistics were reported on these or other cognitive tests
McCrea[70]	1998	CR	SAC	FB	HS/C	M	33	NA†	Compared to preinjury baseline and compared to normal controls at baseline, concussed athletes obtained significantly lower total scores on the SAC ($p<0.0001$) and on SAC orientation ($p<0.0001$), memory ($p<0.0001$), concentration ($p<0.0007$) and delayed recall ($p<0.0001$) subtests immediately following injury
Guskiewicz[33]	1997	CCS	Trail Making A, Digit Span, Stroop Test, HVLT	NA	C	M/F	11	11	On day 1 postinjury, there were no significant differences between concussed athletes and controls on Trail Making A, Digit Span or HVLT
McCrea[71]	1997	CR	SAC	FB	HS	M	6	NA	Total scores for concussed athletes on the SAC were significantly lower than a non-concussed sample ($p<0.0001$) and below baseline performance ($p<0.05$)
Macciocchi[3]	1996	CCS	PASAT, SDMT, Digit Span, Trail Making Tests	FB	C	M	183	48	At 24 h postinjury, concussed athletes showed significantly less improvement from baseline on the PASAT, Digit Symbol test and Trail Making Test A & B
Maddocks[13]	1995	CCS	Orientation and recent memory questions (Orientation=name, DOB, age, year, month, day, date, time. Recent memory = grounds (location), quarter, time in quarter, who kicked last goal, most recent opponent, did they win last week)	OT (Aus. FB)	P	M	28	28	Controls performed better than concussed athletes on orientation items administered within 10 min of injury, but no items reached statistical significance. Controls scored significantly better than concussed athletes on all recent memory items

*ANAM abbreviations for specific tasks: ANAM, Automated Neuropsychological Assessment Metrics; CDD, Coding Substitution Delayed; CDS, Coding Substitution Learning; MTH, mathematical processing; M2S, matching to sample; SRT, simple reaction time; SR2, simple reaction time (second administration); all ANAM data reported are based on throughput scores. All ANAM data reported are based on throughput scores.
†568 Athletes and controls with baseline results; 33 injured athletes compared to baseline and matched control baseline performance.
Author, the last name of the first author; No., reference number; year, the year of publication.
Study type is coded as follows (per the Oxford Centre for Evidence based Medicine): CCS, case control studies (retrospective); CR, case reports; CrS, cross-sectional studies; CS, clinical series (some kind of control, including historical controls); PHC, prospective and historical cohort studies; RCT, randomised clinical trials.
Measures refer to specific tests (eg, SCAT2, BESS, etc).
Sports coded as follows: BX, boxing; FB, football; FH, field hockey; IH, ice hockey; LX, lacrosse; OT, other; RB, rugby; SCR, soccer; WR, wrestling.
Age/level is coded as follows: C, college; HS, high school; O, other; P, professional; Y, youth.
F/M indicates gender: F, female and M, male; list both if it applies.

Table 4 Studies using balance tests on the day of injury

Reference		Study design		Population					
First author	Year	Study type	Measures	Sport	Age/level	M/F	Concussed N	Controls N	Findings
Prichep[43]	2012	PHC	BESS	FB	HS, C	M	65	0	Divided into mild and moderate concussion groups based on the severity of symptoms at the time of injury. No significant group differences were observed on BESS
Barr[42]	2012	PHC	BESS	FB	HS, C	M	59	31	At the time of injury, there were no differences in BESS scores between the concussed and control groups (17.6, SD 11.0 vs 17.7, SD 6.6)
Echlin[57]	2010	PHC	Modified BESS from SCAT2	IH	HS, C	M	15	0	Only 5 individuals had modified BESS data available at baseline and the time of injury assessment (derived from figure 3 in paper). 3/5 concussed athletes demonstrated an increased number of errors at the time of injury compared to baseline
Register-Mihalik[47]	2007	CCS	BESS	FB, SCR, LX, OT	HS, C		145 (study arms 1 & 3)		No significant effects of baseline or post-traumatic headache reporting and performance on BESS postinjury
Broglio[29]	2007	PHC	SOT	FB, SCR, OT	C	M 62, F 13	94	0	SOT data available on 63/75 individuals (abnormal defined as 1 SD below baseline). 39/63 were identified as having impaired postural control on at least 1 SOT variable within 24 h of sustaining a concussion 24/63 showed no impairment compared with baseline
Peterson[31]	2003	PHC	SOT	FB, SCR, OT	C	M 18, F 6	24	18	Significant deficits demonstrated on composite balance and vestibular ratio scores for concussed athletes on day 1 postinjury assessment. No significant differences were found on the somatosensory ratio
McCrea[2]	2003	PHC	BESS	FB	C	M	79	56	Significant deficits were observed on BESS scores immediately after concussion (5.8, 95% CI –0.7 to 12.3), postgame or practice (5.7, 95% CI 1.3 to 10.1) and day 1 postinjury (2.7, 95% CI –0.1 to 5.6)
Guskiewicz [35]	2001	PHC	SOT and BESS	Not stated	C	M 18, F 11	36	36	Significant differences were observed for all balance measures (composite score, visual ratio and vestibular ratio on SOT and BESS) on day 1 assessment in the concussed group, whether compared with baseline or control group data
Riemann[34]	2000	PHC	SOT and Balance Error Scoring System (BESS)	Not stated	C	M 15, F 1	16	16	Significant differences were observed between concussed athletes and controls on testing with both the computerised balance system (lower SOT composite score) and clinical tests of balance (higher BESS error rate) on day 1 postinjury
Guskiewicz[33]	1997	PHC	Sensory Organizational Test (SOT)	Not stated	C	M 8, F 3	11	11	Composite score, visual ratio and vestibular ratio deficits observed in concussed athletes compared to controls at day 1 assessment
Guskiewicz[32]	1996	PHC	Chattecx Balance System	FB, OT	HS, C	M 18, F 1	19	19	Significant increase in sway index on day 1 postinjury in the concussed group (on all 3 platforms—normal, foam and moving). No significant changes were observed in the control group over time

Author, the last name of the first author; No., reference number; year, the year of publication.
Study type is coded as follows (per the Oxford Centre for Evidence based Medicine): CCS, case control studies (retrospective); CR, case reports; CrS, cross-sectional studies; CS, clinical series (some kind of control, including historical controls); PHC, prospective and historical cohort studies; RCT, randomised clinical trials.
Measures refer to specific tests (eg, SCAT2, BESS, etc).
Sports coded as follows: BX, boxing; FB, football; FH, field hockey; IH, ice hockey; LX, lacrosse; OT, other; RB, rugby; SCR, soccer; WR, wrestling.
Age/level is coded as follows: C, college; HS, high school; O, other; P, professional; Y, youth.
F/M indicates gender: F, female and M, male; list both if it applies.

McCrea M, et al. Br J Sports Med 2013;47:272–284. doi:10.1136/bjsports-2013-092145

Table 5 Studies using electrophysiological measures on the day of injury

Reference		Study design		Sample					
First author	Year	Study type	Measure	Sports	Age/level	M/F	Concussed N	ControlsN	Findings
Prichep[43]	2012	PHC	qEEG/TBI index	FB	HS/C	M	65 (51 'mild' and 14 'moderate')	NA	873 Player seasons involved in baseline testing. After injury, TBI Index was greater in moderate vs mild concussion at the time of injury (p<0.01). TBI Index at the time of injury was significantly associated with the length of time to return to play. TBI index at the time of injury yielded a sensitivity of 55% and specificity of 94%
Barr[42]	2012	CCS	qEEG/TBI index	FB	HS/C	M	59	31	qEEG mTBI discrimination score was greater in the concussed group than the control group on the day of injury (t=3.8, p=0.0004) and day 8 postinjury (t=2.8, p=0.008), but not on day 45 (t=1.5, p=0.15)
McCrea[41]	2010	CCS	qEEG/BrainScope	FB	HS/C	M	28	28	Analyses of the qEEG data revealed significant within-group differences from baseline to the first 24 h postinjury (F=2.5, p=0.039) and 8 days postinjury (F=3.3, p=0.013). No differences were found among controls. Differences between the concussed and control groups were found within the first day postinjury (F=4.4, p=0.002) and day 8 (F=2.53, p=0.04), but not at day 45 postinjury (F=0.60, p=0.74)

Author, the last name of the first author; No., reference number; year, the year of publication.
Study type is coded as follows (per the Oxford Centre for Evidence based Medicine): CCS, case control studies (retrospective); CR, case reports; CrS, cross-sectional studies; CS, clinical series (some kind of control, including historical controls); PHC, prospective and historical cohort studies; RCT, randomised clinical trials.
Measures refer to specific tests (eg, SCAT2, BESS, etc).
Sports coded as follows: BX, boxing; FB, football; FH, field hockey; IH, ice hockey; LX, lacrosse; OT, other; RB, rugby; SCR, soccer; WR, wrestling.
Age/level is coded as follows: C, college; HS, high school; O, other; P, professional; Y, youth.
F/M indicates gender: F, female and M, male; list both if it applies.

Table 6 Studies using other assessment devices and tests on the day of injury

Reference		Study design		Sample					
First author	Year	Study type	Measure	Sports	Age/level	M/F	Concussed N	Controls N	Findings
Galetta[72]	2011	CCS CrS	King-Devick Test (K-D)	BX/MMA	O	M/F	39	NA	There were no differences in prefight K-D scores across groups, with slightly lower mean time scores in the second prefight testing session. ICC for two prefight sessions was 0.97. Postfight K-D time scores were significantly worse for participants with head trauma during the match (as determined by an independent ringside physician; n=8; p<0.0001). Among head trauma individuals, participants with LOC (n=4) had even higher (worse) postfight K-D scores. Worse postfight K-D scores and greater worsening of scores were correlated with postfight Military Acute Concussion Evaluation scores. Worsening by 5 s or more was a distinguishing characteristic noted only among the participants with head trauma
Galetta[73]	2011	CCS	K-D Test	FB, SCR, BB		M/F	10	NA	For the 10 athletes who had concussions, K-D testing on the sidelines showed a significant worsening from baseline (46.9 vs 37.0 s, p=0.009), with all except one athlete demonstrating a worsening from baseline (median 5.9 s)
Pearson[74]	2007	CR	Saccadometer (measure of visual response)	BX	NA	M	12	0	A tally of blows to the head was used as a measure of trauma (no actually measured concussion). 7 min after the match, the trend was that the more blows there were to the head, the greater would be the increase in latency of saccades. Latency returned to normal levels over a few days
Johnson[52]	2002	CCS	Cybex Reactor agility task	RB, IH	C	M/F	9	9	There was no significant difference in the time to complete the agility task between the injured individuals and controls at 1, 3, 5 or 10 days postconcussion

Author, the last name of the first author; No., reference number; year, the year of publication.
Study type is coded as follows (per the Oxford Centre for Evidence based Medicine): CCS, case control studies (retrospective); CR, case reports; CrS, cross-sectional studies; CS, clinical series (some kind of control, including historical controls); PHC, prospective and historical cohort studies; RCT, randomised clinical trials.
Measures refer to specific tests (eg, SCAT2, BESS, etc).
Sports coded as follows: BX, boxing; FB, football; FH, field hockey; IH, ice hockey; LX, lacrosse; OT, other; RB, rugby; SCR, soccer; WR, wrestling.
Age/level is coded as follows: C, college; HS, high school; O, other; P, professional; Y, youth.
F/M indicates gender: F, female and M, male; list both if it applies.

non-injured control athletes or both. This ability to detect and quantify acute cognitive impairment is evident on both brief screening measures (ie, the SAC) and conventional and computerised neuropsychological test batteries. Relatively few studies report sensitivity/specificity data on the ability of particular cognitive tests to differentiate concussed versus non-concussed athletes at the individual case level.

Postural stability/balance tests

Numerous studies illustrate that balance is typically affected in concussed athletes in the early postinjury period[2 29–34] (see table 4). The majority of studies examine group data in concussed athletes compared with their own baseline and/or compared with uninjured controls.[2 29–34] Initial studies involved the use of sophisticated computerised test platforms, which are not practical for sideline assessments. Guskiewicz and colleagues later reported that simple clinical tests (eg, Balance Error Scoring System, BESS) could also detect balance deficits following injury.[34 35] A study by Broglio *et al*[29] assessed the ability of balance testing to detect a significant change (defined as 1 SD below baseline) in the individual athlete following a concussion. Most, but not all, concussed athletes had significant balance deficits following injury.

Taken together, these studies show that balance is an important component of the sideline assessment.[36 37] Currently, SCAT2 contains a modified BESS (M-BESS) which utilises the three BESS stances on a hard surface only. Further research is required to examine the sensitivity and reliability of the M-BESS for the detection of balance deficits in concussed athletes assessed on the sidelines.

Electrophysiological tests

Electrophysiological measures have been used to examine athletes and non-athletes following concussion.[38–40] Only recently have researchers examined the role of these measures during the acute phase of injury (see table 5). McCrea *et al*[41] conducted a prospective non-randomised study of 28 high school and college athletes who sustained a concussion while playing football. Analyses of the qEEG data revealed significant within-group differences from baseline to the first 24 h postinjury and at 8 days postinjury. Differences between the concussed and control groups were found within the first day postinjury and at 8 days postinjury.

Barr *et al*[42] reported significant differences using qEEG between the injured and control groups within the first 24 h and 8 days postinjury; no differences were found between groups at 45 days. Drawing from the same cohort of athletes and using the same measures as the previous two studies, Prichep *et al*[43] found statistically significant differences between athletes with mild and moderate concussion within 24 h, 8 days and 45 days postinjury. Sensitivity to moderate concussion was reported as 55% (95% CI 28% to 79%) and specificity was noted to be 94% (95% CI 84% to 98%) within 24 h of injury.

Other assessment measures

There are references in the literature and mainstream media regarding new paradigms, tests and devices in development for the intended use of assessing sport-related concussion. Only three studies in the literature included the day of injury data (see table 6). No conclusion can be drawn at this point regarding the eventual usefulness of these methods or others yet in the development pipeline.

DISCUSSION

Results from this critical review of the scientific literature inform our understanding of the acute clinical presentation of sport-related concussion and an array of tests in use for concussion assessment. Concussion clearly produces a constellation of self-reported symptoms and impairments in cognitive functioning, balance and other functional capacities during the acute phase (eg, initial 24 h). This review illustrates that clinical tests are capable of detecting and quantifying those effects on the day of injury.

It is important to appreciate that tests do not *diagnose* whether a concussion has occurred. Rather, tests provide data on the physiological, cognitive, psychological and behavioral changes associated with the injury that can aid the clinician in the overall diagnostic formulation, gauging the gradient of injury severity, assessing clinical recovery and determining fitness to resume participation in sport.

Although concerns are routinely expressed about athletes under-reporting concussion or the resulting symptoms,[44] this review suggests that symptom assessment remains a critical component of concussion assessment. The studies reviewed indicate large effect sizes in self-reported symptoms on the day of injury, typically larger than the deficits seen in performance-based methods. In sum, the literature clearly supports the continued use of symptom scales in the assessment of concussed athletes, ideally in combination with other functional tests.

This review illustrates that the effects of concussion are not confined to one domain (eg, cognitive functioning). That is, athletes, to varying degrees, experience a complex combination of symptoms and exhibit deficits across multiple domains of functioning. As a result, reliance on a single test or multiple measures in a single assessment domain will very likely be less accurate than a multimodal assessment. A multidimensional approach that integrates assessment of self-reported symptoms and other functional domains (eg, cognitive function and balance) known to be affected by concussion is recommended. The specific tests selected to form the multidimensional assessment approach not only need to be reliable and valid, but also may vary depending on the situational constraints of the sporting environment, athlete population and the experience of the assessor. SCAT2 integrates a multimodal assessment into a single outcome measure for use in the competitive sporting environment. Individual components of SCAT-2 have been the focus of recent studies, but further research is required to illustrate the reliability, sensitivity and clinical utility of the entire SCAT2.

The evidence base on the utility of neuropsychological testing has been greatly advanced over the past two decades. Although many critical questions have been answered, further research is required to specifically address a number of important questions related to the usefulness of cognitive testing. Priorities for future study are listed below.

- Comparing the added value of computerised versus brief cognitive screening tests on the day of injury and at subsequent assessment points.
- Determining how the day of injury cognitive test performance might predict the course and duration of recovery (including markers indicating the risk of prolonged recovery).
- Comparing the reliability, validity, sensitivity and specificity of baseline versus no baseline models of cognitive assessment in measuring the acute effects of concussion.

A small number of recent studies provide preliminary data regarding the use of electrophysiological and other measures in

 McCrea M, *et al*. *Br J Sports Med* 2013;**47**:272–284. doi:10.1136/bjsports-2013-092145

What are the new findings?

- Major progress has been made towards the development and validation of standardised methods for the assessment of sport-related concussion over the past 20 years.
- Several tests and measures are appropriate for use in the assessment of acute concussion on the day of injury in the competitive sporting environment.
- A multimodal approach that includes formal symptom assessment and standardised testing of cognitive ability and balance is recommended to maximise the sensitivity of clinical evaluation on the day of injury.

How might it impact on clinical practice in the near future?

- Concussion tests provide important data on the symptoms and functional impairments that clinicians can incorporate into their diagnostic formulation, but they should not solely be used to diagnose concussion.
- Inclusion of standardised measures will provide clinicians with a more systematic and accurate approach to concussion assessment.
- Accurate assessment on the day of injury can drive informed clinical management and return to play decision making that improves athlete safety and outcome after sport-related concussion.

the acute evaluation of concussion[43 45] and suggest that physiological recovery may persist significantly beyond recovery as assessed by clinical measures (eg, symptoms, balance and cognition).[41] Although these methods show promise, further research is required to support their use in the sporting environment.

CONCLUSION

Based on the complex and heterogeneous clinical presentation of concussion, a multimodal approach is recommended to maximise the sensitivity of clinical evaluation on the day of injury. This approach includes formal symptom assessment and standardised testing of cognitive ability and balance. Several tests and measures are appropriate for use in the assessment of acute concussion on the day of injury in the competitive sporting environment. These tests provide important data on the symptoms and functional impairments that clinicians can incorporate into their diagnostic formulation, but they should not solely be used to diagnose concussion. Future research should focus on the incremental value of these assessment instruments for predicting an athlete's recovery course, influencing injury management strategies and reducing risks associated with sport-related concussion.

Acknowledgements The authors acknowledge and appreciate the assistance of Adam Pfaller, Research Assistant in the Brain Injury Research Program at the Medical College of Wisconsin, with the literature search and data extraction for this systematic review.

Contributors MM, GI, RE, MM and MR made substantial contributions to: conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; and final approval of the version to be published. All authors included on a paper fulfil the criteria of authorship. There is no one else who fulfils the criteria but has not been included as an author.

Competing interests See the supplementary online data for competing interests (http://dx.doi.org/10.1136/bjsports-2013-092145).

Provenance and peer review Commissioned; internally peer reviewed.

REFERENCES

1 Guskiewicz KM, Weaver NL, Padua DA, *et al*. Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med* 2000;28:643–50.
2 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.
3 Macciocchi SN, Barth JT, Alves W, *et al*. Neuropsychological functioning and recovery after mild head injury in collegiate athletes. *Neurosurgery* 1996;39:510–14.
4 Meehan WP III, D'hemecourt P, Comstock RD. High school concussions in the 2008–2009 academic year: mechanism, symptoms, and management. *Am J Sports Med* 2010;38:2405–9.
5 Kelly JP, Rosenberg JH. Diagnosis and management of concussion in sports. *Neurology* 1997;48:575–80.
6 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.
7 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.
8 Benson BW, Meeuwisse WH, Rizos J, *et al*. A prospective study of concussions among National Hockey League players during regular season games: the NHL-NHLPA Concussion Program. *CMAJ* 2011;183:905–11.
9 Pellman EJ, Powell JW, Viano DC, *et al*. Concussion in professional football: epidemiological features of game injuries and review of the literature—part 3. *Neurosurgery* 2004;54:81–94; discussion 94–6
10 Duhaime AC, Beckwith JG, Maerlender AC, *et al*. Spectrum of acute clinical characteristics of diagnosed concussions in college athletes wearing instrumented helmets. *J Neurosurg* 2012;117:1092–9.
11 Lau BC, Kontos AP, Collins MW, *et al*. Which on-field signs/symptoms predict protracted recovery from sport-related concussion among high school football players? *Am J Sports Med* 2011;39:2311–18.
12 Guskiewicz KM, McCrea M, Marshall SW, *et al*. Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *JAMA* 2003;290:2549–55.
13 Maddocks DL, Dicker GD, Saling MM. The assessment of orientation following concussion in athletes. *Clin J Sport Med* 1995;5:32–5.
14 McCrory PR, Ariens T, Berkovic SF. The nature and duration of acute concussive symptoms in Australian football. *Clin J Sport Med* 2000;10:235–8.
15 Lovell MR. Evaluation of the professional athlete. Paper presented at: new developments in sports-related concussion conference1996, Pittsburgh, PA.
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 Collins MW, Field M, Lovell MR, *et al*. Relationship between postconcussion headache and neuropsychological test performance in high school athletes. *Am J Sports Med* 2003;31:168–73.
19 Iverson GL, Gaetz M, Lovell MR, *et al*. Relation between subjective fogginess and neuropsychological testing following concussion. *J Int Neuropsychol Soc* 2004;10:904–6.
20 Iverson GL, Gaetz M, Lovell MR, *et al*. Cumulative effects of concussion in amateur athletes. *Brain Inj* 2004;18:433–43.
21 Lovell MR, Collins MW, Iverson GL, *et al*. Recovery from mild concussion in high school athletes. *J Neurosurg* 2003;98:296–301.
22 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.
23 Lovell MR, Echemendia RJ, Burke CJ. Traumatic brain injury in professional hockey. In: Lovell MR, Echemendia RJ, Barth J, *et al*. eds. *Traumatic brain injury in sports: an international neuropsychological perspective*. Lisse: Swets-Zietlinger, 2004:221–31.
24 Lovell MR, Burke CJ. The NHL concussion program. In: Cantu R ed. *Neurologic athletic head and spine injury*. Philadelphia: WB Saunders, 2002:32–45.
25 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.
26 Patricios J, Collins R, Branfield A, *et al*. The sports concussion note: should SCAT become SCOAT? *Br J Sports Med* 2012;46:198–201.

27 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.
28 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.
29 Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the concussion assessment battery. *Neurosurgery* 2007;60:1050–7; discussion 1057–8.
30 Guskiewicz KM. Postural stability assessment following concussion: one piece of the puzzle. *Clin J Sport Med* 2001;11:182–9.
31 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.
32 Guskiewicz KM, Perrin DH, Gansneder BM. Effect of mild head injury on postural stability in athletes. *J Athl Train* 1996;31:300–6.
33 Guskiewicz KM, Riemann BL, Perrin DH, *et al*. Alternative approaches to the assessment of mild head injury in athletes. *Med Sci Sports Exerc* 1997;29(7 Suppl): S213–21.
34 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.
35 Guskiewicz KM, Ross SE, Marshall SW. Postural stability and neuropsychological deficits after concussion in collegiate athletes. *J Athl Train* 2001;36:263–73.
36 Susco TM, McLeod TC Valovich, Gansneder BM, *et al*. Balance recovers within 20 minutes after exertion as measured by the balance error scoring system. *J Athl Train* 2004;39:241–6.
37 Wilkins JC, McLeod TC Valovich, Perrin DH, *et al*. Performance on the balance error scoring system decreases after fatigue. *J Athl Train* 2004;39:156–61.
38 Slobounov S, Sebastianelli W, Hallett M. Residual brain dysfunction observed one year post-mild traumatic brain injury: combined EEG and balance study. *Clin Neurophysiol* 2012;123:1755–61.
39 Moeller JJ, Tu B, Bazil CW. Quantitative and qualitative analysis of ambulatory electroencephalography during mild traumatic brain injury. *Arch Neurol* 2011;68:1595–8.
40 Arciniegas DB. Clinical electrophysiologic assessments and mild traumatic brain injury: state-of-the-science and implications for clinical practice. *Int J Psychophysiol* 2011;82:41–52.
41 McCrea M, Prichep LS, Powell MR, *et al*. Acute effects and recovery after sport-related concussion: a neurocognitive and quantitative brain electical activity study. *J Head Trauma Rehabil* 2010;25:283–92.
42 Barr WB, Prichep LS, Chabot R, *et al*. Measuring brain electrical activity to track recovery from sport-related concussion. *Brain Inj* 2012;26:58–66.
43 Prichep LS, McCrea M, Barr W, *et al*. Time course of clinical and electrophysiological recovery after sport-related concussion. *J Head Trauma Rehabil* 2012, doi:10.1097/HTR.0b013e318247b54e
44 McCrea M, Hammeke T, Olsen G, *et al*. Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med* 2004;14:13–17.
45 Barr WB, Prichep LS, Chabot R, *et al*. Measuring brain electrical activity to track recovery from sport-related concussion. *Brain Inj* 2012;26:58–66.
46 McCrea M, Guskiewicz K, Randolph C, *et al*. Effects of a symptom-free waiting period on clinical outcome and risk of reinjury after sport-related concussion. *Neurosurgery* 2009;65:876–82; discussion 882–73.
47 Register-Mihalik J, Guskiewicz KM, Mann JD, *et al*. The effects of headache on clinical measures of neurocognitive function. *Clin J Sport Med* 2007;17:282–8.
48 Hynes LM, Dickey JP. Is there a relationship between whiplash-associated disorders and concussion in hockey? A preliminary study. *Brain Inj* 2006;20:179–88.
49 Bruce JM, Echemendia RJ. Concussion history predicts self-reported symptoms before and following a concussive event. *Neurology* 2004;63:1516–18.
50 Field M, Collins MW, Lovell MR, *et al*. Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *J Pediatr* 2003;142:546–53.
51 Piland SG, Motl RW, Ferrara MS, *et al*. Evidence for the factorial and construct validity of a self-report concussion symptoms scale. *J Athl Train* 2003;38:104–12.
52 Johnson PD, Hertel J, Olmsted LC, *et al*. Effect of mild brain injury on an instrumented agility task. *Clin J Sport Med* 2002;12:12–17.
53 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.
54 McLeod TC Valovich, Bay RC, Lam KC, *et al*. Representative baseline values on the Sport Concussion Assessment Tool 2 (SCAT2) in adolescent athletes vary by gender, grade, and concussion history. *Am J Sports Med* 2012;40:927–33.
55 Jinguji TM, Bompadre V, Harmon KG, *et al*. Sport Concussion Assessment Tool-2: baseline values for high school athletes. *Br J Sports Med* 2012;46:365–70.
56 Moriarity JM, Pietrzak RH, Kutcher JS, *et al*. Unrecognised ringside concussive injury in amateur boxers. *Br J Sports Med* 2012;46:1011–15.
57 Echlin PS, Tator CH, Cusimano MD, *et al*. Return to play after an initial or recurrent concussion in a prospective study of physician-observed junior ice hockey concussions: implications for return to play after a concussion. *Neurosurg Focus* 2010;29:E5.
58 Makdissi M, Darby D, Maruff P, *et al*. Natural history of concussion in sport: markers of severity and implications for management. *Am J Sports Med* 2010;38:464–71.
59 Covassin T, Stearne D, Elbin R. Concussion history and postconcussion neurocognitive performance and symptoms in collegiate athletes. *J Athl Train* 2008;43:119–24.
60 Moriarity J, Collie A, Olson D, *et al*. A prospective controlled study of cognitive function during an amateur boxing tournament. *Neurology* 2004; 62:1497–502.
61 Bleiberg J, Cernich AN, Cameron K, *et al*. Duration of cognitive impairment after sports concussion. *Neurosurgery* 2004;54:1073–8.
62 Bruce JM, Echemendia RJ. Delayed-onset deficits in verbal encoding strategies among patients with mild traumatic brain injury. *Neuropsychology* 2003;17:622–9.
63 Daniel JC, Nassiri JD, Wilckens J, *et al*. The implementation and use of the standardized assessment of concussion at the U.S. Naval Academy. *Mil Med* 2002;167:873–6.
64 McCrea M, Kelly JP, Randolph C, *et al*. Immediate neurocognitive effects of concussion. *Neurosurgery* 2002;50:1032–40.
65 Barr WB, McCrea M. Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion. *J Int Neuropsychol Soc* 2001;7:693–702.
66 Macciocchi SN, Barth JT, Littlefield L, *et al*. Multiple concussions and neuropsychological functioning in collegiate football players. *J Athl Train* 2001;36:303–6.
67 McCrea M. Standardized mental status testing on the sideline after sport-related concussion. *J Athl Train* 2001;36:274–9.
68 Warden DL, Bleiberg J, Cameron KL, *et al*. Persistent prolongation of simple reaction time in sports concussion. *Neurology* 2001;57:524–6.
69 Collins MW, Grindel SH, Lovell MR, *et al*. Relationship between concussion and neuropsychological performance in college football players. *JAMA* 1999;282:964–70.
70 McCrea M, Kelly JP, Randolph C, *et al*. Standardized assessment of concussion (SAC): on-site mental status evaluation of the athlete. *J Head Trauma Rehabil* 1998;13:27–35.
71 McCrea M, Kelly JP, Kluge J, *et al*. Standardized assessment of concussion in football players. *Neurology* 1997;48:586–8.
72 Galetta KM, Barrett J, Allen M, *et al*. The King-Devick test as a determinant of head trauma and concussion in boxers and MMA fighters. *Neurology* 2011;76:1456–62.
73 Galetta KM, Brandes LE, Maki K, *et al*. The King-Devick test and sports-related concussion: study of a rapid visual screening tool in a collegiate cohort. *J Neurol Sci* 2011;309:34–9.
74 Pearson BC, Armitage KR, Horner CW, *et al*. Saccadometry: the possible application of latency distribution measurement for monitoring concussion. *Br J Sports Med* 2007;41:610–12.

Day of injury assessment of sport-related concussion

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

Br J Sports Med 2013 47: 272-284
doi: 10.1136/bjsports-2013-092145