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Diagnostic tools for return-to-play decisions in sports-related concussion

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Abstract

Research has improved the understanding of sports related concussion (SRC), and several classification systems and guidelines are available in the literature. The exact timing and clearing of athletes for return-to-play (RTP) is still based primarily on subjective reports of concussion symptoms, however symptoms link poorly to objective recovery. Current literature suggest that symptoms alone cannot accurately identify either all concussed athletes or their recovery. The difficult task of interpreting which symptoms are directly related to concussion, and which are related to other conditions, speaks for an increased focus on the RTP process itself. This study examines the literature on neurocognitive assessments and their importance as indicators of accurate timing of when athletes can return to either ball training with duels or the playing field. Entries in three electronic databases (PubMed, Web of Science, and SURF) were searched from January 2000 to June 2022. Search terms were *concussion, mild traumatic brain injury (mTBI), sport, athlete, expert, elite, professional, diagnostic, testing, return to play, management, neurocognitive, and cognitive*. Inclusion criteria comprised performance-based participation in a team sport and being in the age range of possible peak performance (18–40 years). In addition, only studies with pre-post designs were considered. The PEDro scale was used to assess methodological quality. The methodological quality of the fifteen included studies ranged from 5 (one study) to 6 (fourteen studies) from a maximum of 10. Despite being symptom-free, athletes in all fifteen studies showed lower performance compared to controls on tests of visual and verbal memory (approx. 3–5% deficit) and on processing speed (approx. 6% deficit) after mTBI. All studies report specific neurocognitive deficits after mTBI, although the athletes were declared clinically symptom-free. Therefore, the systematic consideration of neurocognitive parameters in RTP decision making is recommended, especially in light of subsequent muscular injuries of the lower musculoskeletal system, recurrence of mTBI, and residual neurodegenerative disorders.

Keywords
mild traumatic brain injury, cognitive, team sport, recovery, testing

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Introduction

Sports-related concussion (SRC) is an ongoing safety issue and a common neurological injury in contact sports.[1] Athletes sustain SRC primarily through direct contact to the head or body (e.g., body checks or accidental collision) during contact sport,[1] such as ice hockey or rugby, not only in games, but also in training.[2,3] Estimation suggest up to 3.8 million concussions occur annually in the United States due to sports-related activities, with up to 50% of concussions going unreported.[4] At the elite level, concussions are even more common, as evidenced by a concussion rate of 66.1 (per 10,000 athlete exposures) during the 2012–2013 and 2013–2014 National Football League (NFL) seasons.[5]

SRCs are a heterogeneous condition with varied neuropathophysiology and clinical symptoms that are related to severity and location of impact, age, or sex.[1] Clinical features are broad and vary, including neurocognitive symptoms, autonomic dysfunction, and vestibular impairment.[1] In addition, impairments in cognitive abilities such as visual-motor reaction time, information processing, memory, visual tracking, problem solving, and sensorimotor balance can occur with SRC.[6,7] It is critical to detect SRC in a timely manner and to safely determine when an athlete can return to play (RTP) after diagnosis. Premature RTP can put athletes at an increased risk

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of lower extremity injuries,[2,7–9] secondary brain injury,[1,6,9–11] persistent post-concussion symptoms,[12] and chronic neurologic deficits,[1,3,11,12] and even cognitive problems under conditions of physical or psychological stress, even if they report full recovery.[13–15] After sustaining an SRC, it is recommended that athlete's RTP follows a stepwise progression, through which the athlete should first participate in athletic activity without recurrence of symptoms before returning to competition.[1]

However, determining when an athlete has fully recovered from SRC is difficult. To manage SRC, current protocols involve an initial period of rest (24–48 h) followed by a stepwise rehabilitation protocol that includes gradually increasing physical and cognitive demands.[1,16,17] Each stage takes 24 h to complete and progression is dependent on meeting appropriate criteria (e.g., heart rate, duration of exercise) without recurrence of concussion-related symptoms. If symptoms do recur, the athlete should drop back to the previous asymptomatic stage for a further 24 h. Clearance for RTP is determined by completion of the graded rehabilitation protocol and passing clinical assessment at each stage. However, assessing symptoms in the recovery phase can be difficult and subject to bias.[18] For example, symptoms such as headache or difficulty concentrating do not directly belong to SRC[19] and it can be challenging to differentiate concussion-related symptoms from pre-morbid conditions such as chronic sleep dysfunction, migraines, anxiety, and attention problems.[20,21] Currently, clinicians rely heavily on symptom emergence following the fundamental exercises of the protocol, which may not necessarily indicate full recovery. Relying solely on subjective self-reported symptoms of athletes may also leave them at risk of returning to play too early.

The evaluation of neuropsychological deficits after concussion has been reported throughout the literature and reviewed in depth previously.[22–24] Additionally, there is increasing evidence to suggests that physiological recovery from concussion may outlast clinical recovery, even after successful completion of a graduated RTP protocol, athletes may still be at higher risk of neurological and non-neurological injury.[25] Balance assessments, which are a common tool used to assess recovery, may also not be sufficient in detecting continued impairments since cognitive deficits can persist beyond balance impairments.[26] Cognitive assessments have potential to aid in RTP decisions following SRC. Monitoring a cognitive marker during the rehabilitation phase, and even after symptoms resolve, could provide an objective measure of neurophysiological recovery from injury that could complement clinical assessment in RTP decision making. This is why standardised neurological and cognitive assessment scales have been developed to assist the sideline diagnosis of SRC and aid in RTP decision.[27] However, there is mixed evidence for cognitive testing in subacute SRC.[18,28,29] Despite the focus on concussion assessment protocols and tools, most lack quantitative objectivity, which raises doubts about their ability to measure readiness for RTP following a concussion. Given the limitations of clinical assessment in determining RTP following SRC, an objective indicator of neurophysiological recovery is needed to allow clinicians to make safer RTP decisions.

Therefore, our systematic review aims to identify cognitive impairments from computerised testing batteries, paper-pencil testing, postural stability, and diverse tests that have been assessed after SRC and throughout recovery from SRC. We examine the major pathological impairments involved in SRC and highlight the neurocognitive key marker from each pathway, evaluating their time course post SRC and their relationship to clinical recovery. This might help identify objective neurophysiological recovery from SRC that could have potential use in determining RTP decisions.

Methods

Search strategies

The systematic review of the literature was conducted in accordance with the four-phase PRISMA guideline. We searched in three online databases: PubMed, Web of Science (all databases), and Federal Institute of Sports Science Germany (BISp SURF). Title, abstract, keywords, and full text were examined. In all databases we used the same strategy. A comprehensive search was performed from July 2 to July 20, 2022. The following search terms were used:

> (((((((concuss* OR mild traumatic brain injury)) AND (sport OR athletes OR expert* OR elite OR professional)) AND (diagnostic* OR testing)) AND (return to play)) AND (neuro* OR cogni*)) NOT children).

The inclusion or exclusion criteria resulted in fifteen publications being eligible for further evaluation (see Figure 1).

Inclusion criteria

Studies were included if they were written in English or German and if the full text was available. We considered only original publications with human participants and publications from January 2000 up to July 2022. The athlete had to play a team/field sport and had to belong to an age range of possible top performance (18–40 years). Only experimental studies with baseline data and posttests were considered. Moreover, the SRC had to be diagnosed by medical staff (doctor, team physician, certified athletic trainer). Narrative reviews, single case reports, abstracts, and letters to the editor on the subject were excluded. Additionally, studies involving amateur athletes and studies in which there were less than two measured time points, were excluded. A screening strategy was used to identify studies for inclusion in the review. First, study titles were screened for relevance and second, for duplicates. The remaining abstracts were subsequently screened

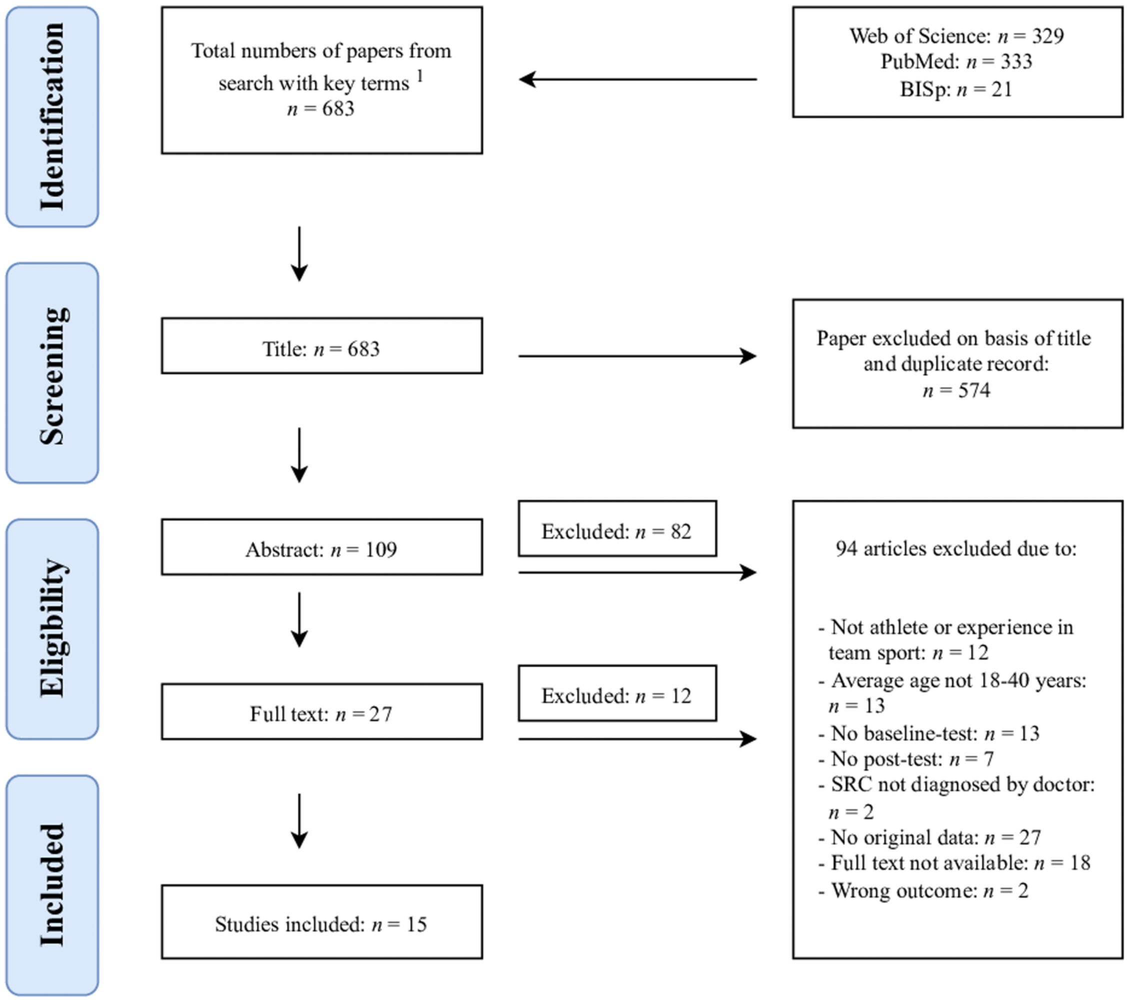

Figure 1. Study selection flow chart on the basis of the PRISMA statement key terms: (((((((concuss* or mild traumatic brain injury)) and (sport or athletes or expert* or elite or professional)) and (diagnostic* or testing)) and (return to play)) and (neuro* or cogni*)) NOT children).

for inclusion and exclusion criteria to identify relevant articles. Articles that satisfied title and abstract review underwent an in-depth full-text screen for inclusion and exclusion criteria. Reference lists of each included study were manually reviewed to identify relevant studies.

Examination of methodological quality (PEDro scale)

The two authors (WD & ZK) rated the fifteen included articles independently for methodological quality using the Physiotherapy Evidence Database Scale (PEDro scale) based on the Delphi list developed by Verhagen et al.[30] at Maastricht University. The PEDro scale contains a validated checklist that can be used to assess the methodological quality of studies on eleven criteria. The first criterion relates to external validity (generalizability of the study). Because this is not a quality criterion, it is not included in the calculation of the PEDro scale score. Items 2–9 refer to internal validity, whereas items 10–11 provide information on the statistical interpretability of the study's results. There are two options for each item: Each "yes" scores one point and each "no" scores zero points. Points are summed up for the overall assessment. A maximum of ten points can be reached. Fifteen studies could be assigned to evidence level A with 6 points on the scale. The remaining study fulfilled the B criterion with 5 points. Item 5[e] of the PEDro Scale was not evaluated because it is difficult to blind participants in the RTP process (Table 1).

Results

Search result

A total of 683 papers were identified from the search with key terms in Web of Science (all databases, 329 papers), Pub Med (333 papers), and BISp SURF (21 papers). Thus, we identified a total number of 683 papers in phase 1 (identification). In phase 2 (screening), we excluded

Table 1. Included studies rated by methodological quality (PEDro scale) legend.

Reference	Criterion											Score
	1[a]	2[b]	3[c]	4[d]	5[e]	6[f]	7[g]	8[h]	9[i]	10[j]	11[k]	
Asken et al.[6]	1	0	0	1	0	0	0	1	1	1	1	5
Collie et al.[31]	1	0	1	1	0	0	0	1	1	1	1	6
Covassin et al.[32]	1	0	1	1	0	0	0	1	1	1	1	6
Gill et al.[33]	1	0	1	1	0	0	0	1	1	1	1	6
Makdissi et al.[34]	1	0	1	1	0	0	0	1	1	1	1	6
McCrea et al.[26]	1	0	1	1	0	0	0	1	1	1	1	6
Merchant-Borna et al.[35]	1	0	1	1	0	0	0	1	1	1	1	6
Pedersen et al.[7]	1	0	1	1	0	0	0	1	1	1	1	6
Pryhoda et al.[36]	1	0	1	1	0	0	0	1	1	1	1	6
Sicard et al.[14]	1	0	1	1	0	0	0	1	1	1	1	6
Morris et al.[37]	1	0	1	1	0	0	0	1	1	1	1	6
Lempke et al.[38]	1	0	1	1	0	0	0	1	1	1	1	6
Powell et al.[29]	1	0	1	1	0	0	0	1	1	1	1	6
Caccese et al.[39]	1	0	1	1	0	0	0	1	1	1	1	6
Fickling et al.[40]	1	0	1	1	0	0	0	1	1	1	1	6

[a]Inclusion and exclusion criteria have been specified (not included in the total score).
[b]Subjects were randomly assigned to the groups.
[c]Allocation to the groups was hidden.
[d]At the beginning of the study, the groups were similar in terms of the main forecasting indicators.
[e]All subjects were blinded.
[f]All therapists who carried out therapy were blind.
[g]All investigators who measured at least one central outcome were blinded.
[h]Of more than 85% of the subjects originally assigned to the groups at least one central outcome was measured.
[i]All subjects for whom outcome measures were available received the treatment or control application as assigned, if this was not the case, data for at least one central outcome analyzed by an "intention to treat" method.
[j]Results of statistical group comparisons were reported for at least one central outcome.
[K]Study reports both point and dispersion measures for at least one central outcome.

574 papers as duplication records and on basis of titel. The remaining 109 papers were again checked for inclusion and exclusion criteria and evaluated by abstract (phase 3: eligibility). A total of 82 papers did not meet the criteria and were excluded. Upon review of full texts, 12 of these were excluded as they also did not meet the criteria. Finally, 15 key papers were included (phase 4: included).

Studies had moderate to good quality with a mean value of 5.93 ± 0.25. We present the results of the included studies by cognitive parameter in Tables 2–6

Discussion

The purpose of this systematic review was to collate and evaluate cognitive diagnostic tools for RTP decisions after SRC. Recommended assessments like computerised tests (such as ImPACT, CogSport, Switch task) and paper-and-pencil tests (DSST, TMT-B), neuropsychological test batteries (EEG), postural stability tests (BESS), and questionnaires (SACT[3]) as well as other experimental tests for cognitive diagnostics, were investigated. All these approaches could show a variety of cognitive impairment and have been evaluated following SRC. Cognitive impairments including cognitive control, visual memory, verbal memory, visual motor speed, reaction time, and working memory are raised after SRC and show varying time courses of recovery post-concussion. In addition, they show a correlation with severity of concussion measured either by symptom severity or duration for RTP.[31]

The current evidence base has a few limitations. These include the study design, which affects the conclusions that can be drawn from the findings. Presented studies[6,7,35,38,40] did not include a matched control group without SRC (same age, gender, and sport). A lack of standardisation in the process makes comparisons more complex as the included studies varied in follow-up periods and assessments of exposures and outcomes. An explanation for this may lie in the absence of a valid indicator for cognitive recovery time after SRC in these studies. Further factors such as sleep, history of previous concussion, and attentional impairment can also affect results.[42–44] Additionally, significant differences in cognitive performance between individuals may result from lifestyle factors, such as level of education, type of sport, and general cognitive ability before brain injury.[45] Consequently, studies of rehabilitation methods must carefully balance their study populations to provide usable

Table 2. Computerised testing batteries.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
Asken et al.[6]	Various sports $n = 84$	Baseline: $M = 18.9$ $SD = 0.7$ Post commotional: $M = 20.4$ $SD = 1.3$	University	ImPACT (Composite Score: verbal memory, visual memory, visual motor speed, reaction time)	2.9 ± 2.3 days after concussion then	missed days $M = 9.6$ $SD = 13.2$	Verbal memory ($t_{83} = 3.10$, $p = .003$) and visual motor speed ($t_{83} = 2.74$, $p = .008$) declined post-concussion. No differences in days missed between athletes with or without reliable decline
Collie et al.[31]	Australian Football players $n = 615$	Symptomatic: $M = 22.3$ $SD = 3.6$ Asymptomatic: $M = 23.3$ $SD = 3.9$ CG: $M = 23.4$ $SD = 3.6$	Not mentioned	CogSport: (SRT, CHRT, CXRT, DIVA, OBK, MATCH, LRN)	within 11days of injury	missed the next game (16.4%) Range 6–8 days	Greater number and duration of symptoms for symptomatic vs. asymptomatic group Symptomatic: Large decline in SRT ($t_{24} = 3.33$, $p = .003$), CHRT ($t_{24} = 3.28$, $p = .003$) & CXRT ($t_{24} = 2.54$, $p = .018$) Asymptomatic: Large decline in DIVA ($t_{35} = 3.23$, $p = .003$).
Gill et al.[33]	Various sports $n = 632$	Injured athletes: $M = 19.1$ $SD = 1.1$ CG athletes: $M = 18.7$ $SD = 0.67$ CG Nonathlete: $M = 19.2$ $SD = 0.9$	College	ImPACT (Composite Score: verbal memory, visual memory, visual motor speed, reaction time)	1. after 6 h 2. after 24 h 3. after 72 h 4. after 7 days of injury	RTP $M = 21.7$ $SD = 42.9$ Range 2–263 days	IA did not significantly change in cognitive performance from baseline to 7 days vs CG. Verbal memory ($p = .160$), Visual memory ($p = .890$), Visual motor speed ($p = .620$), Reaction time ($p = .529$). IA with long RTP, no significant change in mean. Cognitive performance from baseline to 7 days post-SRC compared to SRC athletes with short RTP.
McCrea et al.[26]	Football players $n = 1631$	Injured athletes: $M = 20.0$ $SD = 1.3$ CG: $M = 19.2$ $SD = 1.4$	College	Hopkins Verbal Learning Test Symbol Digit Modalities Test Stroop	1. right after 2. after 3 h 3. after 1 day 4. after 2 days 5. after 3 days 6. after 5 days 7. after 7 days 8. after 90 days injury	NA	Baseline vs. recovery in IA and CG: Mean difference (95% Confidence interval) right after: -2.94 (-4.38 to -1.50), after 3hrs: -2.15 (-3.26 to -1.04), day 1: -1.59 (-2.43 to -0.75), day 2: -0.72 (-1.51 to 0.08), day 3: -0.46 (-1.25 to 0.32)

(continued)

Table 2. Continued.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
							Milder deficits persist up to day 5 and on average, resolved by day 7.
Merchant-Borna et al.[35]	Various sports $n = 403$	Injured athletes: $M = 19.2$ $SD = 1.2$	College	ImPACT (Composite Score: verbal memory, visual memory, visual motor speed, reaction time)	2 right after injury 1. after 3 days 2. after 7 days	NA	Negative correlation between double-legged stance on a firm surface and visual-motor speed ($r = -0.47$, $p = .043$). Positive correlation between impulse control ($r = 0.54$, $p = .02$) and total symptom score ($r = .53$, $p = .02$). Negative correlation between tandem stance on a firm surface with visual-motor speed ($r = -0.49$, $p = .03$), positive with reaction time ($r = 0.61$, $p = .005$) and total symptom score ($r = 0.62$, $p = .004$). Positive correlation between double-legged stance on a foam surface with impulse control ($r = 0.66$, $p = .002$) and total symptom score ($r = 0.52$, $p = .02$).
Pedersen et al.[7]	Ice Hockey players $n = 74$	Injured athletes: $M = 23.0$	College	ImPACT (Composite Score: verbal memory, visual memory, visual motor speed, reaction time)	1. right after injury 2. either same night or next morning	NA	IA declined in immediate recall for words, $t_{13} = 2.24$, $p < .05$, and designs, $t_{13} = 2.72$, $p < .05$. IA less able to remember target words, $t_{13} = 2.67$, $p < .05$, and designs, $t_{13} = 3.12$, $p < .01$, at the delayed condition. Athletes less able to identify distracter words, $t_{13} = 2.18$, $p < .05$, at the delayed condition.
Lempke et al.[38]	Various sports $n = 187$	Injured athletes: Male: $M = 19.7$ $SD = 1.4$	College	ImPACT	<48 h of symptom recovery <48 h of clinical recovery	Symptom recovery $M = 5.9$ $SD = 5.2$ Clinical recovery	IA 282.4 ± 457.1 m (median = 181.1 m, range [– 0.6 to 2201.9 m]) Above sea 17.1 ± 8.3°C (median = 17.8°C; range [– 6.1 to 35.6°C]

(continued)

Table 2. Continued.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
						$M = 10.7$ $SD = 6.8$	heat index. ImPACT composite scores not modified by heat index ($p \geq .200$).
Sicard et al.[14]	Various sports $n = 80$	Injured athletes: $n = 40$ $M = 21.5$ $SD = 2.1$ CG: n = 40 $M = 20.7$ $SD = 1.8$	University	Switch Task	once they successfully completed step 4 of the Berlin RTP protocol	NA	No difference between IA and CG in HR ($t_{78} = 0.29$, $p = .77$), power (Watt), RPE, average HR, and % APMHR conditioning. Main effects for hetero ACC, hetero IES, global ACC cost, global IES cost, working memory ACC cost, and working memory IES cost ($F_{1,76} \geq 4.73$, $p \leq .03$, $\eta2 \geq 0.06$, $\varphi \geq 0.50$) IA lower in hetero ACC (86.2 ± 14.8%), higher in IES (11.8 ± 3.3 ms/%) relative to control group (93.0 ± 3.9m/%; 9.5 ± 1.63 ms/%; $t_{78} \geq 2.18$, $p \leq .03$). IA higher global ACC cost (11.2 ± 14.4%), higher global IES cost (6.6 ± 3.2 ms/%) and relative to the control group (4.1 ± 3.6%; 5.4 ± 1.6 ms/%; $t_{78} \geq 2.24$, $p \leq .03$). IA higher working memory ACC cost (9.6 ± 14.7%), higher working memory IES cost (5.9 ± 3.2%) relative to controls (2.8 ± 3.7%; 4.64 ± 1.3; $t_{78} \geq 2.27$, $p \leq .03$).

Key: M = arithmetic mean, SD = standard deviation, IA = injured athlete, CG = control group, NA = not applicated, TMT = Trail Making Test, DSST = Digit Symbol Substitution Test, SRT = Simple reaction time, CHRT = Choice reaction time, CXRT = Complex reaction time, DIVA = Divided Attention, OBK = one-back, MATCH = Matching, LRN = Continuous learning, ERPs = Event-related potentials, HR = heart rate, APMHR = age-predicted maximal heart rate, IES = inverse efficiency score, ACC = increased response accuracy, ImPACT = Immediate post-concussion assessment and cognitive test

Table 3. Paper-Pencil testing.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
Collie et al.[31]	Australian Football players $n = 615$	Symptomatic: $M = 22.3$ $SD = 3.6$ Asymptomatic: $M = 23.3$ $SD = 3.9$ CG: $M = 23.4$ $SD = 3.6$	Not mentioned	DSST, TMT-B	within 11days of injury	missed the next game (16.4%) Range 6–8 days	Symptomatic vs. Asymptomatic group Symptomatic: Main effect of TMT ($F_{1,142} = 8.56$, $p = .004$), DSST ($F_{1,142} = 15.677$, $p = .001$) Asymptomatic: Incline in DSST ($t_{35} = 3.48$, $p = .001$) and the TMT ($t_{35} = 2.98$, $p = .006$) CG: Improvement in follow up on DSST ($t_{83} = 4.29$, $p = .01$) and TMT ($t_{83} = 2.61$, $p = .011$)
Makdissi et al.[34]	Australian Football $n = 158$	Injured athlete: $M = 24.7$ CG: $M = 24.6$	Professional	DSST, TMT-B	before RTP	92% missed no game 8% missed one game	Baseline to RTP DSST ($p = .002$) and TMT-B ($p = .011$) improved significantly
McCrea et al.[26]	Football players $n = 1631$	Injured athlete: $M = 20.0$ $SD = 1.3$ CG: $M = 19.2$ $SD = 1.4$	College	Controlled Oral Word Association, Stroop Color Word Test	1. right after 2. after 3h 3. after 1 day 4. after 2 days 5. after 3 days 6. after 5 days 7. after 7 days 8. after 90 days injury	NA	Baseline vs recovery in concussion and control participants: Cognitive impairments at time of injury. Persisted through postinjury day 2. Milder deficits persist up to day 5. Impairments resolved by day 7.
Lempke et al.[38]	Various sports $n = 187$	Injured athletes: Male: $M = 19.7$ $SD = 1.4$	College	SCAT[3]	<48 h of symptom recovery <48 h of clinical recovery	Symptom recovery $M = 5.9$ $SD = 5.2$ Clinical recovery $M = 10.7$ $SD = 6.8$	IA 282.4 ± 457.1 m (median = 181.1 m, range [− 0.6 to 2201.9 m]) Above sea 17.1 ± 8.3°C (median = 17.8°C; range [− 6.1 to 35.6°C]) heat index. Symptom severity not modified by heat index ($p \geq .200$). Clinical recovery male: shortened by 7.12 days. Previous concussion clinical recovery by 2.88 days Each increase of the heat index by one degree:

(continued)

Table 3. Continued.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
							Symptom recovery: variables sex ($p = .002$) and concussion history ($p = .05$). Male shortened recovery by 3.71 days. Previous concussion lengthened recovery by 0.99 days.
Covassin et al.[32]	Various sports *n* = 186	Injured athletes: Male: *M* = 18.5 *SD* = 2.7 Female: *M* = 18.1 *SD* = 2.6 CG: Male: *M* = 18.2 *SD* = 2.4 Female: *M* = 17.8 *SD* = 2.4	High School & College	SCAT[3]	within 72 h 5 days within 1-day RTP 45 days RTP	RTP M = 18.2 SD = 10.5 Range 5–69 days	Females, greater symptom severity score than males at day 0 ($t_{182} = 4.4$, $p < .001$, $ds = 0.99$). No significant differences at other time point. Same within CG.
Sicard et al.[14]	Various sports *n* = 80	Injured athletes: *M* = 21.5 *SD* = 2.1 CG: *M* = 20.7 *SD* = 1.8	University	SCAT[3]	once they successfully completed step 4 of the Berlin RTP protocol	NA	No difference for age, height, weight, years of sports participation, and years of education ($t_{78} \leq 1.78$, $p \geq .08$). Symptoms on day of testing did not differ between groups ($t_{78} = 0.99$, $p = .33$), and intensity ($t_{78} = 1.34$, $p = .18$).

Key: M = arithmetic mean, SD = standard deviation, IA = injured athlete, CG = control group, NA = not applicated, TMT = Trail Making Test, DSST = Digit Symbol Substitution Test, SCAT[3] = sports concussion assessment tool – 3rd edition

Table 4. Postural stability.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
Gill et al.[33]	Various sports $n = 632$	Injured athletes: $M = 19.1$ $SD = 1.1$ CG athletes: $M = 18.7$ $SD = 0.6$ CG nonathletes: $M = 19.2$ $SD = 0.9$	College	BESS	1. after 6 h 2. after 24 h 3. after 72 h 4. after 7 days of injury	RTP M = 21.6 SD = 42.9 Range 2–263 days	IA: no significant change in postural stability (baseline to 7 days) vs CG. IA: long RTP, no significant change in balance (baseline to 7 days) vs to IA with short RTP. Floor: Double leg ($p = .445$), Single leg ($p = .551$), Tandem ($p = .203$) Foam: Double leg ($p = .688$), Single leg ($p = .772$), Tandem ($p = .126$)
McCrea et al.[26]	Football players $n = 1631$	Injured athletes: $M = 20.0$ $SD = 1.3$ CG: $M = 19.2$ $SD = 1.4$	College	BESS	1. right after 2. after 3 h 3. after 1 day 4. after 2 days 5. after 3 days 6. after 5 days 7. after 7 days 8. after 90 days injury	NA	IA vs CG: Mean difference (95% Confidence interval) right after: 5.81 (−0.67 to 12.30), After 3hrs: 5.66 (1.27 to 10.06), day 1: 2.72 (−0.14 to 5.57), day 2: 2.33 (−0.30 to 4.95), day 3: 1.46 (−1.22 to 4.14) Balance deficits: first 24 h, resolved by day 5.
Merchant-Borna et al.[35]	Various sports $n = 403$	$M = 19.2$ $SD = 1.2$	College	BESS WBB	2 right after injury 1. after 3 days 2. after 7 days	NA	BESS: Day 3 to day 7 tandem stance on firm surface decreased (difference -0.68 ± 1.20; $p = .02$). WBB: Baseline to day 3 difference. AP amplitude (0.36 ± 0.53; $p = .004$), AP SD (0.39 ± 0.48; $p = .001$), and AP path velocity (0.26 ± 0.62; $p = .043$). Day 3 to day 7, 5 WBB variables decreased
Lempke et al.[38]	Various sports $n = 187$	Injured athletes: Male: $M = 19.7$ $SD = 1.4$	College	On-Field BESS	<48 h of symptom recovery <48 h of clinical recovery	Symptom recovery $M = 5.9$ $SD = 5.2$ Clinical recovery $M = 10.7$ $SD = 6.8$	IA 282.4 ± 457.1 m (media n = 181.1 m; range [− 0.6 to 2201.9 m]). Above sea 17.1 ± 8.3°C (median = 17.8°C; range [− 6.1 to 35.6°C]) heat index. BESS total errors not modified by heat index or altitude in the regression models ($p \geq .200$).
Pryhoda et al.[36]	Various sports $n = 117$	Injured athletes: $M = 19.5$ CG: $M = 19.6$	University	BESS	<3 days 1 week 1 month 6 months	NA	Moderate or large effect sizes at all timepoints, fair or higher AUROC, and $J > 0.5$, IA vs CG: Double-leg stance, hard surface: Ellipse area: <3 days ($d = .60$, $p = .84$), 1 month

(continued)

Table 4. Continued.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
							(d = .65, p = .12): COP velocity: <3 days (d = 1, p = .06), 1 week (d = .75, p = .01), 1 month (d = .82, p = .02), 6 months (d = .75, p = .01): COP ML velocity: <3 days (d = 1.06, p = .05), 1 week (d = .81, p = .01), 1 month (d = .87, p = .01), 6 months (d = .82, p = .01): COP AP velocity: <3 days (d = .63, p = .11), 1 week (d = .55, p = .03). Double-leg stance, foam surface: <3 days (d = .57, p = .17), 1 week (d = .56, p = .03), 6 months (d = .22, p = .01). Tandem stance, foam surface: Ellipse area: <3 days (d = .56, p = .01), 1 week (d = .55, p = < .01): COP velocity: <3 days (d =, 81, p = .01), 1 week (d = .83, p = .01), 1 month (d = .87, p = .01), 6 months (d = .66, p = .01): COP AP velocity: <3 days (d = .69, p = <.01), 1 week (d = .74, p = <.01), 1 month (d = .67, p = <.01), 6 months (d = .73, p = < .01)

Key: M = arithmetic mean, SD = standard deviation, IA = injured athlete, CG = control group, NA = not applicated, BESS = Balance error score system, WBB = wii balance board, AUROC = area under the ROC curve, COP = center of pressure, ML = mediolateral, AP = anterior posterior

Table 5. Divers.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
Fickling et al.[40]	Ice Hockey players $n = 47$	$M = 18.4$ $SD = 1.0$	Professional	EEG (ERP translated to 6 vital brain signs: amplitude and latency for auditory sensation, cognitive processing & basic attention)	1.within the first 24 h of injury 2. at RTP	RTP Range 4–70 days	Significant Baseline vs Concussion: auditory sensation amplitude increased ($t_{11} = 3.36$, $p = .0064$), auditory sensation latency decreased ($t_{11} = -2.90$, $p = .0144$), basic attention amplitude increased ($t_{11} = 3.32$, $p = .0069$), basic attention latency decreased ($t_{11} = -3.32$, $p = .0069$), cognitive processing amplitude increased ($t_{11} = 2.54$, $p = .0275$), and cognitive processing latency decreased ($t_{11} = -2.28$, $p = .0435$). Significant differences concussion to return-to-play: auditory sensation amplitude decreased ($t_{11} = -3.23$, $p = .0080$), auditory sensation latency increased ($t_{11} = 2.65$, $p = .0227$), basic attention latency increased ($t_{11} = 2.63$, $p = .0236$), cognitive processing amplitude decreased ($t_{11} = -2.29$, $p = .0429$). Significant increase baseline to return-to-play: basic attention amplitude ($t_{11} = 2.24$, $p = .0466$).
Gill et al.[33]	Various sports $n = 632$	Injured athletes: $M = 19.1$ $SD = 1.1$ CG Athletes: $M = 18.7$ $SD = 0.6$ CG Nonathletes: $M = 19.2$ $SD = 0.9$	College	Digital array technology (tau concentration)	1. after 6 hrs 2. after 24 hrs 3. after 72 hrs 4. after 7 days of injury	RTP $M = 21.6$ $SD = 42.9$ Range 2–263 days	Tau higher at 6 h, 24 h, 72 h and 168 h post IA and in CGA vs HC ($p < .01$) Tau lower post SRC vs CGA at 24 h (6.06 vs 7.89 pg/ mL, $p = .030$) and 72 h (5.19 vs 6.94 pg/mL, $p = .041$). Tau at 6 h and 72 h higher and could predict players with longer RTP (>10d) 6 h: 10.98 vs 7.02 pg/mL, $p < .01$; AUC 0.81; 95% CI 0.62– 0.97, $p = .01$

(continued)

Table 5. Continued.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
							- 72 h: 6.29 vs 3.94 pg/mL, $p = .022$; AUC 0.82; 95% CI 0.68– 0.96, $p < .01$
Covassin et al.[32]	Various sports $n = 186$	Injured athletes: Male: $M = 18.5$ $SD = 2.7$ Female: $M = 18.1$ $SD = 2.6$ CG: Male: $M = 18.2$ $SD = 2.4$ Female: $M = 17.8$ $SD = 2.4$	High School & College	EEG eBFI SAC	Within 72 h 5 days within 1-day RTP 45 days RTP	RTP $M = 18.2$ $SD = 10.5$ Range 5–69 days	eBFI: IA impaired eBFI vs CG. Main effect of sex ($F_{1,181} = 3.9$, $p = .05$). Females lower eBFI (33.9 ± 30.7) vs male (40.4 ± 33.0). SAC: Main effect in IA overall, SAC score at day 0 (26.8 ± 2.3).
Lempke et al.[38]	Various sports $n = 187$	Injured athletes: Male: $M = 19.7$ $SD = 1.4$	College	On-Field Heat Index	<48 h of symptom recovery <48 h of clinical recovery	Symptom recovery $M = 5.9$ $SD = 5.2$ Clinical recovery $M = 10.7$ $SD = 6.8$	IA: 282.4 ± 457.1 m (median = 181.1 m; range [– 0.6 to 2201.9 m]) Above sea 17.1 ± 8.3°C (median = 17.8°C; range [– 6.1 to 35.6°C]) heat index. Heat index predicted with every one-degree increase in shortening symptom recovery by 0.05 days ($p = .047$, $r2 = .06$) and shortening clinical recovery by 0.14 days ($p = .006$, $r2 = .09$). Away competitions, days to clinical recovery ($p < .001$, $r2 = .25$) and symptom recovery ($p = .006$, $r2 = .18$). Heat index ($p = .006$), variables sex ($p = .008$) and concussion history ($p = .008$), were significant.
Caccese et al.[39]	Various sports Year 1 $n = 2579$ Year 2 $n = 1131$	Injured athletes: 6 h: $M = 19.0$ $SD = 1.1$ 24–48 h: $M = 18.9$	College	Clinical Reaction Time	6 h 24 h to 48 h RTP Initiation	NA	Six hours post-concussion: 99 IA vs 942 CG Year 1 baseline results, observed a time-by-group interaction ($F_{1,1039} = 62.088$, $p < .001$). RT_{clin}:18 milliseconds slower in IA and 5 milliseconds faster in CG.

(continued)

Table 5. Continued.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
		SD = 1.1 RTP: *M* = 18.9 *SD* = 1.1 CG: *M* = 19.0 *SD* = 1.0					Baseline RT_{clin} performance (IA = 197 ± 23 milliseconds, CG = 199 ± 24 milliseconds). RT_{clin} slower in IA 215 ± 34 milliseconds vs. CG = 194 ± 25 milliseconds. 24 to 48 post-concussion: 176 IA vs 924 CG. Year 1 baseline results, observed a time-by-group interaction ($F_{1,1116} = 73.319$, $p < .001$). RTclin: 15 milliseconds slower in IA and 6 milliseconds faster in CG. Baseline RT_{clin} performance IA = 197 ± 24 milliseconds, CG = 200 ± 24 milliseconds). RT_{clin} was slower in IA 212 ± 36 milliseconds, CG = 194 ± 25 milliseconds. RTP Initiation: 214 IA vs 942 CG Year 1 preseason baseline results, observed no time-by-group interaction.

Key: M = arithmetic mean, SD = standard deviation, IA = injured athlete, CG = control group, CGA = control group athletes, NA = not applicated, eBFI = enhanced brain function index, EEG = electroencephalography, RT_{clin} = clinical reaction time,

Table 6. Protocols.

Author	Participants	Age (years)	Competition Level	Method/Test (Dependent Variable)	Measuring points	Return to Play	Results
Powell et al.[41] *	Rugby Male ≈ 100 Female ≈ 100	Injured athletes: > 18 years	University	Cognitive: Reaction Time & Amplitude Discrimination Balance: SCAT[5] Gait & Turning: SCAT[5] Two-minute walk test HIMAT Visual: SCAT[5] Visual Oculomotor Screen Questionnaires: NDI, LEFS, IPAQ, DHI, NII	Post injured with in 72 h post 7–14 days post RTP post season	NA	Study Protocol Protocol for a multimodal approach. Provide insightful and more objective assessment for RTP in SRC. Better understanding of interconnection of cognitive impairments following concussion. New digital technologies may augment traditional approaches in SRC.
Morris et al.[37] *	Various sports Phase 1: $n = 80$ Phase 2: $n = 200$	Range: 18–30	NCAA-Division I	Phase 1 CAP mTBI athletes: MFI, PSQI, I-PRRS RTclin Phase 2 MC: RTclin	Phase 1 within 48 h of mTBI within 24 h of starting RTP within 24 h of being medical cleared 6 months after injury	NA	Study Protocol Two-phase approach Phase 1: will determine to what extent and for how long reactive postural responses are impaired after mTBI. Phase 2: Determine the association between reactive postural responses and prospective musculoskeletal injury risk.

Key: M = arithmetic mean, SD = standard deviation, IA = injured athlete, CG = control group, NA = not applicated, SCAT[5] = sports concussion assessment tool – 5th edition, RT_{clin} = clinical reaction time, HIMAT = high level mobility assessment tool, NDI = neck disability index, LEFS = lower extremity function scale, IPAQ = international physical activity questionnaire – short form, DHI = dizziness handicap inventory, NII = neurosymptoms inventory index, CAP = care affiliated project, MFI = multidimensional fatigue inventory, PSQI = Pittsburg sleep quality index, I-PRRS = injury – psychological readiness to return to sport, MC = matched contro results,[34,46,47] especially with these interindividual differences.[48] The assessments help with diagnostics and RTP grading of an SRC, but it could be argued that it doesn't help players holistically. For example, for muscle or tendon injuries, there is a clear guideline that actively (isometric contraction, tens, stretching, strengthening) rehabilitees the injured tissue before returning to play. These activities are also used in the prevention of such injuries. In comparison, this form of rehabilitation is rarely used for cognition after SRC (before RTP) because of a disproportionate focus of trainers on motor and vestibular-ocular symptoms. An interesting and additional approach could be provided by Giza and Hovda[49] they showed that moderate physical activity as well as cognitive activity compared with high activity and no activity leads to optimal neurocognitive outcomes after concussion. This demonstrates that graduated guidelines are essential for returning to sport.[50]

Similarly, the cognitive assessments and approach to post-injury rehabilitation must consider the individual areas of impairment, individual goals, and critical skills needed to return to activity.[51,52] For example, Gavett et al.[53] and Zemper et al.[54] have shown that cognitive training can improve sport-specific performance. Gavett et al.[53] improved shooting accuracy with lacrosse players and Zemper et al.[54] on-field passing with soccer player. In both studies, the intervention was tailored to specific cognitive skills thought to support performance. Stephens et al.[55] propose that neuropsychological assessment should be combined with a motor control task to obtain more independent information about the damaged regions of the brain or all damaged areas by using dual tasks, multitasking, and virtual reality. As a result, none of these tests can currently be used on the field or sidelines for exclusion from the activity or RTP. Due to the strict rules of many sports, which do not allow for stoppages and substitutions, these tests cannot be conducted and evaluated in their entirety, that would allow safe RTP.[56]

However, Sicard et al.[14], McCrea et al.[26], Pryhoda et al.[36] and Fickling et al.[40] could show that RTP clearance may not fully indicate cognitive recovery following SRCs, particularly for high-risk sports such as football and ice hockey. Sicard et al.[14] and McCrea et al.[26] showed strongest evidence for computer testing (cognitive control, verbal memory, visual motor speed, and reaction time), which were assessed in single cohorts with good sample sizes, multiple measuring points, and consistent use of control group, with extensive matching for history of head injury. Pryhoda et al.[51] evaluated a modified BESS (double-leg stance on hard surface and tandem stance on foam) in multiple cohorts, but in each case, a small cohort and control group were used. EEG brain vital signs (reaction time) in Sicard et al.[14] showed the weakest evidence which were from a small sample, in a design without control group. The limited evidence base suggests that more powerful and standardised studies are needed to improve our knowledge. A holistic impression is provided by the protocol of Powell et al.[41] in a repeated measures observational study using a range of multimodal assessment tools (symptom, cognitive, visual, and motor). Morris et al.[37] protocol, using the push-and-release test, attempts to examine reactive postural responses to balance restoration in athletes. Considering the statistical quality of the fifteen papers, only two papers[14,33] used an a-priori power analysis. Pryhoda et al.[36] and Caccese et al.[39] reported effect sizes according to Cohen. Covassin et al.[32] provided an a-priori power analysis and effect sizes. Without information on power analysis and effect sizes, the interpretation of the results is limited, especially in studies with small sample sizes.[7,35,38,40] Future studies should at least include post-hoc power analyses (better a-priori) and report the statistical effect size.

Despite these limitations there is evidence to support further research into the potential use of cognitive testings to assist clinicians to make RTP decisions. The present review identifies several cognitive impairments including cognitive control, verbal memory, visual motor speed, and reaction time that show deviations post SRC and not return to baseline by clinical recovery from injury. Sampling these impairments post-concussion and regularly throughout rehabilitation could provide valuable information on cognitive recovery.

In the future, improvement of a cognitive domain to baseline levels could be included in the criteria for RTP in addition to clinical recovery and successful completion of a stepwise rehabilitation programm. Neurophysiological recovery may differ from clinical recovery, thus leading an athlete, who has clinically recovered from SRC, being excluded from RTP due persistent cognitive abnormalities. These present findings and evaluation provide references for further exploration of the potential use of cognitive parameters to help clinicians make better RTP decisions.

Conclusion

We found that there was great variation between studies and showed a lack of standardisation in the RTP process after SRC.[15] There is currently no unified approach to cognitive diagnostic assessment including timing and frequency of measuring points after SRC, as well as for follow-ups after the RTP decision.

Furthermore, our findings reveal that some test selections are not sensitive enough. For example, while the Scat[5] can be a useful tool for neurological screening but is lacking in vestibular-ocular screening. Vestibular-ocular symptoms such as dizziness and blurred vision are associated with a greater risk of protracted recovery.[57] Vestibular-cular motor screening tests evaluate vestibular-ocular dysfunction, visual motion sensitivity, rapid eye movements, and smooth visual pursuits.[58] Kontos et al.[59] found that athletes with concussions were likely to experience symptoms such as dizziness or nausea here, while this is not the case in healthy individuals. Accordingly, there is a need for sensitive and multimodal cognitive testing during the RTP protocol that is not contaminated by learning effects. Preventing this could be via a combination of different approaches. Using, for example, Powell's et al.[41] protocol, may enhance sensitivity and objectivity of measures used to make activity removal-decisions, support diagnose SRC, and make RTP decisions.

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