Acute evaluation of sport-related concussion and implications for the Sport Concussion Assessment Tool (SCAT6) for adults, adolescents and children: a systematic review

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ABSTRACT

Objectives To systematically review the scientific literature regarding the acute assessment of sport-related concussion (SRC) and provide recommendations for improving the Sport Concussion Assessment Tool (SCAT6).

Data sources Systematic searches of seven databases from 2001 to 2022 using key words and controlled vocabulary relevant to concussion, sports, SCAT, and acute evaluation.

Eligibility criteria (1) Original research articles, cohort studies, case–control studies, and case series with a sample of >10; (2) ≥80% SRC; and (3) studies using a screening tool/technology to assess SRC acutely (<7 days), and/or studies containing psychometric/normative data for common tools used to assess SRC.

Data extraction Separate reviews were conducted involving six subdomains: Cognition, Balance/Postural Stability, Oculomotor/Cervical/Vestibular, Emerging Technologies, and Neurological Examination/Autonomic Dysfunction. Paediatric/Child studies were included in each subdomain. Risk of Bias and study quality were rated by coauthors using a modified SIGN (Scottish Intercollegiate Guidelines Network) tool.

Results Out of 12 192 articles screened, 612 were included (189 normative data and 423 SRC assessment studies). Of these, 183 focused on cognition, 126 balance/postural stability, 76 oculomotor/cervical/vestibular, 142 emerging technologies, 13 neurological examination/autonomic dysfunction, and 23 paediatric/child SCAT. The SCAT discriminates between concussed and non-concussed athletes within 72 hours of injury with diminishing utility up to 7 days post injury. Ceiling effects were apparent on the 5-word list learning and concentration subtests. More challenging tests, including the 10-word list, were recommended. Test–retest data

WHAT IS ALREADY KNOW ON THIS TOPIC

⇒ The Sport Concussion Assessment Tool (SCAT) tools are used worldwide to assist in the evaluation and management of sport-related concussion.

⇒ The SCAT tools have evolved over time based on clinical findings, clinician input, scientific investigations and systematic reviews of the literature.The SCAT tools are designed to be self-sufficient without the use of ancillary equipment.

WHAT THIS STUDY ADDS

⇒ The SCAT tools are effective in discriminating between concussed and non-concussed athletes within 72 hours of injury.

⇒ Except for the Symptom Scale, the SCAT tools have limited utility in return to play decisions beyond 7 days post injury.

⇒ The SCAT5 concentration subtests exhibit marked ceiling effects. Increasing task complexity would be beneficial.

⇒ The SCAT3 and SCAT5 5-item word lists have significant ceiling effects whereas the 10-item word list is normally distributed.

⇒ Increasing complexity of specific tasks (eg, months in reverse, tandem gait) will likely increase the clinical utility of these tools.

⇒ Empirical data are limited in pre-adolescent, women and para athletes, sport type, and in geographical and culturally diverse athletes.

⇒ Differences were found on demographic, social/cultural, and linguistic variables, which amplify the importance of developing robust multitiered, language and age-appropriate normative SCAT data, including in para athletes.

HOW THE STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This study provides evidence for changes to that SCAT tools that will directly impact clinical practice and spur new research that validate such changes and create new normative data.

revealed limitations in temporal stability. Studies primarily originated in North America with scant data on children.
Conclusion Support exists for using the SCAT within the acute phase of injury. Maximal utility occurs within the first 72 hours and then diminishes up to 7 days after injury. The SCAT has limited utility as a return to play tool beyond 7 days. Empirical data are limited in pre-adolescents, women, sport type, geographical and culturally diverse populations and para athletes.
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INTRODUCTION

The recognition, evaluation, diagnosis and management of SRC is complex, dynamic, and multidimensional. The CISG introduced the SCAT^{TM} primarily as a tool to assist clinicians by standardising the concussion assessment across several domains of function. It was first published alongside the 2004 Summary and Agreement Statement of the Second International Symposium on Concussion in Sport.[1] The tools (SCAT, Child SCAT) evolved through several iterations prior to their current versions, SCAT5[1–3] and Child SCAT5.[4] Historical information on the tools is available in the SCAT6 tools documents.[5–7] The tools were intended to aid in the diagnosis of SRC but were not designed to be diagnostic tools per se. Table 1 provides the reader with acronyms and their meaning that are used throughout the documents.

The current review is substantially more sizeable than the previous CISG SCAT5 review[8] due to (1) an expanded review focus to include all literature covering domains, instruments or approaches relevant to acute phase SRC assessment and (2) the 2-year pandemic-enforced extension of the consensus process that necessitated a second literature search. This systematic review evaluated the empirical literature regarding acute evaluation of SRC in children (ages 5–12 years), adolescents (ages 13–18 years), and adults (>18) with a goal of improving the SCAT tools. The complexity and volume of research for this search necessitated *a priori* creation of six overlapping content subdomains: Cognition, Balance/Postural Stability, Oculomotor/Cervical/Vestibular, Emerging Technologies, Neurological Examination/Autonomic Dysfunction, and Paediatric/Child. A seventh category, Symptoms, was added during the preparation stage of this manuscript. The assessment of children and adolescents was included across each of these subdomains to undergird the age-appropriate development of the Child SCAT6. Also, the complexity and volume of articles identified in this review led to an *a priori* decision to separate studies that involved the collection of normative data or assessment of psychometric properties without examination of SRC athletes (n=204) from those studies that evaluated SRC outcomes (n=423). Only those studies that evaluated SRC will be presented here while findings from the remaining 'normative' studies will be presented in a subsequent paper.

Table 1 List of abbreviations and acronyms used in this review

AFL	Australian Football League	OM PCSS	Oculomotor Post-Concussion Symptom Scale
AUC	Area under curve	PPV	Positive predictive value
BESS	Balance Error Scoring System	PRISMA	Preferred Reporting items for Systematic Reviews and Meta-Analyses
BFI	Brain Function Index	PRESS RCI	Peer Review of Electronic Search Strategy Reliable Change Index
CFE	Cervical flexor endurance test	RCT	Randomised control trials
CFRT	Cervical flexion rotation test	REHO	Regional homogeneity
CISG	Concussion In Sport Group	ROM	Range of motion
DA	Diagnostic accuracy	rs-fMRI	Resting state functional MRI
DVA	Clinical dynamic visual acuity	S100B	S100 calcium-binding protein B
EEG	Electroencephalography	SAC	Standardised Assessment of Concussion
FA	Fractional anisotropy	SCAT	Sport Concussion Assessment Tool
GCS	Glasgow Coma Score	SIGN	Scottish Intercollegiate Guidelines Network
GFAP	Glial fibrillar acidic protein	sncRNAs	Small non-coding RNAs
HBI	Health and Behaviour Inventory	SNR	Signal-to-noise ratio
HPT	Head perturbation test	SOT	Sensory organisation test
HTT	Head thrust test	SRC	Sport-related concussion
ImPACT	Immediate Postconcussion Assessment and Cognitive Testing	SSEVP	Steady-state visual-evoked potentials
JPE	Joint position error	T-Tau	Total Tau
KD	King-Devick	TBI	Traumatic brain injury
LOC	Loss of consciousness	TUG	Timed-up-and-go
mBESS	Modified Balance Error Scoring System	UCH-L1	Ubiquitin C-terminal hydrolase-L1
MRI	Magnetic resonance imaging	VOD	Vestibulo-ocular dysfunction
NF-L	Neurofilament light chain	VOMS	Vestibular ocular motor screen
NFL	National Football League	VOR	Vestibulo-ocular reflex
NHL	National Hockey League	PCSS	Post-Concussion Symptom Scale
NPC	Near point convergence	RCI	Reliable Change Index

Due to the heterogeneity of outcomes, a narrative synthesis was completed for and across each of the seven domains listed. We present the systematic review process of the existing literature to guide an evidence-based modification of the SCAT tools. A guiding principle was to maintain continuity with previous SCAT tools whenever possible while making evidence-based improvements.

METHODS

This systematic review was conducted with guidance from the Cochrane handbook,[9] reported per the PRISMA statement,[10] and pre-registered with PROSPERO. The review was designed and presented to inform the 6th International Consensus Statement on Concussion in Sport, with the details of the methodology in an accompanying paper.[11]

Search strategy and eligibility criteria

The following databases were searched (2001 to 25 March 2022): MEDLINE(R) and Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Daily (Ovid), Embase (Ovid), APA PsycInfo (Ovid), Cochrane Central Register of Controlled Trials (Ovid), CINAHL Plus with Full Text (EBSCO), SPORTDiscus with Full Text (EBSCO), and Web of Science Core Collection (including SCI-Expanded, SSCI, A&HCI, CPCI-S, CPCI-SSH and ESCI).[12]

The search strategy (see online supplemental table A) was created by a health sciences librarian, using the standard sport and concussion concepts[11] and adding a third concept: Sideline (defined as both the location of injury and the time frame immediately post injury). The sideline search terms were created using relevant subject headings, and text words (keywords) searched within the title, abstract, and author-supplied keyword fields. The search strings used database operators and Boolean operators to create a highly sensitive search strategy. The primary search was created for MEDLINE and the search was peer-reviewed by a second health sciences librarian using the PRESS guidelines.[13] Suggestions were incorporated before the search was translated to all other databases. The records from the database searches were downloaded in .RIS or .txt format and uploaded to Covidence for deduplication and screening (see online supplemental A).

Inclusion criteria for all articles: (1) publication date from 2001 to 2022; (2) original research articles (ie, diagnostic accuracy studies, cohort studies, RCTs, case–control studies, and case series with a sample of >10); (3) ≥80% SRC as mechanism of injury; and (4) studies using a screening tool/technology to assess suspected concussion in the acute period (<7 days) and/or a study containing psychometric and normative baseline data for common instruments used to assess concussion. Articles were excluded if they did not use any tools or outcome measures to assess concussion and/or were commentaries, conference proceedings, or review articles.

Study selection

Rapid screening was performed by AMB on all included articles to remove any abstracts that did not assess concussion in humans (regardless of the mechanism of injury) or were not original studies. Three authors completed inter-rater reliability on 50 randomly selected citations prior to the title and abstract screen (RJE, AMB, KJS). Remaining title and abstract screening was completed (RJE, KJS, AMB) independently, with authors resolving conflicts by consensus. Full-text screening was completed independently by two coauthors, with a third reviewer resolving conflicts. The final inclusion list was circulated to all authors to scan and provide any references that may have been missed by the search.

Data extraction, Risk of Bias and Strength of Recommendation Taxonomy

Data extraction tables were created *a priori,* reviewed and piloted by the project team. Risk of Bias (ROB) assessments and data extraction were completed by two authors (methods author and a coauthor). Modified versions of the SIGN checklists[14] based on study design were used for the ROB assessments, which assigned study ratings as high-quality, acceptable or inadmissible. Conflicts were resolved either by consensus or a third reviewer. Grading the evidence was conducted by each domain lead author using the Strength of Recommendation Taxonomy (SORT.[15]

Online supplemental table B contains an expanded narrative review of papers by domain, ROB assessment is presented in online supplemental table C, study demographics can be found in online supplemental table D, the data extraction table can be found in online supplemental table E, and the PRISMA checklist may be found in online supplemental table F.

RESULTS

Figure 1 presents a modified 2020 PRISMA flow diagram.

Figure 2 presents the studies grouped by study design, location of study, demographics, year of publication, and clinical domains. Most studies were identified as prospective cohort designs followed by diagnostic accuracy and cross-sectional designs. Most studies originated in North America (USA and Canada) comprising approximately 84% of the studies. The remaining seven countries accounted for 16% of the studies.

Most studies were published between 2015 and 2022 with a notable trend towards year-over-year increasing publication numbers. The age distribution of study participants reveals most participants were 18 years of age or older. Only one study focused solely on children (ages 5–12), although mixed samples including children, adolescents, and adults were identified. On average, studies included approximately 24% female participants. Most studies focused on the SCAT cognitive domain (eg, the SAC), followed by emergent technologies, postural control assessments, oculomotor/cervical/vestibular function, and neurological examination/screening.

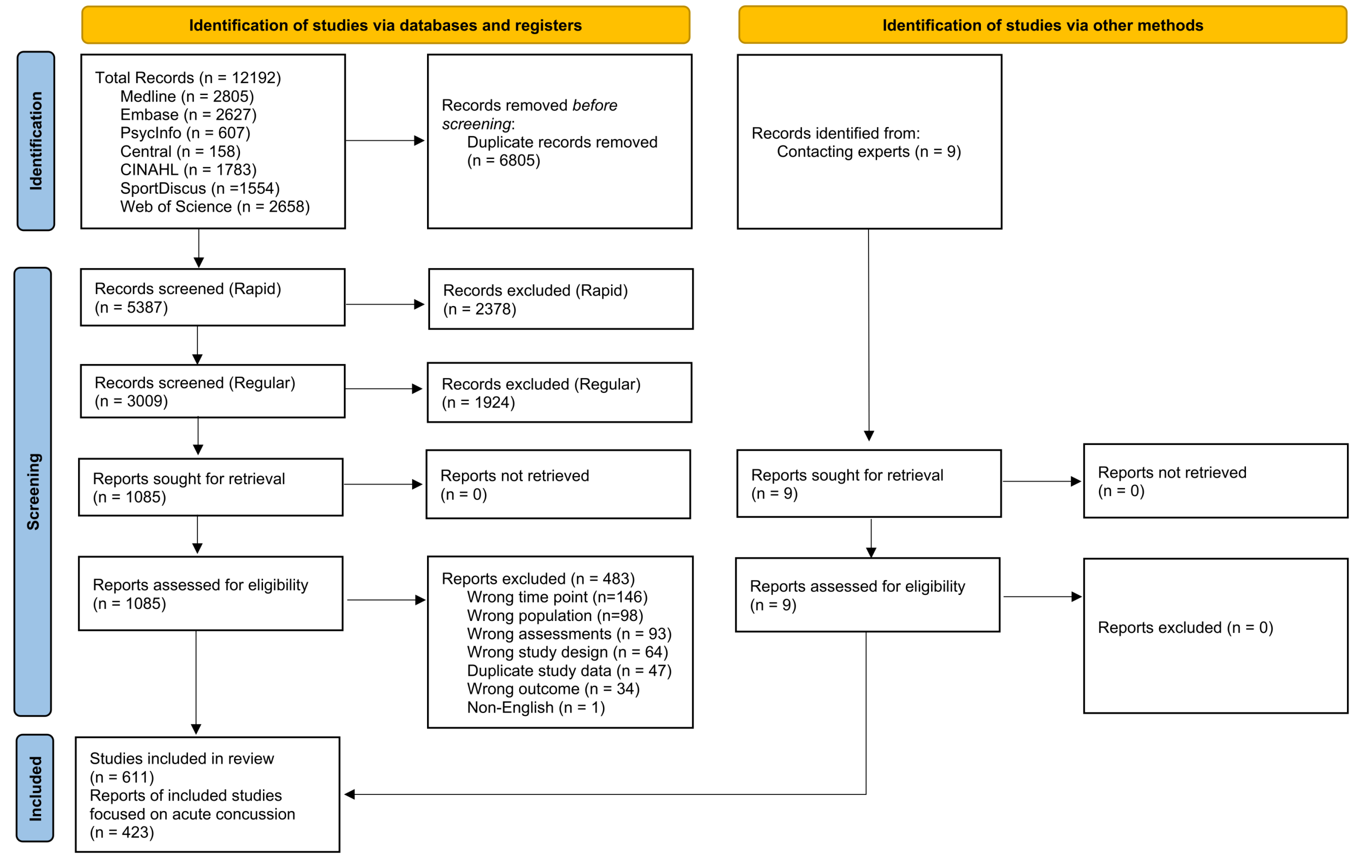
Figure 3 depicts the results of the ROB quality ratings. Of the 423 included SRC studies, approximately 21% were judged to be inadmissible or representing an unacceptably high ROB. In contrast, less than 9% of the studies were rated as high quality, with the remaining 70% identified as acceptable.

Data synthesis by domain

Findings from each article were organised into seven domains. Given the heterogeneity of outcomes, and complexity of the overlapping domains, a narrative synthesis was completed for and across each of the domains. Due to space limitations, a truncated narrative of each of the domains is presented below. A detailed data synthesis for each domain is presented in the online supplemental materials.

Of note, the SCAT6 guidelines included instructions against adding measures that include instrumentation other than items that are readily available (eg, athletic tape for tandem gait). In some instances, instruments that do not meet this guideline are included in the domain narratives below due to the prominence

Modified PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources



From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Figure 1 Modified PRISMA flow diagram. PRISMA, Preferred reporting items for systematic review and meta-analysis.

of the measure in the literature and the fact that instrumentation was not an exclusion criterion for the review.

Symptoms

ROB: Of the 241 papers reporting symptoms, 36 (15%) were inadmissible, 183 (76%) were rated acceptable, and 22 (9%) were high quality. Using the SORT taxonomy, the symptoms papers largely fell at the B level.

Of the included high-quality and acceptable studies, 100% noted elevated symptoms within 24 hours and 48 hours. When symptoms were assessed within 3 days, 4 days, 5 days and 7 days post concussion, symptoms were elevated compared with baseline and/or control values in 97%, 93%, 76%, and 64% of the articles, respectively.

Several studies have examined face validity and empirically derived domain-based index scores for the PCSS. Most studies settle on some variant of physical (eg, balance problems, headache), emotional (eg, sadness), cognitive (eg, difficulty remembering), and sleep (eg, fatigue or low energy) subscales.[16–19] Endorsement of specific symptoms differs according to recovery trajectory, with cognitive and physical symptoms being most predominant immediately following injury.[20]

Abbreviated self-report scales administered acutely may offer a near equivalent ability to discriminate between athletes diagnosed with concussion and controls, and may be useful for screening purposes when time is limited.[21 22] Several studies examined normative values and base rates of PCSS scores, confirming that concussion symptoms are non-specific to concussion and vary depending in part on socio-demographic factors, as well as physical and emotional health.[23–31] Although use of the PCSS as a baseline wellness screener in non-concussed athletic populations has shown promise at the collegiate level,[16 17] more work is needed in diverse populations. In populations that have established PCSS normative data, clinicians should review player baseline symptom report, and in cases with elevated or atypical symptom patterns follow-up with additional assessment and/or treatment as clinically indicated.

The Child SCAT incorporates a different symptom assessment, using the Child-report and Parent-report of the Health and Behaviour Inventory (HBI).[32] The HBI component of the Child SCAT has been shown to be reliable.[33 34] In 5–13 years old children, younger children self-reported more symptoms than older children, but parents rated more severe symptoms for older than younger children.[34] In 9–12 years old females, the Child-report demonstrated good test–retest reliability (Interclass Correlation Coefficient (ICC) ≥0.80) both pre-exercise and post-exercise.[33] The HBI symptom scale differentiates concussed from non-concussed children (both uninjured controls, and children with orthopaedic injury).[35] With child development over time, baseline symptom evaluation in children may be unreliable, unless the baseline is re-assessed at regular intervals (eg, every 3–6 months). The method of administering the symptom scale in children may influence the results, with fewer symptoms reported when administered verbally than with written responses.[35] Using the SORT taxonomy, the Child Symptoms papers largely fell at the B level.

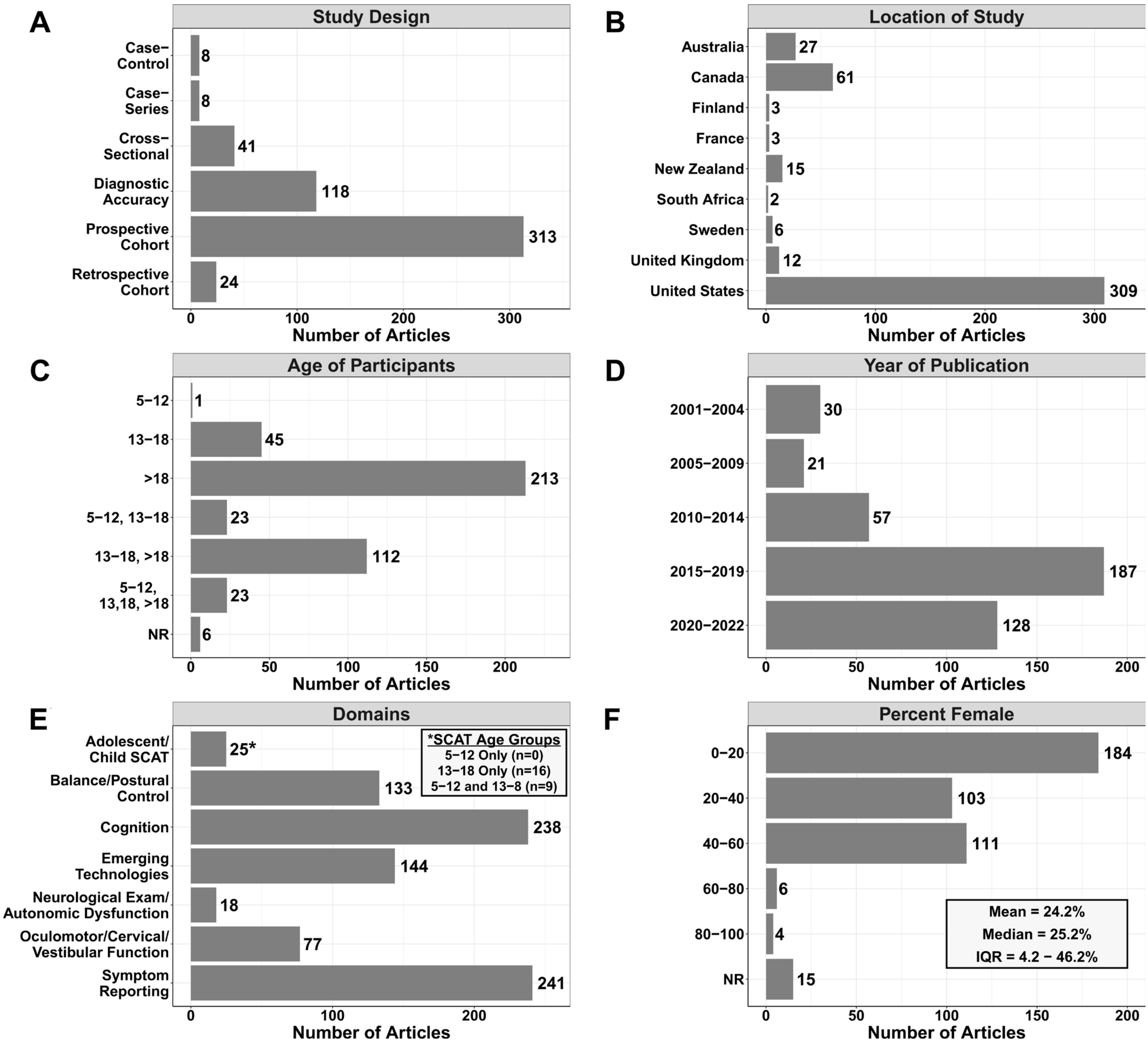


Figure 2 Characteristics of included studies. Note: Some included articles contained more than one study design, were conducted in more than one country, and/or included tests within more than one domain. Therefore, the total value of articles within the study design, location of study, and domain panels exceeds the total number of references included. SCAT, Sport Concussion Assessment Tool.

Cognition

ROB: Of the 238 included studies within the Cognition domain, approximately 19% (n=44) were deemed inadmissible, 73% (n=174) were acceptable, and 8% (n=20) were of high quality. Using the SORT taxonomy, the body of evidence generated by these papers fell at the B level.

Ability to discriminate between concussed athletes and controls—Both computerised and paper-and-pencil cognitive tests differentiated athletes diagnosed with concussion from controls with medium to large effects during the first 24–48 hours post injury.[36–42] Figure 4 depicts a forest plot of the acceptable and high-quality studies that compared overall SAC scores between acute concussed athletes and controls or baseline values. Inadmissible studies and/or those that did not report an overall SAC score, were not included. The standardised mean difference (SMD) was calculated for various time points across the first week of injury, including an overall score for all time points. The data show that while the overall SMD was lower when collapsed across time points, the greatest differences can be seen within the first 48-hours post-injury. Twenty studies using baseline/post-injury paradigms and including matched controls examined the ability of various iterations of the SAC to assist with the diagnosis of SRC.[42–61] Large effects were found when the SAC was administered immediately following concussion.[42] One study using the SCAT2 found that SAC scores significantly differentiated concussed collegiate athletes and controls approximately 1 day following injury.[59] One study found that the SAC (SCAT3) did not discriminate between concussed athletes and controls 3–5 days post injury.[56] The SCAT5 introduced the option of using a 10-item immediate memory word list, rather than a 5-item word list. The 10-item word list, but not concentration (digits backward plus months in reverse), differentiated

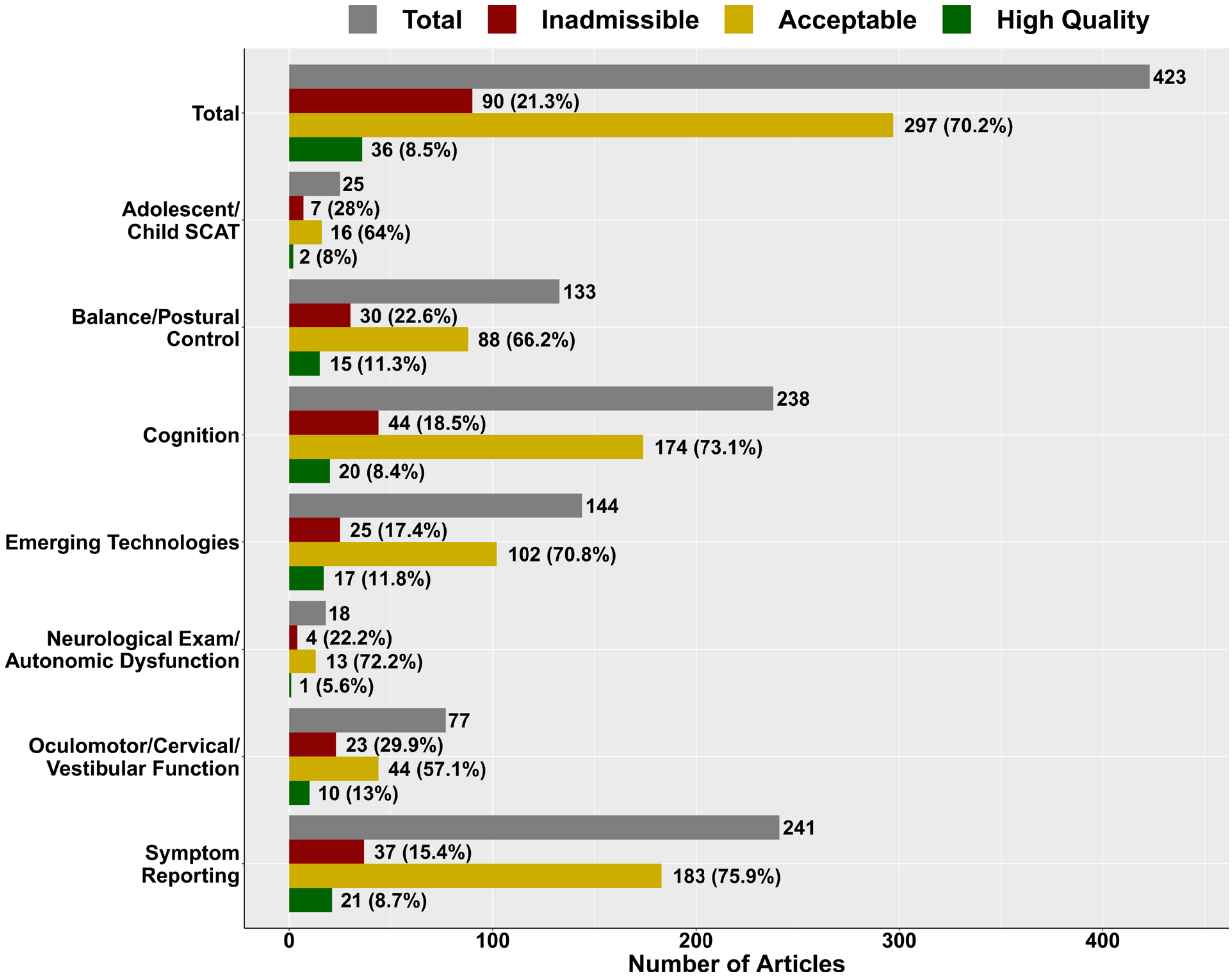


Figure 3 Risk of Bias quality ratings by domain. Note: Some included articles were included in more than one domain. Therefore, the sum of the seven domains exceeds the total number of articles. SCAT, Sport Concussion Assessment Tool.

concussed and non-concussed professional hockey players within 1 day of injury.[60] The 10-item word list version of the SAC composite similarly differentiated concussed collegiate athletes and controls shortly after injury.[62] In both studies, SCAT5 cognitive subtests accounted for unique variance in concussion diagnosis above symptom report alone. In contrast, a separate study using the 10-item word list did not differentiate concussed and control collegiate athletes tested within 7 days post injury.[63]

Test characteristics/psychometrics—Eight studies examining SRC also presented normative data on the SCAT5 in collegiate,[27 62 64] high school,[65] and professional athletes,[66–69] and found differences based on age, sex, health status, and language preference—underscoring the importance of using well-developed stratified norms. The 10-item word list of the SCAT5 exhibits improved psychometric properties over the 5-item word list, which shows ceiling effects.[70] The 10-item list scores approximately a normal distribution at baseline.[67] However, differences were found among the three forms of the list learning task,[68] suggesting that the forms are not equivalent in difficulty. Five studies published test–retest reliability for SCAT5 subtests. Test–retest reliability for component and total SAC scores was poor, ranging between 0.22 and 0.52.[61 62 71–73] Base rates enable the quantitative interpretation of multiple tests simultaneously, reducing the risk of false-positive results. One study examined base rates of decline on the SCAT5 using reliable change indices.[71] Findings showed that decline at the 0.80 CI (32.3% of sample) or 0.90 CI (20.7% of sample) level on only one of three considered SCAT5 subtests was relatively common in a non-concussed sample.[71] In contrast, decline on one SCAT5 test at the 0.95 CI (12.9% of sample) or two or more tests at the 0.80 CI (8.3% of sample) is sufficiently rare to warrant clinical concern supporting possible concussion diagnosis. Documented methods for improving the reliability/accuracy of cognitive measures in sports included: use of multiple baselines[74 75]; development of cognitive composite scores[76–79]; use of tests that minimise test ceiling/floor effects; and incorporating measures/procedures to ensure performance validity at baseline.[80–85] As noted above, a comprehensive article on SCAT normative data will be forthcoming.

Value of baseline testing—Seven papers examined the value of baseline testing using the SCAT. In four studies, neither the SCAT2, SCAT3, nor SCAT5 showed an increased value of baseline testing over standard normative and clinical evaluation.[52 56 59 60] One paper did show that for the 5-item word list delayed recall portion of the SCAT2, control athletes improved their performance significantly over baseline (consistent with a practice effect), whereas the concussed group did not show an improvement.[20] One paper found that using SCAT5 SAC reliable change metrics improved diagnostic sensitivity over the use of normative data alone[62] and another study applying machine learning algorithms found that using SAC baseline data outperformed the use of SAC normative cut-offs when classifying athletes diagnosed with concussion.[55]

 Echemendia RJ, *et al*. *Br J Sports Med* 2023;**57**:722–735. doi:10.1136/bjsports-2022-106661

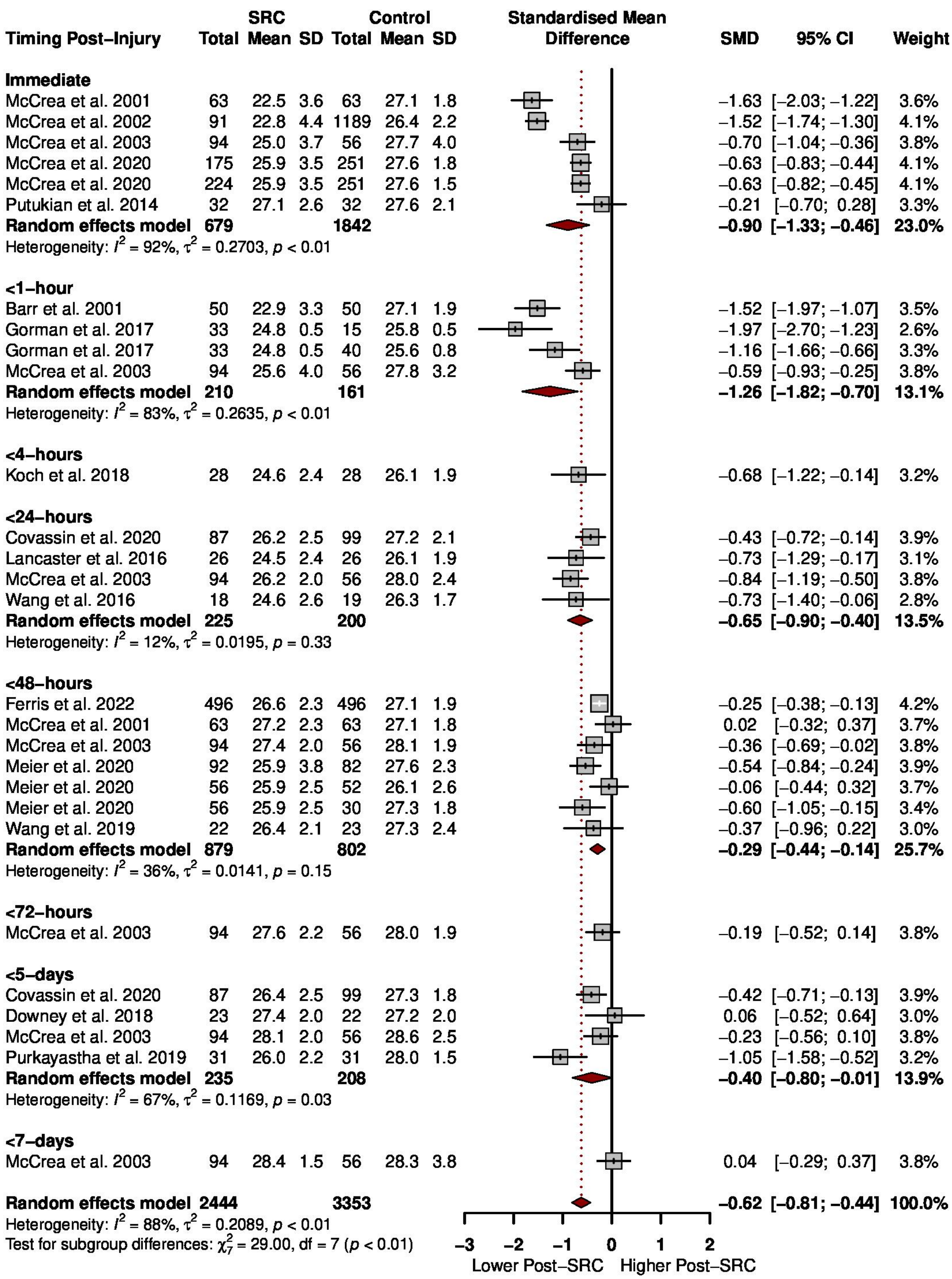


Figure 4 Acute total Standardised Assessment of Concussion scores by group. Note: Only studies with acceptable and high quality Risk of Bias are included. SRC, sport-related concussion; SMD, standardised mean difference.

Postural control

ROB: Of the 133 included studies that examined postural control, 23% (n=30) were inadmissible, 66% (n=88) were acceptable, and 11% (n=15) were high quality. Using the SORT taxonomy, the evidence largely fell at the B level.

Postural control tests employed within the first week of SRC, including examiner-rated balance performance (eg, mBESS),[86–95] instrumented balance measures (eg, inertial sensors, force plates),[87 91 96–106] and measures of tandem, steady-state or other forms of overground walking gait (eg, walking on a treadmill)[91 93 107–116] are useful in discriminating between concussed and non-concussed athletes. At the time of this review, there were limited or no empirical data to inform widespread recommendations for postural control among individuals with physical disabilities.

Balance: Although likely cost-prohibitive in many settings and not suitable for inclusion in the SCAT6, the instrumented SOT appears to have the strongest overall ability to detect concussion-related impairment in the acute phase.[97 100 102 104–106] Among examiner-rated measures of balance, the BESS and mBESS can each adequately assist in differentiating concussed and non-concussed adolescent and adult athletes with limited evidence in child athletes.[86–91 93 94] Studies have also reported no group differences between concussed and non-concussed adolescent and adult athletes within 72 hours of injury for both the BESS and mBESS.[87 91] The BESS and mBESS have reported sensitivities of 60% and 71%, respectively, during the first week following SRC when compared with baseline values[86] and area under the receiver operating curve (AUC (95%)) has been reported at 0.71 (0.62 to 0.79).[93] Inter-rater reliability for the mBESS appears to be fair to strong (Cronbach's α between 0.78 and 0.98).[117] For baseline BESS testing with child athletes, test-retest (ICC (95% CI) = 0.90 (0.88 to 0.92)), intra-rater (0.96 (0.95 to 0.97)) and inter-rater reliability (0.93 (0.79 to 0.97)) appear to be high according to one study with four raters.[118] For adults, BESS intra-rater reliability has been reported as good (ICC=0.86) and inter-rater reliability as moderate (ICC=0.75).[95] However, reported intra-rater minimum detectable change scores for the BESS ranged from 3.9 to 8.6 errors, and inter-rater minimum detectable change scores ranged from 11.3 to 12.6 errors,[95 118] suggesting the importance of having the same clinician evaluate both pre-injury and post-concussion BESS test performances. Other estimates of intra-tester reliability have also been reported as high (ICC=0.86 to 0.97) when rating adult and adolescent athletes, respectively, with a moderate accompanying inter-rater reliability (ICC=0.75) among adult athletes.[95 119] Athlete gender/sex and sport may be associated with mBESS test performance, but age, prior concussion history and preferred language do not appear to be associated with mBESS or BESS test performance among the included studies.[68 120–122]

Gait: Time to complete the tandem gait test discriminates among child, adolescent, and adult concussed athletes.[93 107 109 110 115 116] Further, a dual-task tandem gait testing paradigm including a simple cognitive task such as counting backward by a specified integer, and repeating months of the calendar year (or days of the week in child athletes) may provide important added complexity to acute concussion assessment.[93 109 114–116] Incorporating measures of cognitive task accuracy (eg, per cent correct) and processing speed (number of cognitive tasks completed during a trial) within dual-task paradigms may improve testing efficiency, but this requires further research. Although not an included study in the review due to exceeding the post-injury time frame, the single-task tandem gait test yielded 87.5% sensitivity, 72.4% specificity and correctly classified 82.4% of adolescents within 10 days of SRC (most participants were within 7 days post injury) as concussed or control using a cut-point of 16 s.[93] In the same study, the dual-task tandem gait test, using a cut-point of 22 s, was observed to have 84.8% sensitivity, 72.4% specificity and correctly classified 80.6% of patients as concussed or control.

Value of baseline testing—At the time of this review, there was insufficient evidence to support the need for pre-injury baseline testing for measures of postural control; however, clinicians may choose to conduct baseline balance and gait assessments if resources are available. Those who have the means to incorporate baseline testing should replicate the baseline testing conditions when performing post-injury evaluations, including having the same clinician perform the evaluations at each time point when possible. Additionally, clinicians should consider athlete sport and height when comparing a concussed athlete to normative data.

Relevance to the SCAT6: At the time of this review, there was not enough empirical evidence to inform the replacement of the mBESS/BESS tasks as easily administered and deployable measures of balance within the SCAT6. As previously stated, one of the guiding factors in modifying the SCAT5 for the SCAT6 was that no additional instrumentation should be necessary in any domain. Instrumented balance measures (eg, SOT, wearable inertial sensors) were identified in the literature search and met inclusion criteria for this study; however, they require time, cost and training resources that may not be widely available or feasible in many settings, and they were not considered for inclusion in the SCAT6.

There was sufficient evidence to consider tandem gait measures of dynamic postural control as meaningful additions to the acute assessment paradigm and within the SCAT6. An approach to postural control assessment that increases in task complexity as clinically indicated to inform the acute assessment of concussion is recommended, including beginning with a measure of static balance (eg, mBESS) and progressing to single-task and dual-task tandem gait measures, when feasible and clinically indicated. Additionally, if baseline testing is used for clinical decision-making, we recommend that the same examiner performs both the pre-injury and post-injury postural control assessments, when possible, as detailed above. It is not recommended that the mBESS be used while wearing skates.[123]

Oculomotor/cervical/vestibular

ROB: Of the 77 included studies, approximately 30% (n=23) were deemed inadmissible, 57% (n=44) were acceptable, and 13% (n=10) were of high quality.

Of the 77 studies included, only six studies focused on the cervical spine.[112 124–128] Findings were heterogeneous and evaluated a variety of cervical spine outcomes (cervical spine range of motion, tenderness on palpation, muscle spasm, joint position sense, cervical flexion rotation test, cervical flexor endurance, cervical spine strength, and head perturbation test) either as part of an overall clinical evaluation,[124 125] independently[112 126 127] or evaluated changes with physical exertion.[128] One cohort study of acceptable quality identified that cervical spine testing (cervical flexion rotation test, cervical flexor endurance, cervical spine strength, and a head perturbation test) were significantly worse following concussion compared with preseason.[112] Using the SORT criteria,[15] inclusion of cervical spine outcomes following concussion was rated as B.

Fifteen studies evaluated oculomotor function employing clinician observed tests of smooth pursuit, saccades or accommodation,[61 124] using eye trackers including pursuits, saccades, saccade latency, optokinetic nystagmus[129–131] or KD.[55 73 131–133] Studies including eye tracking presented variable results, but suggest that saccade latency and amplitude may be altered following concussion.[134] There was discrepancy in the literature regarding the ability of the KD test to differentiate between concussion and controls with reported diagnostic accuracy statistics varying widely across studies, with some showing strong discriminative ability and others not.[61 135–139]

The VOMS was evaluated in 22 studies, including four high quality studies. The VOMS was usually administered as per Mucha *et al*,[140] and was found to (1) discriminate concussion from no concussion with high levels of sensitivity, particularly in the acute phase of injury (ie, <24 hours), and (2) identified increased total VOMS symptom scores and/or greater proportion of the sample with scores above the cut-point post concussion[52 141–143] even in the absence of baseline testing.[52] Seven studies evaluated the function of the VOR with variable results and used several different outcomes. The KD test and near point of convergence (NPC, cm) were found to have lower levels of sensitivity than the VOMS (21–39% and 9–64%)[55] in collegiate athletes. A recommendation for the VOMS as a screening tool for concussion in the acute and subacute time period was rated as SORT A.[15]

Neurological examination/screen

ROB: Of the 18 included studies that examined the neurological examination, 22% (n=4) were inadmissible, 72% (n=13) were acceptable, and 6% (n=1) were high quality. Using the SORT taxonomy,[15] the evidence was rated at the B level.

The principal role of the acute neurological examination has generally been to identify signs of structural intracranial injury (moderate–severe TBI) or cervical spine injury necessitating hospitalisation and possible surgical intervention. Some neurological examination components have been incorporated into the SCAT and Child SCAT.[2 4] Observable neurological signs may be identified during an in-person examination or by video review (see below).[144] At times, these observations may portend more serious injury and along with the 'Red Flags'[6] necessitate immediate assessment and possible emergency transport to a hospital. Cervical spine assessment (including pain, tenderness, range of motion, strength, and sensation testing) is also included to identify potential cervical cord and spine injury.

Other components of the SCAT contribute to the neurological examination. Orientation is assessed by the Maddocks questions,[145] cognitive screening is provided by the SAC,[2 42] balance is assessed by the mBESS and tandem gait[146] and the neurological screen component assesses active cervical spine movement, extraocular movements, finger-nose-finger and tandem gait. Of the current neurological examination components in the SCAT tools, only the SAC and BESS have been evaluated with regards to their diagnostic utility for acute SRC.

Combination of tests/measures

One acceptable quality prospective cohort study evaluated a combination of physical examination findings among university athletes approximately 4 days post injury.[124] At the first visit, abnormal physical exam (PE) signs were significantly greater in concussed versus control athletes.[124] A combination of measures including symptoms, mBESS, and SAC total score had a sensitivity of 61% within 1 hour, 67% 1–24 hours, and 55% 24–72 hours post injury[55] when compared with pre-injury data. A separate study with collegiate athletes[49] demonstrated individual sensitivities of 55.0%, 95.0%, and 97.5% for the SOT, ImPACT, and symptom reports, respectively, with a combined 100% sensitivity in detecting concussion within 24 hours of concussion.[105] In an acceptable quality cohort study of 13–17 years old elite ice hockey players, a battery completed at preseason and post concussion (median of 4 days) identified significant worsening of cervical spine outcomes and divided attention following concussion.[112] When incorporating the VOMS with the full SCAT3, sensitivity was reported to increase 9% and the AUC was improved 4.4% to 0.85 up to 48 hours post-concussion in a high-quality study including collegiate athletes.[142] An acceptable quality cross-sectional study evaluated symptoms, ImPACT and VOMS on testing in adolescent athletes and found the three-component model accounted for 69.2% of the variance observed.[147] Overall, the literature is consistent and a combination of tests and outcomes received a SORT A recommendation.

Emerging technologies

ROB: Of the 144 included studies within the emerging technology domain, approximately 17% (n=25) were deemed inadmissible, 71% (n=102) were admissible, and 12% (n=17) were of high quality. Using the SORT taxonomy,[15] the body of evidence in this domain fell at the B level.

Accelerometers were examined in 12 papers[148–159]; post-impact accelerations alone have limited utility when used independently to diagnose concussion.[154] Impact density examines impact magnitude and adjusts for time before previous impacts. Concussed athletes showed significantly more head impacts in the 3 hours prior to the final impact that led to a concussion ($p<0.03$) and showed significantly higher linear ($p=0.016$) and rotational ($p=0.029$) impact values compared with controls. The authors concluded that there is a higher probability of concussion when considering both the magnitude of the impact and timing between impacts when compared with magnitude alone.[154]

Blood biomarkers were the focus of 18 papers and showed potential utility in aiding SRC diagnosis when blood is collected within hours post injury.[46 160–176] S100 calcium-binding protein, serum Tau-C, T-Tau, interleukin-6 have shown elevations within 6 hours of injury.[162 163] No included studies conducted point of care testing, thereby limiting diagnostic utility. Studies have also supported the analyses of sets of biomarkers given that concussion is a heterogeneous injury that reflects various pathological processes.

The literature on metabolomics and saliva biomarkers included a limited number of papers (10) with small sample sizes.[48 177–185] Future studies will need to identify the most sensitive and specific metabolites for concussion diagnosis[178] and isolate pertinent miRNA markers at point of care.[183 184]

Neuroimaging was the focus of 46 papers.[43 44 47 50 51 174 185–222] Conventional MRI revealed limited utility in the diagnosis of concussion.[206] In contrast, advanced sequences reflecting various aspects of brain function and physiology were shown to be sensitive to the effects of acute concussion at the group level, including functional MRI,[47 198] diffusion MRI,[44 174 199] relaxometry (for myelin volume),[207] proton magnetic resonance spectroscopy,[203] cerebral blood flow, and quantitative susceptibility mapping.[187]

EEG showed promise in distinguishing concussed athletes from controls. However, a standardised approach is needed regarding electrode placement, data processing, and task(s) completed by athletes.[45 96 223–229]

Video-based observable signs of concussion were examined in 19 papers.[70 157 230–245] Among professional athletes, visible signs were identified in 53%–78.9% of concussions. Visible signs with the highest specificity include, tonic posturing (97%), impact seizure (96%), suspected loss of consciousness (93%), ataxia/motor incoordination with difficulty getting up (81%), abnormal behaviour (55%), and blank/vacant/dazed look (62%). Specificity also increased when more visible signs were present, increasing from 0.22 to 0.90 when two vs four signs were present.

Child/paediatric

ROB: 25 studies examined children and/or adolescents. Of these, 28% (n=7) were inadmissible, 64% (n=16) were acceptable, and 8% (n=2) were high quality. Using the SORT taxonomy,[15] the body of evidence was B.

The need for a developmentally appropriate concussion evaluation tool for children (ages 5–12 years) in the acute stage is apparent.[80 246] Only five studies[28 33–35 247] were included relevant to the clinical utility of the Child SCAT tool in the acute stage and no studies examined the outcome of SRC. Additional studies exist for specific subcomponents of the Child SCAT including the symptom scale[35] and balance exam[118] in child samples.

Overall, the child and parent symptom scales demonstrate the most robust evidence of internal consistency and stability over time,[33 34] differentiation of concussed from controls,[35] and consistent relationships to age, sex, and history of concussion or other developmental/medical disorders.[28 34 248] The mBESS exhibits variability in its underlying psychometric characteristics.[33 118] The cognitive measure of the Child SCAT had low test–retest stability[33] with a single study showing low clinical discrimination of injured/uninjured in child athletes to date.[249]

Implications for the SCAT tools

The systematic review presented above identified SCAT6 areas/components that may be improved for identifying, evaluating, and managing the concussed athlete. Box 1 presents the recommendations that were submitted to the expert panel for review and discussion. These recommendations arose from the data extracted in this review, which were used to inform the development of the tools. The discussions at the expert panel meeting highlighted the importance of considering the scientific evidence and recommendations from the SR as well as pragmatic considerations for development and utility of the tools. For example, there was hesitancy among expert panel members to make changes that would invalidate existing normative data. Also, changes to the SCAT6 and Child SCAT6 must be considered in the context of the broader SCAT tools, including the Sport Concussion Office Assessment Tool (SCOAT) and the Concussion Recognition Tool (CRT). For example, the addition of an oculomotor measure such as the VOMS may be a better option for inclusion in the SCOAT rather than the SCAT6 due to the time constraints that exist during the acute evaluation. The decisions made by the expert panel were then the subject of detailed discussions during the 'tools day', which focused on the pragmatics involved in creating the actual tools.

DISCUSSION

This review systematically identified and evaluated the literature related to the assessment of SRC in the acute phase of injury and used this information to generate recommendations for modification of the SCAT tools. Key guiding principles included: (1) continuity with prior versions of the tools; (2) maintaining the tools free of ancillary equipment; (3) administration of tools in a reasonably short time; and (4) creation of paper and electronic versions of the tools that are freely and widely available.

Considerable support exists for using the SCAT tools within the first 72 hours of injury to differentiate concussed versus non-concussed athletes, but after 7 days its clinical utility diminishes. The diminished sensitivity of these tasks may result from ceiling effects, low test–retest reliability, and/or other psychometric issues. Each of these, alone or in combination, affects the ability of a measure to detect subtle functional changes. The clinical manifestations of SRC can be quite varied but generally resolve quickly, which leaves a very weak signal to track.[250] The pathophysiology of concussion also changes dynamically,[251] creating a 'moving target' that may require different tools at different points throughout recovery. We have reported on the role of baseline testing in those areas where empirical data exist, namely cognitive measures and balance/postural stability. Additional research is needed to examine the utility of baseline testing in all other components of the SCAT tools not only across functional domains but across populations and subpopulations. Lastly, since SRC is a clinical diagnosis that presents with a broad array of signs and symptoms, it is unlikely that a unitary signal exists. It is unlikely that a single measure can capture the full complexity of concussion, thereby underscoring the need to assess multiple functional domains. Accordingly, the SCAT is one component of the diagnostic process and not a singular diagnostic tool. Understanding the diagnostic 'accuracy' of each component enhances the clinical utility of the tool but does not make it a diagnostic tool *per se*.

Box 1 Key recommendations for Sport Concussion Assessment Tool (SCAT6) and Child SCAT6 tools modifications

SCAT6:

⇒ Create both paper and electronic formats.
⇒ Explore the development of alternate forms for serial evaluation.
⇒ Improve psychometric properties by including only the 10-item word list and eliminating the 5-item word option.
⇒ Develop a cognitive composite score to improve test–retest reliability and reduce the number of false positives.
⇒ Due to differences found among the existing 10-item word list forms consider regression-based norms to equate versions (particularly for an electronic version).
⇒ Increase complexity of the digit backward subtest to reduce ceiling effects.
⇒ Revise months in reverse to include a component of timed information processing.
⇒ Consider addition of other tasks where speed is measured (eg, timed serial 7's).
⇒ Add 'time to complete' in tandem gait.
⇒ Add a dual-task paradigm (ie, counting backward by a specified integer).
⇒ Consider tests and/or procedures to assess performance validity of baseline testing.
⇒ Consider mobile Post-Concussion Symptom Scale symptom option (particularly Child SCAT).
⇒ Add a more robust set of visible signs to the SCAT/Child SCAT/CRT including:
  ⇒ Falling with no protective action.
  ⇒ Tonic posturing.
  ⇒ Impact seizure.
  ⇒ Ataxia/motor incoordination.
  ⇒ Altered mental status.
  ⇒ Blank/vacant/dazed look.
⇒ Create stratified normative databases that include age, education, cultural background, para-athletes.
⇒ Consider adding Vestibular Ocular Motor Screen as an optional task.

Child SCAT6:

⇒ Consider re-examination of subcomponents of the cognitive measures and removal if non-discriminating between concussion and controls (eg, reverse order of days), or in the absence of data, clinical consensus suggests removal/replacement.
⇒ Consider adding standardised symptom ratings before and after the Child SCAT battery to assess exertional effects of cognitive activity (ie, worsening symptoms).[257]
⇒ With respect to the Modified Balance Error Scoring System balance examination, examine and possibly incorporate the scoring methods of Hansen *et al*,[118 258] given the demonstrated test–retest stability.
⇒ Symptom scale: Examine the wording of the symptoms and possibly the number of items, particularly for younger children.

Consistent with our prior review,[8] the PCSS is the best measure for distinguishing concussed players from non-concussed controls acutely and throughout a typical period of recovery. This finding is not surprising since symptoms are the cornerstone of most diagnostic frameworks of concussion. The reviewed body of literature consistently finds significant sample-based differences in symptom reporting if athletes are assessed within 4 days post injury, with reduced likelihood of significant group findings by 1 week. Research now shows that abbreviated symptom scales may also be useful when diagnosing acute concussion in time limited contexts. However, symptom expression may change during recovery. As such, symptom scales should be monitored over time and should represent a breadth of common symptoms, including emotional, cognitive, physical, and sleep difficulties. Additionally, a careful balance needs to be struck regarding the frequent post-injury use of the symptom scales since repetitive use may inadvertently reinforce a hyperfocus on somatic complaints and disability.

Clinically, it is important to emphasise that the use of total scores for symptoms and symptom severity may mask the pattern and severity of individual symptoms. For example, it is possible for two individuals to have a total symptom score of 10 with markedly different symptoms being endorsed. Similarly, a symptom severity score of 12 may represent scores of 6 on headache and 6 on neck pain for one person, while an identical symptom severity score of 12 is obtained by someone scoring 1 on 12 different symptoms. As such, when norms and validation studies are available, PCSS subscales may be useful as both a behavioural health screener during baseline evaluation and for treatment planning and monitoring during recovery.

As was the case in the 2017 review,[8] the need for baseline neurocognitive testing, whether using computer-administered or examiner-administered, neuropsychological tests and/or the SCAT tools, remains a topic of discussion. Generally, when well-developed normative data are available, the absolute need for individual neurocognitive baseline data is less supported. Quality normative data, however, may not be available for a broad range of athletes, and particularly those with psychiatric/neurologic history, learning disabilities (LD)/ attention defici hyperactivity disorder (ADHD), giftedness, cultural/linguistic differences, or para athletes.[252 253] In these situations, neuropsychological testing with regression-based models incorporating both baseline testing and demographic data may represent the most robust and reliable diagnostic approach.[71 75] In sum, widespread baseline testing may be useful when resources (eg, financial, personnel, time) permit, such as at the professional or elite level, but the evidence does not support across-the-board mandatory use at other levels of sport, such as at the child and adolescent level.

Postural control measures, including BESS/mBESS, and timed tandem gait can adequately discriminate between concussed and non-concussed adolescent and adult athletes acutely and should be included in a multimodal concussion assessment battery. Dual-task tandem gait testing paradigms, including simple cognitive tasks, show promise of providing an additional approach with moderately high diagnostic accuracy. More research is required to identify which cognitive tasks provide the best discriminative ability, especially among different age groups. Sufficient evidence now exists to add single and dual-task tandem gait assessments as time efficient tests in multimodal assessment batteries.

The acute neurological examination is critical for aiding in the identification of intracranial and cervical spine injuries (ie, 'red flags') necessitating emergency transport and possible hospitalisation among all age groups. The role of these components in the diagnosis of SRC is less clear. Although the neurological examination is beneficial among adolescents, the paucity of data related to the acute evaluation of children with SRC complicates the development of evidence-based recommendations for the Child SCAT tool. With respect to the 5–12 years age group, consideration in developing future systematic reviews should be given to broadening the scope to include non-sports related injury and the setting (ie, sideline vs emergency department (ED) vs primary care)) given vastly different medical resources available in children's sports.

Our previous review[8] suggested that ocular-motor measures showed promise as additional components for evaluation of acute SRC. This review more fully shows that the VOMS has been shown to discriminate between concussed and healthy athletes and could be a useful addition to SRC tools, although this tool is based on symptom report and flexibility may be necessary in the selection of components for administration (ie, some vs all the components given time constraints), and in the timing of administration. As with the PCSS, the relatively favourable findings of the VOMS in discriminating between athletes with and without a diagnosis of concussion may be due to the heavy role that symptoms play in this outcome measure. The KD in isolation was not found to be sensitive to acute SRC. Eye tracking devices may be useful in identifying changes post concussion, but research is limited, particularly with respect to their clinical application. Objective clinical assessments of the VOR appear to be useful as part of a multifaceted examination to inform diagnosis, but on their own do not appear to add much unique information.

Emerging technologies show promise at the group level with SRC, but few studies have examined their diagnostic accuracy at the individual athlete level, limiting their clinical utility. The use of accelerometers to discriminate concussive from non-concussive impacts has generated mixed findings, limiting their utility to independently identify concussion. Although routine clinical MRI has not been found to be helpful in diagnosing SRC, advanced imaging techniques show promise for use in acute SRC, but data represent heterogeneous methodological approaches, are limited at the individual athlete level, and present significant resource and accessibility challenges. Advanced imaging techniques remain a research tool at this time.

Limited data exist on the Child SCAT and its components with no studies examining children with SRC relative to a control sample. Overall, the child and parent symptom scales demonstrate the most consistent and robust psychometric characteristics with appropriate evidence of internal consistency and stability over time. The cognitive measures had limitations in both reliability of the scores over time and diagnostic accuracy. Similarly, the balance measures exhibited mixed reliability and limited efficacy beyond 5 days post injury.

Overall, most studies were from North America. While this robust research productivity is encouraging, such disproportionate geographical representation limits the generalisability of the study findings and hinders the ability to produce representative, clinically useful normative data. Efforts to increase global representation in research studies is warranted. Science has helped us understand that culture plays a critical role in cognitive performance—underscoring that the relationship between culture and cognition is as significant as it is complex.[254] Although a detailed discussion of these factors is beyond the scope of this review, culture and an individual's level of acculturation to a majority culture have multilayered influence on cognitive test performance. These influences range from sharing a common language, to basic nutrition, education and quality of education, and racial differences, to arguably more complex yet less obvious factors such as access to technology (eg, use of a mouse), environmental differences, the meaning of time (eg, work as fast you can), relationship to authority (eg, subordinate vs dominant, trust vs distrust) and interpersonal relationships (teammates, coaches, medical staff, staff). Understanding the inter-relationships among these factors and their impact on the data obtained, and behaviours observed, will lead to a more complete understanding of players diagnosed and recovering from SRC.[255]

This review is largely consistent with the findings of our previous review.[8] Both reviews concluded that the SCAT tools are useful in identifying differences between concussed and non-concussed adolescent and adult athletes in the acute phase of injury. The current review found more evidence for differences among several performance measures relating to demographic (eg, age, sex, education) and cultural/and linguistic differences. Similar differences are expected for para athletes who may require modification of standard test items[256] and mode of administration of tools. These differences underscore the importance of using robust multitiered and age-appropriate normative data in the interpretation of measures included in the SCAT, and acute measurement tools in general.

The acute phase of injury was defined as <7 days for this review. Although consistent with the existing literature, such a demarcation point is admittedly arbitrary and reflects heterogeneous clinical presentation and performance on outcome measures. It is well known, and further demonstrated in this review, that behavioural outcomes at 24 hours are likely quite different than at 7 days. Future studies would benefit from a more granular approach that tracks functioning in each of the domains listed above across the first 7 or even 14 days post injury. Such an approach may not only reveal the natural recovery patterns within domains but may also more fully identify variability across domains at any given time point.

It is recommended that any future modification of the SCAT tools beyond this review be subject to review and approval by coauthor representatives to best ensure validation of these modified tools and consistency with the scientific foundations of the tools. To this end, it is also important for clinicians to understand that simple translations of the SCAT tools are not adequate nor permitted. Translation coupled with cultural/linguistic adaptations of the tools is imperative.

Limitations

Although comprehensive, this systematic review is not without limitations. There are notable limitations in methodology, study design and quality of data among the included studies. Total ROB data found approximately 21% of the included articles to be inadmissible while only 9% were deemed to be of high quality. Limitations of study quality included mixed methodologies, small sample sizes, non-existent or inadequate control groups, limited psychometric and diagnostic accuracy data, poor to modest temporal stability of measures, markedly limited diversity of samples/populations in age, ethnicity, race, sport, sex, linguistic, and language representation. Although many of these limitations may be related to the complexity and dynamic features of this injury, the field will be better served by developing unified efforts for improving the basis by which we identify, manage, and treat this injury across all groups.

Most studies that examined the SCAT were limited in geographical and cultural/linguistic diversity, which may be due in part to restricting the search strategy to English-language populations only. Nonetheless, concerted efforts need to be made to promote/encourage global data collection and analysis. Also, by limiting the scope of the review to empirical studies we may have narrowed our ability to identify novel or emerging approaches to identifying and evaluating SRC in the acute setting. The review was also restricted to sport-related mechanisms of injury, which caused us to exclude significant studies that employed the SCAT among individuals injured outside of sports, particularly within the paediatric population. These limitations should be carefully considered in future iterations of these papers.

CONCLUSION

Review of the scientific literature regarding the acute assessment of SRC yielded 612 (189 normative and 423 SRC) included publications across seven subdomains involving child, adolescent and adult athletes. Designed to assist in the multimodal examination of athletes, the SCAT tools are most effective in discriminating between concussed and non-concussed athletes within 72 hours of injury and up to 7 days post injury, although their clinical utility appears to diminish after 72 hours. Except for the PCSS, these findings suggest that the SCAT tools may not be appropriate for use in the Return-to-Sport (RTS) decision-making process beyond 7 days post injury. Empirical data are limited in pre-adolescent, women and para athletes, sport type and in geographical and culturally diverse athletes. Despite the limited data, differences were found on demographic, and social/cultural and linguistic variables, which amplify the importance of developing robust multitiered and age-appropriate normative SCAT data that include these factors and para athlete populations. The data support modifications to the SCAT with the intention of standardising clinical examinations and increasing diagnostic utility among children, adolescents, and adults while maintaining its wide implementation with the need for minimal equipment. Taken together, the components of the SCAT tools are effective in their intended use but exhibit limitations that can be improved on to better serve the broad range of athletes that seek care and guidance before and after SRC.

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