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Understanding Abnormal Examination Findings During Concussion Recovery

A Retrospective Chart Review

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Class of Evidence
Criteria for rating therapeutic and diagnostic studies
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Abstract

Background and Objective

Physical examination findings in athletes with sport-related concussion (SRC) are not well described in the literature. The objective of this study was to describe physical examination findings during the first month following concussion in athletes, with a focus on the effect of sex, age, and time since injury.

Methods

This was a retrospective electronic medical record (EMR) review of physical examination findings in 500 patients aged 6–24 who were initially seen within 15 days of SRC at a multidisciplinary outpatient academic concussion clinic between 2017 and 2019. A standardized concussion examination built in the EMR recorded mental status, cranial nerve, vestibulo-ocular motor screen, and balance findings for all patients. The primary outcome was the frequency of abnormal examination findings during the first 30 days postinjury, which was further analyzed by sex, age, and time since injury using mixed logistic regression models.

Results

The most common abnormal examination findings overall were eyes-closed single-leg stance, vestibular-ocular reflex, visual motion sensitivity, the neck examination, and eyes-closed tandem stance. Abnormal findings were more frequent in female athletes for vestibular ocular reflex and visual motion sensitivity. The frequency of abnormal findings increased with age for vestibulo-ocular reflex, visual motion sensitivity, the neck examination, convergence testing, and eyes-open single-leg stance, whereas abnormalities decreased in frequency with age for eyes-open tandem stance and tandem gait. The frequency of abnormal findings generally decreased with time over the first 4 weeks following injury.

Discussion

A comprehensive physical examination is pivotal for evaluation of athletes with concussion. These findings highlight high-yield components of the concussion examination and support use of these examination components as injury markers. Future work should investigate associations between physical examination findings and postconcussion symptoms and recovery outcomes.

Classification of Evidence

This retrospective cohort study provides Class IV evidence that neurologic examination with specifically designed clinical tests are helpful for diagnosis of traumatic brain injury in young athletes at age 6–24.

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Introduction

More than half of youths in the United States participate in sports, with nearly 8 million high school athletes and approximately 500,000 college student-athletes.[1] Despite the many benefits of physical activity, athletes are at a greater risk of experiencing mild traumatic brain injury or concussion resulting from direct or indirect head trauma.[1,2] Every year, there are estimated to be more than 250,000 emergency department visits for sport-related head injuries in individuals aged 18 years or younger,[3] with an overall estimated risk of sports-related concussion in the pediatric and adolescent population of 0.33 per 1000.[4] It is important to note that this estimated number is likely lower than the actual incidence of sport-related head injuries because not all affected athletes report their symptoms or seek medical attention.[5]

In the emergency department or clinic setting, there are currently no reliable, validated, diagnostic concussion imaging findings or serum biomarkers.[6] Concussion diagnosis relies on a clinical evaluation that integrates various factors, including patient history, injury mechanism, reported symptoms, physical examination findings, and clinical judgment. To complement the clinical diagnosis, an array of ancillary tests has been developed, such as the Balance Error Scoring System (BESS), Vestibular/Ocular-Motor Screening (VOMS), Standardized Assessment of Concussion, Sport Concussion Assessment Tool, and King-Devick test. However, these tests are not sensitive or specific enough to be used as standalone diagnostic tools.[7] Additional diagnostic tests such as complex tandem gait and mVOMS (modified VOMS) have attempted to improve the accuracy and speed of the concussion examination.[8,9] Patient-reported symptoms, which are subjective, are frequently used as the primary marker of diagnosis and recovery.

The physical and neurologic examination findings, which we collectively referred to as the concussion examination, lack a clear description of their individual and interrelated components. Guidelines for prioritizing which neurologic examination findings to focus on during a clinical concussion evaluation are currently unavailable. Studies that characterize neurologic examination findings after concussion often lack comprehensive reporting across multiple domains or include small sample sizes, hindering accurate patient characterization and examination of recovery patterns throughout the normal recovery window.[6,10] Progress has been made in standardizing the neuro-ophthalmologic concussion examination[11] and balance testing.[12] Each of these assessments, however, covers only a subset of the neurologic examination, excluding other standard examination elements.

Therefore, we aimed to describe the concussion examination findings after an acute concussion at an academic multidisciplinary concussion clinic for new patients aged 6–24, seen within 15 days from injury. We also investigated the influence of sex, age, and time since injury on examination findings. This study primarily addresses the research question: which components of the physical examination are most frequently abnormal following concussion? A secondary research question addressed by this study is, how do postconcussion physical examination findings differ by sex, age, and time since injury?

Methods

Data Collection/Study Population

We report the concussion examination findings in 500 unique patients with concussion, over a total of 987 visits occurring within 30 days of injury. Concussion was clinically diagnosed based on international consensus statements.[13,14] Although published after our data collection, the Amsterdam criteria for concussion emphasize the rapid-onset, transient neurologic impairments to offer a broader approach to diagnosis, extending beyond the specific mechanisms of injury highlighted in the earlier Berlin definition. This definition shift remains valid and applicable to the patients in our sample, still aligning with the core characteristics of concussion observed in our study. Data were collected through a retrospective chart review at an academic medical center for visits occurring between July 2018 and March 2020. The study population included patients between ages 6 and 24 years, seen by one of 5 concussion specialists (with more than 50 years of combined experience in concussion diagnosis and management) who performed and documented a standardized neurologic examination, initially within 15 days of injury. This time frame was chosen to focus on a typical concussion recovery period.[14] Patients were classified into 3 age groups: childhood (ages 6–12 years), adolescence (ages 13–17), and adulthood (ages 18–24).

Standard Protocol Approvals, Registrations, and Patient Consents

This secondary analysis of clinical data from the electronic medical record (EMR) was approved by the institutional review board at the authors' university.

Standardized Concussion Examination

Our group developed a standardized concussion examination and implemented an associated "NoteWriter" template in the Epic-based EMR in July 2018. The consensus on examination standards was achieved through a structured Delphi process, involving iterative rounds of survey and discussion among multidisciplinary experts, ensuring a comprehensive and representative agreement on the protocols used. The standardized examination includes elements including general appearance, mental status, cranial nerves, modified VOMS, strength, sensation, gait, balance, and cervical examination. All participating physicians contributed to the development of the standardized examination and template and agreed to use it during clinical encounters.

A comprehensive description of the standardized concussion examination can be found in the eMethods section in the Supplement. For the sake of brevity, we will detail only the examination elements that were found to be abnormal in at least 5% of patients during their initial clinical encounter.

The VOMS, as described by Mucha et al.,[11] was modified by categorizing each component as either normal or abnormal. Vestibular ocular reflex (VOR) testing was classified as abnormal if the patient reported any symptoms while horizontally rotating or vertically nodding their head approximately 30°, maintaining their gaze on a visual target held around 60 cm away from their eyes. Horizontal alternating saccade testing was considered abnormal if the patient reported any symptoms while keeping their head still and looking back and forth between 2 targets held about 45 cm from their eyes and spaced around 45 cm apart. An abnormal finding was also recorded if hypometric or hypermetric saccadic eye movements were observed during horizontal alternating saccade testing, including slow initiation, slower than normal motion, or interrupted pursuit with frequent blinking. Horizontal pursuit testing was classified as abnormal if the patient-reported symptoms or if saccadic eye movements were observed while the patient followed a moving visual target back and forth at approximately 45 cm from their eyes.

Visual motion sensitivity (VMS) was classified as abnormal if the patient reported any symptoms or if saccadic eye movements were observed when they fully extended their arm with their thumb up and then rotated at the waist approximately 150° while keeping their gaze fixed on their thumb. Convergence testing was considered abnormal if the patient reported double vision at any distance greater than the clinical cutoff value of 5 cm as described by Mucha et al.,[11] when a visual target, initially placed 20 cm in front of the eyes at the eye level, was moved toward their face. Although we recognize that there may be age-related difference in near-point convergence normative values,[15] we used the standard 5 cm threshold described for the VOMS.[11] The exact distance at which the patient reported double vision, measured from the tip of the nose, was also documented.

Balance was assessed using standard BESS unipedal and tandem stances,[12] with hands on hips on a firm surface under both eyes open and eyes closed conditions. Balance testing was classified as abnormal if the patient swayed or broke their stance during a 10-second testing period. Forward tandem gait was performed by having the patient walk heel-to-toe for approximately 3 m and was considered abnormal if the patient swayed or fell out of the tandem gait. Romberg testing was conducted for about 10 seconds in a standard double stance with feet together, arms extended, and eyes closed. The presence of more than minimal sway or breaking stance were classified as abnormal.

The cervical examination included active range of motion in all planes and palpation over the cervical spinous processes, suboccipital, paraspinal, and upper trapezius muscles. All components of the cervical examination were evaluated together, and the cervical examination was deemed abnormal if the patient reported any stiffness and/or soreness during active range of motion, if significant limitation was observed during active range of motion, or if pain and/or tenderness was reported during palpation.

Data Extraction and Analysis

On entering data into the "NoteWriter" template during each clinical encounter, the information was collectively stored in a centralized Oracle database across all patients and encounters. The data were later extracted using dbForge Studio for Oracle and subsequently formatted for analysis with Microsoft Excel and SPSS v27. The processed data set was then filtered to identify patients who met the study's eligibility criteria previously mentioned.

The 35 concussion examination components were ranked by the frequency of abnormal findings at the initial visit. Twelve examination components with abnormal findings present in at least 5% of patients and with less than 20% missing data were included in further analysis. Since the timing of initial clinic visits was not standardized, the frequency of examination abnormalities during week 1 (through postinjury day 7) and week 2 (postinjury days 8–15), as well as examination abnormality frequencies at each individual postinjury day (i.e., postinjury days 1–15), was compared using chi-square tests to assess the comparability of initial visit results over the 15-day initial visit time window. No significant differences in the frequency of abnormal findings were identified by chi-square analysis for any examination component over the 15-day initial visit time window, confirming comparability of initial visit results across the initial 15-day postinjury period.

The frequency of abnormal findings at the initial visit was then compared by sex and age groups using chi-square tests. To assess the frequency of abnormal examination findings over time, univariate mixed logistic regression models were used to compare findings during postinjury weeks 1, 2, 3, and 4 for each component of the examination. Multivariate mixed logistic regression models, including sex and age group as covariates, were then used to assess examination abnormalities over time, accounting for the effects of sex and age. In the data set, 36 patients were seen twice during the same postinjury week, and in these cases, only the results from the first of the 2 same-week visits were used in the mixed logistic regression models. A false discovery rate correction was applied to each set of analyses to account for multiple comparisons over the 12 individual examination findings.

Data Availability

Anonymized data will be made available by reasonable request to the corresponding author from qualified investigators.

Results

The study population demographics are presented in Table 1. Patients were seen for a mean (SD) of 1.97 (0.85) clinic visits within 30 days of concussion, with initial visits occurring 6.7 (4.0) days after injury.

Table 1 New Patient Visits Within 15 Days of Injury

Total patients	500
Age	15.7 ± 3.0 (6–25)
Age range, n (%)	
Childhood (6–12)	51 (10.2)
Adolescence (13–17)	362 (72.4)
Adulthood (18–24)	87 (17.4)
Sex, n (%)	
Female	20 (41.8)
Male	291 (58.2)
Race, n (%)	
White	409 (81.8)
African American	55 (11)
Asian	11 (2.2)
Other/unknown	25 (5)
New and return visits within 30 days of injury	
Total patient visits	951
Week injury, n (%)	
1	304 (32.0)
2	334 (35.1)
3	184 (19.3)
4	129 (13.6)

Counts are presented as number (%). Continuous values are presented as mean ± SD (range).

Concussion Examination Findings

The components of the examination with greatest frequency of abnormal findings at the initial visit were as follows: 10-second single-leg stance with eyes closed (52%), vestibular-ocular reflex (46%), visual motion sensitivity (43%), neck examination (42%), tandem stance with eyes closed (34%), convergence testing (28%), 10-second single-leg stance with eyes open (20%), horizontal alternating saccades (15%), tandem stance with eyes open (11%), tandem gait (10%), horizontal pursuits (6%), and Romberg test (5%; Table 2). Abnormal mental status (5-item recall) was also present in 33% of initial encounters, although this component of the examination did not meet the study's 80% documentation threshold for additional analysis. Abnormality rates for all other components of the examination were less than 5% (eTable 1 in the Supplement).

Frequency of Examination Abnormalities by Sex

Vestibular ocular reflex and visual motion sensitivity were more frequently abnormal in female than male athletes (VOR: 57% female, 38% male, $p < 0.001$; VMS: 54% female, 36%, male, $p < 0.001$). Frequency of examination abnormalities did not differ by sex for any other component of the examination (all $p > 0.05$; Table 2).

Frequency of Examination Abnormalities by Age Group

When comparing frequencies of examination abnormalities between the child, adolescent, and adult age groups (Table 2), 5 components of the examination had greater frequencies of abnormal findings with increasing age. The frequency of abnormal vestibulo-ocular reflex increased with age (overall $p < 0.001$; $p = 0.016$, $p = 0.004$, $p < 0.001$ for child-adolescent, adolescent-adult, and child-adult pairwise comparisons, respectively). The frequency of abnormal visual motion sensitivity increased with age (overall $p = 0.047$; $p = 0.046$ for child-adult pairwise comparison; child-adolescent and adolescent-adult pairwise comparisons were nonsignificant). The frequency of abnormal neck examination increased with age (overall $p = 0.001$; $p = 0.005$ and $p < 0.001$ for adolescent-adult and child-adult pairwise comparisons, respectively; child-adolescent pairwise comparison was nonsignificant). The frequency of abnormal convergence testing increased with age (overall $p = 0.021$; $p = 0.013$ and $p = 0.022$ for adolescent-adult and child-adult pairwise comparisons, respectively; child-adolescent pairwise comparison was nonsignificant). The frequency of abnormal 10-second single-leg stance with eyes open increased with age (overall $p = 0.002$; $p < 0.001$ and $p = 0.004$ for child-adolescent and child-adult pairwise comparisons, respectively; adolescent-adult pairwise comparison was nonsignificant).

Two components of the examination had lower frequencies of abnormal findings with increasing age. The frequency of abnormal tandem stance with eyes-open decreased with age (overall $p = 0.011$; $p = 0.005$ and $p = 0.016$ for child-adolescent and child-adult pairwise comparisons, respectively; adolescent-adult pairwise comparison was nonsignificant). The frequency of abnormal tandem gait decreased with age (overall $p = 0.001$; $p < 0.001$ and $p = 0.006$ for child-adolescent and child-adult pairwise comparisons, respectively; adolescent-adult pairwise comparison was nonsignificant).

Frequency of Examination Abnormalities Over Time

The frequency of abnormal examination findings tended to decrease over postinjury weeks 1–4 for all 12 examination components analyzed (Table 3), with differences reaching statistical significance for 4 components of the examination (Figure). Significant decreases were observed over time for vestibular ocular reflex (overall $p = 0.028$; week 1–week 2 $p = 0.037$, week 1–week 3 $p = 0.010$, week 1–week 4 $p = 0.017$), single-leg stance with eyes closed (overall $p = 0.013$; week 1–week 3 $p = 0.032$, week 1–week 4 $p = 0.002$), tandem stance with eyes closed (overall $p = 0.028$; week 1–week 3 $p = 0.030$, week 1–week 4 $p = 0.009$), and visual motion sensitivity (overall $p = 0.168$; week 1–

Table 2 Concussion Examination Findings, Which Are Further Divided by Sex and Age

Examination finding	n	Overall examination findings		Examination findings by sex			Examination findings by age group			
				Male (291)	Female (209)		Childhood (51)	Adolescence (362)	Adulthood (87)	
		Normal	Abnormal	Abnormal	Abnormal	Sig (χ^2)	Abnormal	Abnormal	Abnormal	Sig (χ^2)
Single-leg stance (eyes closed)	443	182 (41.0)	261 (58.9)	148 (58.7)	113 (59.2)	0.927	26 (66.7)	191 (59.1)	44 (54.3)	0.43
VOR	489	261 (53.3)	228 (46.6)	109 (38.5)	119 (57.8)	<0.001	13 (27.1)	161 (45.4)	54 (62.8)	<0.001
VMS	490	273 (55.7)	217 (44.2)	105 (37.1)	112 (54.1)	<0.001	16 (32.7)	155 (43.5)	46 (54.1)	0.047
Neck issues	490	280 (57.1)	210 (42.8)	114 (40.1)	96 (46.6)	0.154	14 (27.5)	147 (41.4)	49 (58.3)	0.001
Tandem stance (eyes closed)	416	246 (59.1)	170 (40.8)	93 (39.9)	77 (42.1)	0.656	25 (55.6)	120 (39.7)	25 (36.2)	0.09
Convergence testing	492	350 (71.1)	142 (33.1)	78 (27.3)	64 (31.1)	0.359	11 (21.6)	96 (27)	35 (40.7)	0.021
Single-leg stance (eyes open)	455	354 (77.8)	101 (22.1)	63 (24.2)	38 (19.5)	0.228	18 (43.9)	67 (20.2)	16 (19.5)	0.002
Horizontal alternating saccades	493	418 (84.7)	75 (18.0)	50 (17.4)	25 (12.1)	0.107	10 (19.6)	54 (15.2)	11 (12.8)	0.56
Tandem stance (eyes open)	424	370 (87.2)	54 (12.7)	33 (13.8)	21 (11.4)	0.474	12 (26.7)	35 (11.4)	7 (9.7)	0.011
Tandem walk	478	427 (89.3)	51 (10.6)	28 (10.2)	23 (11.3)	0.688	13 (26)	31 (9)	7 (8.4)	0.001
Horizontal pursuits	493	462 (93.7)	31 (7.61)	17 (5.9)	14 (6.8)	0.694	3 (6.3)	19 (5.7)	5 (6.4)	0.97
Romberg	462	435 (94.1)	27 (5.84)	14 (5.2)	13 (6.7)	0.489	3 (6)	23 (6.4)	5 (5.8)	0.96

Percent (%) abnormal by category is percentage of recorded data.

week 3 p = 0.030). These changes over time remained significant for all 3 examination components when accounting for the effects of sex and age group in multivariate models. There were no other significant differences over time (see Table 3).

Discussion

Our study presents a novel approach to identifying abnormal elements in the neurologic examination during the acute postconcussion recovery period across pediatric, adolescent, and adult populations. Current diagnosis and determination of concussion recovery largely rely on patient-reported symptoms.

Previous studies, such as those by Leddy et al.[10] and Haider et al.,[6] have characterized abnormal physical and neurologic examination findings following concussions. These studies identified abnormalities in various aspects of the examinations, including cervical tenderness, smooth pursuits, convergence, horizontal saccades, VOR, and tandem gait. Our study found similar proportions of patients with neck tenderness, abnormal VOR, and abnormal near point of convergence; however, the Haider study had higher proportions of patients with abnormal horizontal saccades and abnormal tandem gait.

The primary aim of this analysis was to expand on previous literature and pinpoint the most clinically relevant components of a standard concussion examination to enhance clinical efficiency. Our results indicate that vestibulo-ocular testing (such as VOR, VMS, convergence testing, horizontal alternating saccades, and horizontal pursuits), balance testing (including single-leg stance with eyes open and closed, tandem stance with eyes open and closed, and tandem walk), and the cervical spine or neck examination are crucial to include in the physical examination following a concussion. Integrating these components into a standardized concussion examination may aid management and enhance the overall clinical efficiency of concussion evaluation.

Vestibulo-ocular testing (e.g., VOMS) has been consistently cited as an independent marker of concussion symptom severity Babicz.[16] The Berlin consensus statement underscores the importance of the vestibulo-ocular system in concussion, and VOMS has been suggested as a tool to help differentiate concussed from nonconcussed athletes.[11,14] The retrospective chart review by Babicz et al. (2016–2019) involving 158 patients found that vertical saccades and vertical VOR were independently related to symptom severity when accounting for sex, baseline vestibular symptoms, and neurocognitive performance, consistent with our data examining a larger cohort. This study, combined with previous research,

Table 3 Abnormal Examination Findings by Week

	Week 1[a]	Overall sig (χ2)	Week 2	Week 1-week 2 sig (χ^2)	Week 3	Week 1-week 3 sig (χ^2)	Week 4	Week 1-week 4 sig (χ^2)
Single-leg stance (eyes closed)	165 (60.9)	0.013	160 (54.4)	0.065	77 (51.3)	0.032	41 (43.6)	0.002
VOR	139 (46.5)	0.028	127 (39.3)	0.037	63 (35)	0.010	41 (33.9)	0.017
Neck issues	135 (44.9)	0.209	124 (38.9)	0.071	72 (42.6)	0.613	52 (46.8)	0.710
VMS	131 (44)	0.168	120 (37.2)	0.046	66 (36.5)	0.090	44 (35.8)	0.111
Tandem stance (eyes closed)	106 (41.7)	0.028	100 (38)	0.313	43 (31.4)	0.030	22 (26.2)	0.002
Convergence testing	87 (29.1)	0.231	85 (25.8)	0.255	56 (30.6)	0.692	40 (32.8)	0.412
Single-leg stance (eyes open)	63 (22.7)	0.214	52 (17.3)	0.064	28 (17.9)	0.185	15 (15.3)	0.111
Horizontal alternating saccades	41 (13.8)	0.771	41 (12.5)	0.628	21 (11.4)	0.396	13 (10.7)	0.358
Tandem stance (eyes open)	35 (13.7)	0.448	28 (10.3)	0.159	17 (12.1)	0.607	8 (9)	0.607
Tandem walk	32 (11)	0.722	28 (9.3)	0.408	13 (8.3)	0.290	10 (9)	0.514
Horizontal pursuits	20 (6.7)	0.512	16 (4.9)	0.255	10 (5.6)	0.553	9 (7.2)	0.834
Romberg	20 (7.1)	0.652	16 (5.4)	0.273	7 (4.6)	0.281	6 (5.8)	0.617

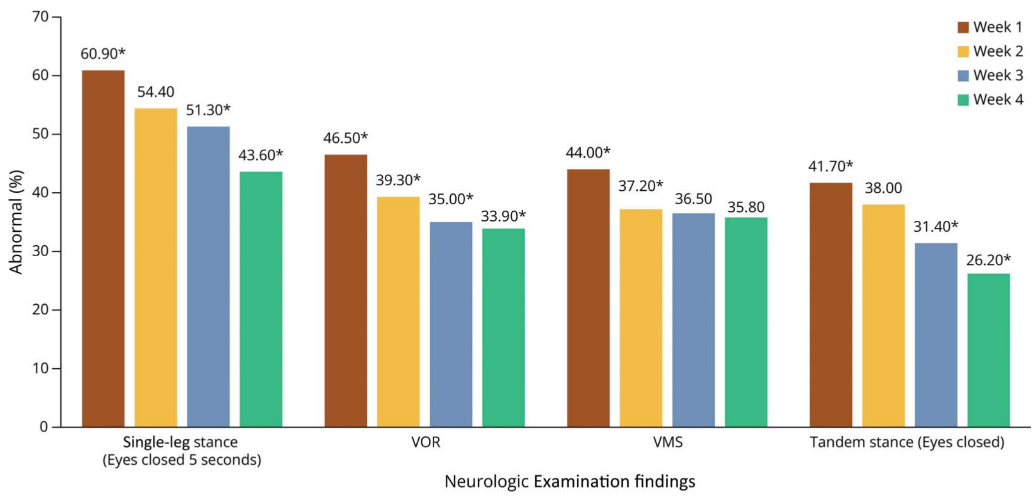
Percent abnormal by category is percentage of recorded data.
[a] Week 1 sig (χ^2) is defined as the intercept.

highlights the importance of including vestibulo-ocular testing in concussion evaluations.

Neck findings were prevalent in our study population and likely contributed to the overall symptom burden, particularly cervicogenic headaches. Furthermore, these neck findings may contribute to balance issues and cervicogenic dizziness, a term that refers to balance problems stemming from proprioceptive and musculoskeletal causes.[17] In our study, we observed abnormal neck findings 57% of the time overall, with higher occurrences in female athletes and increasing frequency with age.

The National Athletic Treatment, Injury, and Outcomes Network Study reported that approximately one-third of high school athletes experience neck pain following a concussion.[18] This finding is consistent with our data in which 42% of the adolescent age group exhibited abnormal neck findings. The study by Cheever and colleagues also revealed that female athletes were more likely to experience neck pain,

Figure Neurologic Examination Findings



Depicts the 4 concussion examination findings that demonstrated statistical significance (*$p < 0.05$) over time, about week 1, and trended toward recovery.

highlighting the significance of cervicogenic findings in concussion assessment and the differences in presentation between sexes.

Balance testing, including methods such as BESS, is commonly used following concussions. Data from the National Collegiate Athletic Association CARE Consortium demonstrated that balance errors gradually improved over time, which is in line with our mBESS findings.[19] However, the diagnostic sensitivity of balance testing varies considerably, ranging from 3% to 35%, in the CARE data. This wide range underscores the need for a comprehensive approach and the incorporation of additional findings mentioned above in the evaluation process.

In our study, we found that visual motion sensitivity and vestibular ocular reflex abnormalities were more common in female than male athletes, consistent with previous literature that also reported a higher prevalence of abnormal findings in female athletes.[20,21] Research on high school athletes has shown that female athletes experience more physical and somatic symptoms, longer symptomatic periods, and greater symptom severity than male athletes.[22-24] Furthermore, cohort studies indicate that female school-age and college athletes take nearly a week longer to return to school or sports than their male counterparts[25-27] and are more likely to experience prolonged symptoms.[28] This disparity may be due to differences in biomechanical factors that increase injury rates in women compared with men.[1,29-33] The higher incidence of abnormal vestibular findings in the outpatient population could provide further insight into sex-related differences in symptom burden.

Our data show that single-leg stance, tandem stance with eyes closed, VOR, and VMS improved with increasing time from injury, suggesting recovery across all age groups and both sexes. Further analysis of these examination elements could provide insight into their effect on concussion recovery and the risk for prolonged symptoms.

Although reflexes, strength testing, coordination, visual fields, sensory testing, and funduscopic examinations were infrequently abnormal in our study, they remain essential for evaluating concurrent nonconcussion injuries such as severe TBI, intracranial hemorrhage, myelopathies, radiculopathies, and other neurologic conditions.

Our analysis offers valuable guidance on the most important examination findings to assess following a concussion. These findings can inform individualized patient management, such as referrals to spine and vestibular therapies, and may serve as metrics for monitoring therapy response and recovery. Normal physical examination findings accompanied by ongoing symptoms may indicate an alternative explanation for symptoms, such as psychosocial distress, which could prolong recovery.

It is crucial for healthcare professionals involved in first-line concussion care and return-to-sport decisions, including athletic trainers, nurses, physician assistants, physicians, and physical therapists, to pay close attention to these examination findings. Our findings can support management strategies based on anticipated findings and recovery trajectories in different subpopulations. The diverse findings in our data highlight the need for precision medicine and individualized recovery plans tailored to each patient's unique examination findings. Addressing these factors is critical for providing appropriate, individualized treatment recommendations during concussion recovery.

In expanding on our study's findings and recommendations, we have identified several key insights and practical implications. Our research highlights the variability in concussion examination findings between the sexes, across different ages, and over time, emphasizing the need for individualized diagnostic approaches. Furthermore, the study underscores the significance of incorporating a comprehensive physical examination in concussion evaluations. Based on these findings, we advocate for further research into age-specific and sex-specific concussion management strategies and the development of tailored rehabilitation protocols. These recommendations aim to enhance the precision and effectiveness of concussion care, contributing to a more nuanced understanding of this complex condition.

A limitation of this study is its dependence on data available within the electronic medical record, as is inherent in a retrospective chart review design. Our use of a standardized neurologic examination template partially mitigated this concern by ensuring consistent documentation for each examination component across visits and providers. At the same time, variation in clinical management styles may affect outcomes. Observed abnormalities may be directly attributable to concussions or represented preexisting baseline findings or related to variation in clinical examiners. Although the study's large size, methodology, and trend toward improvement over time make it unlikely that previously abnormal examination elements significantly influenced the findings, this uncertainty remains. In addition, our vestibulo-ocular and balance testing included modified VOMS and BESS testing, which may limit comparability with studies using formal VOMS or BESS testing, as well as updated or modified versions previously referenced.

The timing and frequency of visits were not standardized, meaning that participants were seen at different postinjury time points and may have experienced varying intervals between visits. In some cases, this resulted in censored data due to multiple visits during the same postinjury week. The imbalance across time points and the natural occurrence of recovery and loss-to-follow-up may artificially inflate symptom presence at later time points, although this realistically reflects the normal variation in outpatient management.

Moreover, the examination template was occasionally incomplete during encounters. Some examination components

TAKE-HOME POINTS

- Vestibulo-ocular testing, balance testing, and the cervical spine examination are frequently abnormal following concussion in athletes and represent key elements of the concussion physical examination.
- Although differences may be present in postconcussion physical examination findings between the sexes and across age groups, the frequency of examination abnormalities can generally be expected to decrease over time during the first month postinjury.
- The physical examination remains a vital component of concussion evaluation and management in athletes.

might not have been documented as the injury's acuity decreased, particularly during follow-up visits when normal findings were present in earlier visits. Despite all providers having expertise in concussion care and agreeing on examination standardization, individual providers may have differing documentation and examination tendencies. In the case of mental status changes, the frequency of missing data was sufficiently high to preclude additional analyses, although a high frequency of initial visit abnormal findings was observed. Our data set did not include orthostatic intolerance or postconcussion symptom scale (PCSS) results, but these elements could be incorporated in future analyses.

Other potential limitations affecting the study's generalizability include the predominance of adolescent and athlete participants and the tertiary referral center setting. In addition, recovery status is not included in this data and is an area of future investigation because it corresponds to examination findings and symptoms.

Although the search for reliable objective markers for concussion, such as imaging or blood biomarkers, continues, the physical and neurologic examination remains a vital and cost-effective component of concussion evaluation and management that can be performed at any time postinjury. Our findings emphasize the importance of focusing on specific elements of the standard concussion examination. The most critical examination components identified in our study include VOR, VMS, convergence testing, tandem stance, single-leg stance, tandem gait, and a neck examination.

Further longitudinal analysis is underway to correlate these findings with reported symptoms and overall outcomes. Our study also underscores the benefits of leveraging large amounts of data through electronic medical records and supports the establishment of multi-institutional collaborations to generate larger patient populations assessed using standardized data elements.

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Appendix *(continued)*

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