BMJ Open Sport & Exercise Medicine

Clinical symptom clusters, neurocognitive function, balance and vestibulo-ocular function in athletes with sport-related concussion

Lea Weike ,[1] Rebecca Reeschke,[1] Claus Reinsberger[1,2,3]

To cite: Weike L, Reeschke R, Reinsberger C. Clinical symptom clusters, neurocognitive function, balance and vestibulo-ocular function in athletes with sport-related concussion. *BMJ Open Sport & Exercise Medicine* 2025;**11**:e002447. doi:10.1136/bmjsem-2024-002447

► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/bmjsem-2024-002447).

Accepted 2 June 2025

[1]Institute of Sports Medicine, Department of Exercise & Health, Faculty of Science, Paderborn University, Paderborn, Germany
[2]Division of Sports Neurology & Neurosciences, Department of Neurology, Mass General Brigham, Boston, Massachusetts, USA
[3]Sport Concussion Program, Mass General Brigham, Boston, Massachusetts, USA

Correspondence to
Prof Claus Reinsberger; reinsberger@sportmed.uni-paderborn.de

ABSTRACT

Objective This cross-sectional study aimed to investigate subjective and objective deficits of neurocognitive function, balance and vestibulo-ocular performance in athletes with sport-related concussion (SRC) compared with healthy control athletes.

Methods 72 patients with SRC and 72 matched healthy controls were included. All participants performed computerised testing of neurocognitive function, device-assisted balance testing and objective evaluation of vestibulo-ocular function (video head impulse and dynamic visual acuity test). Clinical symptom clusters (headache/migraine, anxiety/mood, fatigue, cognitive, vestibular, ocular) were determined for each patient using the Sport Concussion Assessment Tool, 5th edition symptom evaluation. Independent t-tests or Mann-Whitney U tests were calculated to test for group differences in the whole cohort and according to clinical symptom clusters.

Results When investigating the whole cohort, significant differences between patients with SRC and control subjects were found in one parameter of balance testing (sway velocity double-firm), with lower performance in the SRC group (p<0.001, r=0.345). The number of symptom clusters assigned to the SRC patients ranged from 0 (no definite cluster) to 6 (all clusters), and all clusters were frequent in the investigated cohort. Patients with vestibular, cognitive and fatigue symptom clusters demonstrated significantly lower performance in balance testing compared with SRC patients without those clusters (p<0.001 to p=0.005, r=0.368–0.439). Additionally, SRC patients presenting with symptoms of the fatigue cluster demonstrated significantly worse performance in vestibulo-ocular testing compared with SRC patients without the fatigue cluster (p=0.006, d=0.781).

Conclusion SRC patients presented with variable numbers and qualities of clinical symptom clusters. Some subjective clusters were associated with abnormal objective tests of other clusters (vestibular, cognitive and fatigue with abnormal balance; and fatigue with abnormal vestibulo-ocular performance). Clinical symptom clusters and their overlap should be considered when examining patients with SRC.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Neurocognitive function, balance and vestibulo-ocular function can be impaired in patients with sport-related concussion (SRC). Objective tests of these functions may facilitate the diagnosis or monitoring of recovery.
⇒ Clinical symptom clusters can be used to systematically assess signs and symptoms in SRC patients, including headache/migraine, fatigue, cognitive, anxiety/mood, vestibular and ocular.

WHAT THIS STUDY ADDS

⇒ The number and quality of symptom clusters varied among SRC patients.
⇒ Certain subjective symptom profiles were associated with impairments in objective tests. Specifically, patients presenting with vestibular, cognitive and fatigue symptom clusters showed worse performance in balance testing, and patients with fatigue symptoms showed decreased performance in tests of vestibulo-ocular function.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Clinical symptom clusters and their overlap should be considered when examining patients with SRC.
⇒ Future research on neurocognitive, balance and vestibulo-ocular testing should include clinical symptom clusters to better account for the heterogeneity of SRC and gain a better understanding of concussion profiles.

INTRODUCTION

Sport-related concussion (SRC) is a frequent injury with an estimated incidence of 1.6–3.8 million per year in the USA.[1] The clinical presentation of SRC is highly heterogeneous. It can include a wide range of clinical signs and symptoms, which may affect the domains of headache/migraine, fatigue, cognition, anxiety/mood, vestibular or ocular.[2 3] Due to the complexity and variability of the injury, the diagnosis of SRC is challenging, and there is no objective clinical test or marker that can be used in isolation to diagnose concussion.[2] Therefore, a multimodal assessment that covers all potentially affected domains is recommended.[2–4]

One commonly affected domain is neurocognitive functioning, which may include deficits in reaction time, memory or executive function.[4–6] Many patients also present with balance problems and/or impaired vestibulo-ocular function, for example, objectively manifested in changes in the vestibulo-ocular reflex (VOR).[7 8] Objective tests of these functions (eg, neurocognitive test batteries, computerised vestibulo-ocular tests, objective balance tests) can be used in addition to the clinical examination and may aid in facilitating the diagnosis or monitoring recovery. However, a single test may not be able to discriminate between SRC and healthy athletes, as patients may not be affected in all domains.

In this context, grouping symptoms according to clinical profiles may facilitate a systematic evaluation of symptoms. These clinical profiles may include the symptom clusters headache/migraine, fatigue, cognitive, anxiety/mood, vestibular or ocular.[2] While some patients present with a single cluster only, SRC is more commonly associated with a combination of several clusters.[2 9] Recognition of these symptom clusters can potentially help to develop a more targeted assessment and treatment of symptoms.[9 10] Especially for athletes, this could be highly important and may contribute to optimising management and rehabilitation outcomes, for example, during the return-to-sport process. It has already been shown that certain symptom profiles are associated with a longer duration of symptoms or recovery,[11–13] but the specific symptom clusters related to symptom/recovery duration differed between studies. Different risk factors may also be associated with specific symptom clusters.[14] Investigating SRC-related impairments specifically for patients presenting with certain symptom clusters could therefore provide more information than investigating the whole cohort of patients. Additionally, it may provide insight into the relationship and dependency of different clinical clusters.

Therefore, this study investigates whether neurocognitive function, balance, and vestibulo-ocular performance are impaired in athletes with SRC, depending on clinical symptom clusters.

METHODS

For this study, clinical data of athletes with SRC presenting to the Institute of Sports Medicine at Paderborn University between 2017 and 2023 were analysed retrospectively. Data were organised and derived from a Research Electronic Data Capture (REDCap) database[15] containing records from athletes examined after SRC and healthy athletes who underwent concussion baseline testing.

Participants

Patients with SRC and healthy control participants were included in the study. All participants provided informed consent prior to data collection. SRC patients were included if they had a clinical diagnosis of concussion, if they regularly participated in sports, and underwent at least one objective test of the concussion testing battery. A neurologist made the concussion diagnosis according to the criteria of the Concussion in Sport Group.[3] Each SRC patient was matched with one healthy control subject based on sex, age and, if possible, type of sport.

Tests and outcomes

All participants' demographic characteristics (age, height, weight, previous SRC, type of sport) were self-reported and assessed using questionnaires. Additionally, the number of days between injury and assessment was determined for the SRC patients.

Self-reported symptoms were assessed using the symptom inventory of the Sport Concussion Assessment Tool, 5th edition (SCAT-5).[16] The symptom checklist consisted of 22 items that were rated by the participant on a 7-point Likert scale ranging from 0 (none) to 6 (severe). The number (0–22) and severity (0–132) of symptoms were analysed as outcomes.

For the evaluation of neurocognitive functions, a computerised test battery (CNS Vital Signs (CNSVS), Morrisville, North Carolina, USA) was administered.[17] The test battery involves seven clinically validated tests (Verbal Memory, Visual Memory, Finger Tapping, Symbol Digit Coding, Stroop, Shifting Attention and Continuous Performance) that result in 11 raw domain scores,[17 18] which were used as outcome measures in this study. The CNSVS scores were reported to be reliable and comparable to traditional neuropsychological tests and other computerised test batteries.[17]

Balance was measured using the Stability-Evaluation-Test (SET), a computerised balance test performed on a static force plate (VSR Sport, NeuroCom, Clackamas, Oregon, USA). The SET has shown good to excellent test-retest reliability.[19] It consists of three stances (double-leg-stance, single-leg-stance, tandem-stance) that are first carried out on the force plate only (firm condition) and second with an additional foam pad (foam condition). Participants were instructed to stand as motionless as possible for 20 s in each condition, with eyes closed and hands on the hips. The analysed parameters were the sway velocities (°/s) for all six conditions and a composite score.

The vestibulo-ocular function was assessed by video head impulse tests (vHIT)[20 21] using the ICS Impulse System (Otometrics, Taastrup, Denmark). Head movements were performed in three test directions (lateral, left-anterior to right-posterior (LARP), right-anterior to left-posterior (RALP)). Head impulses were performed at a velocity of 120°/s–250°/s for horizontal and 100°/s–250°/s for vertical impulses, with an angle of 10°–20°. The quotient of eye and head velocity results in the test outcome VOR-gain, which can be displayed for all six semicircular canals. The VOR-gain has demonstrated good reliability.[22 23] This study calculated average values for the lateral, LARP and RALP test directions as outcome parameters.

The dynamic visual acuity test (DVAT) was performed as another test of VOR function using the InVision system (Neurocom). Participants first completed a test for static visual acuity, followed by the DVAT during active head movements. Head movements were performed in the lateral testing direction (movements from left to right). Velocity and angle of head movements were predefined to 85°/s–120°/s and 20°, respectively. Head movements were captured with the InVision head tracker and visual feedback was provided to ensure correct execution. The DVAT has shown good reliability and sensitivity for vestibular deficits.[24 25] As a DVAT outcome, the DVA loss (logMAR) was analysed, which represents the difference between static and dynamic visual acuity.

Overall, 22 outcomes from the neurocognitive, balance and vestibulo-ocular tests were analysed.

Symptom clusters

Clinical symptom clusters were determined for each patient using the SCAT-5 symptom evaluation. Symptom clusters were based on the clinical profiles described by Harmon *et al*.[2] The symptom clusters, including the individual symptoms associated with each cluster, are shown in table 1. As the clinical profiles overlap, some symptoms belong to one cluster only (eg, sadness), while others are attributed to several or all clusters (eg, don't feel right).

For each patient, a sum score and average score were calculated for all symptom clusters using the symptom severity scores of the SCAT-5. All clusters where the patient had an average score lower than the control group's mean were excluded from assigning clusters to the patient. Like this, the clusters in which the patient

Table 1 Symptom clusters based on Harmon *et al*[2]

Headache/migraine	Anxiety/mood	Fatigue	Cognitive	Vestibular	Ocular
Headache	Headache	Headache	Headache	Headache	Headache
Pressure in head	Pressure in head	Pressure in head	Pressure in head	Pressure in head	Pressure in head
Neck pain	Neck pain	Neck pain	Neck pain	Neck pain	Neck pain
Nausea or vomiting	Nausea or vomiting	Nausea or vomiting	Nausea or vomiting	Nausea or vomiting	Nausea or vomiting
Dizziness	Dizziness	Dizziness	Dizziness	Dizziness	Dizziness
Blurred vision	Blurred vision	Blurred vision	Blurred vision	Blurred vision	Blurred vision
Balance problems	Balance problems	Balance problems	Balance problems	Balance problems	Balance problems
Sensitivity to light	Sensitivity to light	Sensitivity to light	Sensitivity to light	Sensitivity to light	Sensitivity to light
Sensitivity to noise	Sensitivity to noise	Sensitivity to noise	Sensitivity to noise	Sensitivity to noise	Sensitivity to noise
Feeling slowed down	Feeling slowed down	Feeling slowed down	Feeling slowed down	Feeling slowed down	Feeling slowed down
Feeling like 'in a fog'	Feeling like 'in a fog'	Feeling like 'in a fog'	Feeling like 'in a fog'	Feeling like 'in a fog'	Feeling like 'in a fog'
Don't feel right	Don't feel right	Don't feel right	Don't feel right	Don't feel right	Don't feel right
Difficulty concentrating	Difficulty concentrating	Difficulty concentrating	Difficulty concentrating	Difficulty concentrating	Difficulty concentrating
Difficulty remembering	Difficulty remembering	Difficulty remembering	Difficulty remembering	Difficulty remembering	Difficulty remembering
Fatigue or low energy	Fatigue or low energy	Fatigue or low energy	Fatigue or low energy	Fatigue or low energy	Fatigue or low energy
Confusion	Confusion	Confusion	Confusion	Confusion	Confusion
Drowsiness	Drowsiness	Drowsiness	Drowsiness	Drowsiness	Drowsiness
More emotional	More emotional	More emotional	More emotional	More emotional	More emotional
Irritability	Irritability	Irritability	Irritability	Irritability	Irritability
Sadness	Sadness	Sadness	Sadness	Sadness	Sadness
Nervous or anxious	Nervous or anxious	Nervous or anxious	Nervous or anxious	Nervous or anxious	Nervous or anxious
Trouble falling asleep	Trouble falling asleep	Trouble falling asleep	Trouble falling asleep	Trouble falling asleep	Trouble falling asleep

Clinical profiles and associated symptoms of the Sport Concussion Assessment Tool (SCAT-5) symptom evaluation based on Harmon *et al*.[2]
Symptoms can be assigned to a single, multiple or all six clusters.
All symptoms of the SCAT-5 symptom form are listed in each column. Symptoms written in black font are assigned to the corresponding cluster. Symptoms written in grey font are not assigned to the corresponding cluster.

reported no or very few symptoms were eliminated. In the next step, the remaining clusters were excluded if the average value was lower than the overall symptom average of the respective patient to ensure that only clusters with relatively high symptom reporting were selected. Using this procedure, patients could be assigned to zero to six clusters, consistent with the theoretical assumptions that patients may present with no definite clinical profile, a single clinical profile or multiple profiles.[2 9] The steps in assigning clusters to SRC patients are illustrated in a flow diagram (online supplemental figure S1).

Statistical analysis

All data were tested for normal distribution using the Shapiro-Wilk test. Additionally, the data were checked for associations between potentially confounding intrinsic variables (sex, presence of previous concussion, days between SRC and assessment) and any of the investigated outcomes. To test for group differences between the SRC and control group in demographics (age, height, weight), symptoms (symptom sum, symptom severity) and outcomes of neurocognitive, balance and vestibulo-ocular tests, independent t-tests for normally distributed variables and Mann-Whitney U tests for non-normally distributed variables were calculated. For neurocognitive, balance and vestibulo-ocular outcomes, tests were performed for the whole group and specifically for each symptom cluster. For each cluster, SRC patients assigned to that cluster were first compared with their matched controls and second to SRC patients without the respective cluster. Additionally, Spearman correlation was calculated to investigate the relationship between the neurocognitive, balance and vestibulo-ocular parameters and the symptom sum scores of each cluster (the sum of the symptom severity ratings of all symptoms assigned to the cluster).

To correct for multiple comparisons, Bonferroni correction was applied. Therefore, the level of significance was set at p<0.025 for SCAT-5 parameters, p<0.0045 for CNSVS items, p<0.007 for SET data, p<0.017 for vHIT gain and p<0.05 for DVAT parameters. Effect sizes were determined by Cohen's d or r (calculated as $r=z/\sqrt{N}$). Effect sizes of 0.2, 0.5 and 0.8 (Cohen's d) and 0.1, 0.3 and 0.5 (r) correspond to small, medium or large effects, respectively.[26] The results of independent t-tests are reported as: t(df), p value, effect size Cohen's d; the results of Mann-Whitney U tests are reported as: U, z, p value, effect size r; and the results of Spearman correlations are reported as: Spearman correlation coefficient r_s, p value. Not all participants had complete data for all tests. Reasons for this included the omission of certain tests in early data collection, participants discontinuing tests due to symptoms, and some participants not undergoing all testing conditions. Therefore, the number of analysed participants (n) is reported for each outcome in the results tables. All statistical analyses were performed using IBM SPSS Statistics V.29.0 (IBM, Armonk, New York).

RESULTS

72 athletes with SRC (men: n=61, women: n=11) and 72 matched healthy controls (men: n=61, women: n=11) were included. Demographic characteristics of the SRC and the control group are displayed in table 2. There were no significant differences in age (U=2548, z=–0.176, p=0.860), height (t(140)=–0.817, p=0.415) or weight (t(71)=–1.085, p=0.282) between the groups. Online supplemental table S1 displays demographic data separately for males and females. We found no significant differences between males and females and between individuals with and without previous concussions in any outcome of neurocognitive, balance and vestibulo-ocular testing. There was a significant correlation between 'days between SRC and assessment' and one parameter of balance testing (single-firm: r_s=0.369, p=0.004), but not with any other outcome.

Whole cohort analysis

Patients with SRC reported a significantly higher number of symptoms (median (Mdn)=11.5, IQR=10.0) compared with controls (Mdn=5.0, IQR=8.0; U=780.5, z=–5.022, p<0.001, r=0.464). Symptom severity was also significantly higher in the SRC (Mdn=19.5, IQR=29.0) than in the control group (Mdn=7.0, IQR=12.0; U=784.5, z=–4.994,

Table 2 Demographic characteristics of the SRC group and the control group

	SRC (n=72)	Control (n=72)
	Mean (SD) Min–max	
Age (years)	23.0 (5.6) 13–34	22.9 (5.3) 13–37
Height (cm)	184.4 (12.4) 155–215	182.8 (10.9) 149–209
Weight (kg)	79.8 (15.4) 45–113	75.4 (17.1) 37–115
Days between SRC and assessment	18.7 (51.2) 1–388	n.a.
	n (%)	
Previous SRC		
Yes	40 (55.6%)	21 (29.2%)
No	22 (30.6%)	43 (59.7%)
No information	10 (13.9%)	8 (11.1%)
Type of sport		
Soccer	38 (52.8%)	49 (68.1%)
Basketball	16 (22.2%)	15 (20.8%)
Handball	5 (6.9%)	2 (2.8%)
American football	3 (4.2%)	0 (0%)
Ice hockey	3 (4.2%)	0 (0%)
Other	7 (9.7%)	6 (8.3%)

SRC, sport-related concussion.

Table 3 Symptoms (SCAT-5 symptom inventory), neurocognitive function (CNS Vital Signs), balance (Stability-Evaluation-Test) and vestibulo-ocular function (video head impulse test and dynamic visual acuity test) for the SRC group compared with the control group

Test	Outcome	n (SRC/control)	SRC	Control	P value
			Median (IQR)		
SCAT-5 symptom inventory	Number of symptoms*	64/53	11.5 (10.0)	5.0 (8.0)	**<0.001**†‡
	Symptom severity*		19.5 (29.0)	7.0 (12.0)	**<0.001**†‡
			Mean (SD)		
CNS Vital Signs	Composite memory	53/47	97.1 (8.1)	98.6 (8.5)	0.311‡
	Verbal memory		51.4 (4.4)	51.9 (4.4)	0.471‡
	Visual memory		45.7 (5.4)	46.6 (5.8)	0.414§
	Psychomotor speed		186.5 (16.7)	195.9 (21.3)	0.026‡
	Reaction time*		627.6 (99.8)	588.8 (61.1)	0.028‡
	Complex attention*		7.8 (6.0)	8.5 (6.4)	0.515‡
	Cognitive flexibility		49.9 (10.7)	48.8 (11.1)	0.661‡
	Processing speed		59.4 (9.4)	60.2 (12.3)	0.777‡
	Executive function		51.4 (10.1)	50.9 (10.3)	0.871‡
	Simple attention		38.9 (1.6)	39.2 (1.3)	0.230‡
	Motor speed		125.7 (14.5)	133.9 (14.1)	0.005§
Stability-Evaluation-Test	Sway double-firm*	63/63	0.87 (0.40)	0.66 (0.17)	**<0.001**†‡
	Sway single-firm*		2.04 (1.12)	2.08 (0.81)	0.098‡
	Sway tandem-firm*		1.77 (1.12)	1.48 (0.53)	0.241‡
	Sway double-foam*		2.13 (0.84)	2.07 (0.53)	0.725‡
	Sway single-foam*		4.50 (2.07)	4.18 (1.65)	0.596‡
	Sway tandem-foam*		4.36 (2.90)	4.72 (2.87)	0.382‡
	Sway composite*		2.61 (1.08)	2.56 (0.81)	0.805‡
Video head impulse test	VOR-gain lateral	67/64	0.95 (0.06)	0.96 (0.05)	0.255‡
	VOR-gain LARP	62/65	0.89 (0.06)	0.89 (0.09)	0.978§
	VOR-gain RALP	60/65	0.92 (0.09)	0.93 (0.09)	0.259§
Dynamic visual acuity test	DVA loss lateral*	51/52	0.15 (0.08)	0.15 (0.10)	0.780§

All values are presented as median (IQR) or mean (SD).
n: number of analysed participants for each outcome in the SRC and control group.
*Lower values indicate better scores.
†Significant differences between SRC group and control group after correcting for multiple comparisons (p<0.025 for SCAT-5 symptom inventory, p<0.0045 for CNS Vital Signs, p<0.007 for Stability-Evaluation-Test, p<0.017 for video head impulse test and p<0.05 for dynamic visual acuity test parameters).
‡Mann-Whitney U test.
§Independent t-test.
SCAT-5, Sport Concussion Assessment Tool, 5th edition; SRC, sport-related concussion.

p<0.001, r=0.462) (table 3). The most frequent SRC symptom was 'fatigue' (reported by 84.4%), followed by 'pressure in head' (81.3%) and 'headache' (79.7%).

Results of neurocognitive, balance, and vestibulo-ocular testings are presented in table 3. The SRC group showed significantly worse performance compared with control participants in the neurocognitive domains psychomotor speed, reaction time and motor speed, but this did not stay significant after correcting for multiple comparisons (psychomotor speed: U=924, z=−2.221, p=0.026, r=0.222; reaction time: U=928, z=−2.193, p=0.028, r=0.219; motor speed: t(98)=2.868, p=0.005, d=0.575).

In balance testing, patients with SRC demonstrated significantly higher sway values than control participants in the double-firm condition (U=1203, z=−3.868, p<0.001, r=0.345).

There were no significant differences between the SRC and control group for any vestibulo-ocular parameter.

Symptom clusters analysis

The SCAT-5 symptom evaluation was completed by 64 SRC patients. 9 patients could not be assigned to a definite symptom cluster (14%), 8 patients demonstrated symptoms in one cluster (13%), 11 in two clusters (17%), 11 in three clusters (17%), 14 in four clusters (22%), 6 in five clusters (9%) and 5 patients in all six clusters (8%). The most frequent cluster was anxiety/mood with 33 patients reporting symptoms of this cluster, followed by headache/migraine, fatigue, vestibular (each n=32), cognitive (n=30) and ocular (n=20). The most frequent combinations of clusters were anxiety/mood-fatigue (SRC patients presenting with both clusters: n=28), cognitive-vestibular (n=27), fatigue-vestibular (n=23) and fatigue-cognitive (n=22). A detailed description of the combinations and overlap of clusters can be found in online supplemental table S2.

Results of pairwise comparisons between SRC patients within a cluster and their matched controls, pairwise comparisons between SRC patients within a cluster and SRC patients without the cluster, and Spearman correlations between symptom cluster sum scores and test performance are presented in online supplemental tables S3–S5.

In neurocognitive testing, SRC patients presenting with symptoms of the anxiety/mood cluster demonstrated significantly lower motor speed scores than their matched controls (t(44)=3.511, p=0.001, d=1.039). No significant neuropsychological differences were detected between patients of a particular cluster and patients without this cluster.

When investigating balance, patients within the clusters anxiety/mood (U=275, z=−2.936, p=0.003, r=0.373), fatigue (U=199, z=−2.907, p=0.004, r=0.396), vestibular (U=248, z=−2.724, p=0.006, r=0.358) and ocular (U=71.5, z=−2.897, p=0.004, r=0.483) demonstrated significantly higher sway velocities in the double-firm condition compared with their respective control group (online supplemental table S3). When compared with SRC patients without the respective cluster, there were significant differences in balance outcomes for SRC patients with symptoms in the vestibular cluster (single-firm: U=199, z=−3.314, p<0.001, r=0.439; single-foam: U=215.5, z=−3.042, p=0.002, r=0.403; composite score: U=199.5, z=−3.297, p<0.001, r=0.437), fatigue cluster (single-foam: U=208, z=−3.150, p=0.002, r=0.417; composite score: U=212, z=−3.085, p=0.002, r=0.409) and cognitive cluster (single-foam: U=229.5, z=−2.781, p=0.005, r=0.368; composite score: U=204, z=−3.189, p=0.001, r=0.422) (online supplemental table S4). Additionally, significantly positive correlations between sway velocity in single-foam and the symptom sum scores of all six symptom clusters with large correlations for fatigue (r_s=0.505, p<0.001) and vestibular (r_s=0.503, p<0.001), were detected. Sway composite scores correlated significantly with symptom cluster sum scores of all clusters except for headache/migraine (online supplemental table S5).

Patients with the fatigue cluster demonstrated the lowest VOR-gain values of all clusters. No significant differences existed between the SRC and control groups in any cluster, but significant differences were found between patients with the fatigue cluster and patients without the fatigue cluster in VOR-gain LARP (t(53)=2.873, p=0.006, d=0.781). No significant correlations between vHIT parameters and symptom sum scores were found.

Correlation analysis revealed significant positive correlations between DVA loss and symptom sum scores of the fatigue cluster (r_s=0.298, p=0.047) and cognitive cluster (r_s=0.335, p=0.024), while no differences were found in the respective pairwise comparisons.

DISCUSSION

This study investigated whether neurocognitive function, balance, and vestibulo-ocular performance are impaired in athletes with SRC, depending on clinical symptom clusters. For the whole cohort of patients, we found significant differences between SRC and control subjects in the double-firm condition of balance testing only. Patients with the vestibular, cognitive and fatigue symptom clusters demonstrated significantly lower performance in balance testing than SRC patients without the respective cluster. Also, SRC patients presenting with symptoms of the fatigue cluster demonstrated significantly worse values in vestibulo-ocular testing compared with SRC patients without the fatigue cluster.

Whole cohort analysis

Analysing the whole cohort of SRC patients, only balance testing in the double-firm condition revealed significantly worse performance in patients than in matched control subjects. Higher postural sway in five balance parameters failed to reach significance, but overall, it may contribute to the assumption that postural control is predominantly impaired in athletes with SRC. Regardless of clinical symptoms, this observation may align with previous studies showing lower performance in balance tests in concussed athletes compared with healthy athletes.[27–30]

Computerised testing of the whole SRC cohort revealed a trend towards significance of SRC-associated decrease in motor speed, psychomotor speed and reaction time. Reduced psychomotor speed has been reported to be one of the most relevant domains for traumatic brain injury[18] and several studies found decreased performance in psychomotor speed and reaction time in patients with mild traumatic brain injury.[31 32] Our cross-sectional analysis may have failed to produce significant differences due to the potentially low effect size in this cohort, the relatively mildly affected patients (SCAT-5 symptom severity Mdn=19.5), or the relatively long time between injury and assessment.

Similarly, no significant differences in vestibulo-ocular tests were found when all SRC patients were analysed. Previous studies had reported heterogeneous results regarding vHIT and DVAT in concussion patients.[33–37] However, studies examining patients with persistent symptoms[38] or balance problems[37] have described abnormalities in vestibulo-ocular tests, which might suggest that these tests are more sensitive in patients with more severe or persistent symptoms than in our cohort.

Symptom clusters analysis

To investigate the specificity of objective test results with respect to clinical presentation, patients were grouped according to clinical symptom clusters. The number of clusters in our cohort of patients ranged from 0 (no definite cluster) to 6 (all clusters). This confirms that patients may present with one clinical profile, but more often with symptoms of multiple profiles that may overlap.[2 10] The six clusters were represented relatively equally among patients with anxiety/mood, headache/migraine, fatigue and vestibular, shown in 30–33 patients and ocular as the least frequent clinical cluster (20 patients). Therefore, assessing all potentially affected clinical domains is recommended for the assessment of SRC.

Patients with symptoms within the vestibular cluster demonstrated considerably poorer balance performance in the SET, as indicated by significant differences to controls in double-firm (in comparison to control subjects) and in single-firm, single-foam and composite score (in comparison to SRC patients without vestibular symptoms), confirming the contribution of the vestibular system to balance performance. Significant differences in balance testing were also found in the SRC groups with cognitive and fatigue clusters (compared with SRC patients without symptoms in the respective cluster). Although these results might be less expected, the relationship between fatigue and balance,[39] and between cognition and balance,[40] has already been shown in other populations. As recommended in the latest SRC guideline, a broader application of dual task testing for balance and cognition may further elucidate this connection and overlap of different clusters.[3]

Furthermore, SRC patients with the fatigue cluster demonstrated significant differences from patients without the fatigue cluster in vestibular testing (VOR-gain LARP) and an almost significant correlation between the fatigue symptom sum score and VOR-gain LARP. In addition, higher fatigue symptoms correlated significantly with higher DVA loss. Both lower VOR-gain and higher DVA loss indicate poorer VOR function, which can be impaired after a concussion due to disruptions of the central or peripheral vestibular system.[7 41] On the one hand, it might be surprising that VOR the function may not correlate with high symptom scores of the ocular and/or vestibular cluster. On the other hand, the correlation of fatigue with vestibular performance has already been described in patients with other neurological diseases like multiple sclerosis[42] and should not be overlooked in the clinical assessment of athletes with SRC. Furthermore, patients with affection of the anxiety/mood cluster may also be evaluated carefully in other clusters, as motor speed and balance were also reduced in these patients.

Overall, these results confirm that the presentation of SRC can be very variable, and not every patient may present with abnormalities in all clinical areas. Although some tests may have been impaired across several clusters (eg, sway double-firm) and could therefore be potentially suitable for screening purposes, establishing the full clinical picture of SRC requires an assessment of all clusters. The results further emphasise that it is important to consider the overlapping of clinical clusters/profiles, for example, fatigue symptom cluster and vestibulo-ocular function. Therefore, all domains should be investigated initially, and based on this, further examinations or targeted rehabilitation strategies can possibly be initiated. For example, individualised cognitive-motor training could be applied to target the symptoms/domains affected in the patient. This may be based on the specific deficits found in the assessment, for example, exercises combining specific cognitive domains with coordination/balance demands for patients presenting with a combination of cognitive and vestibular profiles.

Limitations

Several limitations of this study have to be considered. The included cohort of patients was heterogeneous, especially regarding symptom severity and time between injury and examination, which was not considered in the statistical analysis. This could influence the results, as SRC-related symptoms can improve quickly, and tests are most sensitive in the first 72 hours.[3] Furthermore, influencing factors such as performance level could not be controlled for in matching, but could also affect the investigated functions.[43 44] Future studies are necessary to confirm the reported results using larger datasets and controlling for possible confounders, such as the number of days between injury and assessments. Additionally, the study included a high number of outcomes and comparisons. Although the Bonferroni correction was applied to correct for multiple comparisons, this also resulted in small alpha levels and decreased statistical power. Finally, baseline data were not available for most patients. However, performance is individual,[45 46] and even though the control group was matched as accurately as possible, the comparison to individual baseline values could provide more insights than the comparison to a control group.

CONCLUSION

This study investigated neurocognitive function, balance and vestibulo-ocular performance in athletes with SRC, specifically focusing on clinical symptom clusters. The included SRC patients presented with variable numbers and types of clinical symptom clusters. When analysing the whole cohort (regardless of symptom clusters), only balance testing in the double-firm condition revealed significantly lower performance in SRC patients than in matched control subjects. When analysing symptom clusters specifically, certain subjective clusters were associated with abnormal objective tests of other clusters (vestibular, cognitive and fatigue symptom profiles with abnormal balance; and fatigue symptom profiles with abnormal vestibulo-ocular performance). The results of the study confirm the heterogeneous clinical presentation of SRC and emphasise the importance of considering clinical profiles and their overlap in the assessment and treatment of SRC.

Acknowledgements The authors would like to thank Lena Dautzenberg and all other members of the Institute of Sports Medicine who were involved in data collection for this study. They further thank Christian Gölz and Roman Gaidai for the administration of the REDCap database and Nele Weike for the support in data preparation. The authors acknowledge support for the publication cost by the Open Access Publication Fund of Paderborn University.

Contributors CR, LW and RR conceptualised the research. LW conducted the statistical analysis. LW and CR were involved in writing the original draft of the manuscript. RR reviewed and edited the manuscript. All authors read and approved the final version of the manuscript. CR is the guarantor of the work.

Funding This work was financially supported by the German Federal Institute of Sports Sciences (Bundesinstitut für Sportwissenschaft, grant number ZMVI4-070105/19-20) and the Heinz Nixdorf Westfalian Foundation.

Competing interests CR receives grant support from the German Federal Institute of Sports Sciences and the Heinz Nixdorf Westfalian Foundation. He serves as medical officer and as a member of the medical commission of the German Football Association (DFB) and is a medical advisor on concussion for the Union of European Football Associations (UEFA).

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was approved by Ethics Committee of the Westfalian Medical Board in Münster, Germany (2018-522-f-S). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement No data are available. The data that support the findings of this study are not publicly available due to potential traceability of participants.

ORCID iD
Lea Weike http://orcid.org/0000-0003-0302-2400

REFERENCES

1 Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil* 2006;21:375–8.
2 Harmon KG, Clugston JR, Dec K, *et al*. American Medical Society for Sports Medicine Position Statement on Concussion in Sport. *Clin J Sport Med* 2019;29:87–100.
3 Patricios JS, Schneider KJ, Dvorak J, *et al*. Consensus statement on concussion in sport: the 6th International Conference on Concussion in Sport-Amsterdam, October 2022. *Br J Sports Med* 2023;57:695–711.
4 Feddermann-Demont N, Echemendia RJ, Schneider KJ, *et al*. What domains of clinical function should be assessed after sport-related concussion? A systematic review. *Br J Sports Med* 2017;51:903–18.
5 Hou X, Zhang Y, Fei X, *et al*. Sports-Related Concussion Affects Cognitive Function in Adolescents: A Systematic Review and Meta-analysis. *Am J Sports Med* 2023;51:3604–18.
6 Lempke LB, Howell DR, Eckner JT, *et al*. Examination of Reaction Time Deficits Following Concussion: A Systematic Review and Meta-analysis. *Sports Med* 2020;50:1341–59.
7 Valovich McLeod TC, Hale TD. Vestibular and balance issues following sport-related concussion. *Brain Inj* 2015;29:175–84.
8 Quintana CP, McLeod TCV, Olson AD, *et al*. Vestibular and Ocular/Oculomotor Assessment Strategies and Outcomes Following Sports-Related Concussion: A Scoping Review. *Sports Med* 2021;51:737–57.
9 Kontos AP, Sufrinko A, Sandel N, *et al*. Sport-related Concussion Clinical Profiles: Clinical Characteristics, Targeted Treatments, and Preliminary Evidence. *Curr Sports Med Rep* 2019;18:82–92.
10 Collins MW, Kontos AP, Reynolds E, *et al*. A comprehensive, targeted approach to the clinical care of athletes following sport-related concussion. *Knee Surg Sports Traumatol Arthrosc* 2014;22:235–46.
11 Aderman MJ, Brett BL, Ross JD, *et al*. Association Between Symptom Cluster Endorsement at Initiation of a Graduated Return-to-Activity Protocol and Time to Return to Unrestricted Activity After Concussion in United States Service Academy Cadets. *Am J Sports Med* 2023;51:2996–3007.
12 Howell DR, Kriz P, Mannix RC, *et al*. Concussion Symptom Profiles Among Child, Adolescent, and Young Adult Athletes. *Clin J Sport Med* 2019;29:391–7.
13 Howell DR, O'Brien MJ, Beasley MA, *et al*. Initial somatic symptoms are associated with prolonged symptom duration following concussion in adolescents. *Acta Paediatr* 2016;105:e426–32.
14 Nolan KE, Caccese JB, Kontos AP, *et al*. Primary and Secondary Risk Factors Associated With Concussion Symptom Clusters in Collegiate Athletes: Results From the NCAA-DoD Grand Alliance CARE Consortium. *Orthop J Sports Med* 2023;11:23259671231163581.
15 Harris PA, Taylor R, Thielke R, *et al*. Research electronic data capture (REDCap)--a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform* 2009;42:377–81.
16 Echemendia RJ, Meeuwisse W, McCrory P, *et al*. The Sport Concussion Assessment Tool 5th Edition (SCAT5): Background and rationale. *Br J Sports Med* 2017;51:848–50.
17 Gualtieri CT, Johnson LG. Reliability and validity of a computerized neurocognitive test battery, CNS Vital Signs. *Arch Clin Neuropsychol* 2006;21:623–43.
18 Gualtieri CT, Johnson LG. A computerized test battery sensitive to mild and severe brain injury. *Medscape J Med* 2008;10:90.
19 Williams RM, Corvo MA, Lam KC, *et al*. Test-Retest Reliability and Practice Effects of the Stability Evaluation Test. *J Sport Rehabil* 2017;26:2016–0163.
20 MacDougall HG, McGarvie LA, Halmagyi GM, *et al*. Application of the video head impulse test to detect vertical semicircular canal dysfunction. *Otol Neurotol* 2013;34:974–9.
21 MacDougall HG, Weber KP, McGarvie LA, *et al*. The video head impulse test: diagnostic accuracy in peripheral vestibulopathy. *Neurology* 2009;73:1134–41.
22 Sayed SZ, Abdul Wahat NH, Raymond AA, *et al*. Test-Retest Reliability, Effects of Age and Comparison of Horizontal 2 Semicircular Canals Gain Values between Head Impulse and Suppression Head Impulse Paradigms. *J Int Adv Otol* 2023;19:33–40.
23 Singh NK, Govindaswamy R, Jagadish N. Test-Retest Reliability of Video Head Impulse Test in Healthy Individuals and Individuals with Dizziness. *J Am Acad Audiol* 2019;30:744–52.
24 Herdman SJ, Tusa RJ, Blatt P, *et al*. Computerized dynamic visual acuity test in the assessment of vestibular deficits. *Am J Otol* 1998;19:790–6.
25 Kaufman DR, Puckett MJ, Smith MJ, *et al*. Test-retest reliability and responsiveness of gaze stability and dynamic visual acuity in high school and college football players. *Phys Ther Sport* 2014;15:181–8.
26 Cohen J. *Statistical power analysis for the behavioral sciences*. 2nd edn. Hillsdale, NJ: Lawrence Erlbaum Associates, 1988.
27 Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Train* 2001;36:263–73.
28 Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *J Athl Train* 2000;35:19–25.
29 McCrea M, Guskiewicz KM, Marshall SW, *et al*. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA* 2003;290:2556–63.
30 Peterson CL, Ferrara MS, Mrazik M, *et al*. Evaluation of neuropsychological domain scores and postural stability following cerebral concussion in sports. *Clin J Sport Med* 2003;13:230–7.
31 Brooks BL, Khan S, Daya H, *et al*. Neurocognition in the emergency department after a mild traumatic brain injury in youth. *J Neurotrauma* 2014;31:1744–9.
32 Peterson SE, Stull MJ, Collins MW, *et al*. Neurocognitive function of emergency department patients with mild traumatic brain injury. *Ann Emerg Med* 2009;53:796–803.

33 Alkathiry AA, Kontos AP, Furman JM, *et al*. Vestibulo-Ocular Reflex Function in Adolescents With Sport-Related Concussion: Preliminary Results. *Sports Health* 2019;11:479–85.
34 Alshehri MM, Sparto PJ, Furman JM, *et al*. The usefulness of the video head impulse test in children and adults post-concussion. *J Vestib Res* 2016;26:439–46.
35 Schneider KJ, Meeuwisse WH, Palacios-Derflingher L, *et al*. Changes in Measures of Cervical Spine Function, Vestibulo-ocular Reflex, Dynamic Balance, and Divided Attention Following Sport-Related Concussion in Elite Youth Ice Hockey Players. *J Orthop Sports Phys Ther* 2018;48:974–81.
36 Gottshall K, Drake A, Gray N, *et al*. Objective vestibular tests as outcome measures in head injury patients. *Laryngoscope* 2003;113:1746–50.
37 Zhou G, Brodsky JR. Objective vestibular testing of children with dizziness and balance complaints following sports-related concussions. *Otolaryngol Head Neck Surg* 2015;152:1133–9.
38 Gard A, Al-Husseini A, Kornaropoulos EN, *et al*. Post-Concussive Vestibular Dysfunction Is Related to Injury to the Inferior Vestibular Nerve. *J Neurotrauma* 2022;39:829–40.
39 Hebert JR, Corboy JR. The association between multiple sclerosis-related fatigue and balance as a function of central sensory integration. *Gait Posture* 2013;38:37–42.
40 Morris R, Martini DN, Smulders K, *et al*. Cognitive associations with comprehensive gait and static balance measures in Parkinson's disease. *Parkinsonism Relat Disord* 2019;69:104–10.
41 Crampton A, Teel E, Chevignard M, *et al*. Vestibular-ocular reflex dysfunction following mild traumatic brain injury: A narrative review. *Neurochirurgie* 2021;67:231–7.
42 Cochrane GD, Christy JB, Motl RW. Central Vestibular Functions Correlate With Fatigue and Walking Capacity in People With Multiple Sclerosis. *Phys Ther* 2021;101.
43 Paillard T, Noé F, Rivière T, *et al*. Postural performance and strategy in the unipedal stance of soccer players at different levels of competition. *J Athl Train* 2006;41:172–6.
44 Huijgen BCH, Leemhuis S, Kok NM, *et al*. Cognitive Functions in Elite and Sub-Elite Youth Soccer Players Aged 13 to 17 Years. *PLoS One* 2015;10:e0144580.
45 Combs PR, Ford CB, Campbell KR, *et al*. Influence of Self-reported Fatigue and Sex on Baseline Concussion Assessment Scores. *Orthop J Sports Med* 2019;7:2325967118817515.
46 Cottle JE, Hall EE, Patel K, *et al*. Concussion Baseline Testing: Preexisting Factors, Symptoms, and Neurocognitive Performance. *J Athl Train* 2017;52:77–81.