Vestibular and Oculomotor Assessments May Increase Accuracy of Subacute Concussion Assessment

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- near point convergence
- optokinetic stimulation
- gaze stabilization test
- concussion
- mild TBI
- BESS
- SOT

Abstract

In this study, we collected and analyzed preliminary data for the internal consistency of a new condensed model to assess vestibular and oculomotor impairments following a concussion. We also examined this model's ability to discriminate concussed athletes from healthy controls. Each participant was tested in a concussion assessment protocol that consisted of the Neurocom's Sensory Organization Test (SOT), Balance Error Scoring System exam, and a series of 8 vestibular and oculomotor assessments. Of these 10 assessments, only the SOT, near point convergence, and the signs and symptoms (S/S) scores collected following optokinetic stimulation, the horizontal eye saccades test, and the gaze stabilization test were significantly correlated with health status, and were used in further analyses. Multivariate logistic regression for binary outcomes was employed and these beta weights were used to calculate the area under the receiver operating characteristic curve (area under the curve). The best model supported by our findings suggest that an exam consisting of the 4 SOT sensory ratios, near point convergence, and the optokinetic stimulation signs and symptoms score are sensitive in discriminating concussed athletes from healthy controls (accuracy = 98.6 %, AUC = 0.983). However, an even more parsimonious model consisting of only the optokinetic stimulation and gaze stabilization test S/S scores and near point convergence was found to be a sensitive model for discriminating concussed athletes from healthy controls (accuracy = 94.4 %, AUC = 0.951) without the need for expensive equipment. Although more investigation is needed, these findings will be helpful to health professionals potentially providing them with a sensitive and specific battery of simple vestibular and oculomotor assessments for concussion management.

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Introduction

Concussion experts have suggested that clinicians use a multi-faceted approach to assess concussion [9, 14, 18, 30]. Authors of recent concussion position statements recommend including signs and symptoms (S/S), cognitive, and balance assessments into concussion management strategies [4, 18, 30]. Dizziness is a symptom endorsed by over 50 % of concussed athletes [27] and is associated with a greater than 6-fold increased risk for prolonged recovery [27]. Common testimonial of dizziness suggests that concussion causes dysfunction with vestibular and/or visual pathways. This has led to researchers examining the diagnostic value of vestibular and oculomotor assessments in concussion management [1, 9, 32].

Vestibular and oculomotor testing for concussion screening is relatively new, but has shown promise. Mucha et al. (2014) assessed oculomotor function using near point convergence (NPC), smooth pursuits, and rapid volitional saccades, while, the vestibular ocular reflex (VOR) function was assessed using horizontal and vertical gaze stabilization (rapid head and eye movement) [32]. This study reported cutoff scores, which showed that an NPC distance over 5 cm increased the likelihood of correctly identifying concussed individuals by 38 % and endorsing more than 2 symptoms on any of their vestibular/oculomotor assessments increased it by 50 % [32]. The vestibular and oculomotor systems are important in sensing angular and linear acceleration of the head and eyes, which enables a moving individual to maintain gaze on a stable target or a stationary individual to focus on a moving target.

Combining these assessments with others that examine whole-body behavioral output of vestibular, visual, and somatosensory integration (e.g., postural balance) may increase sensitivity and greatly improve concussion management.
Postural assessment is recommended in the National Athletic Trainer's Association concussion position statement [4, 18, 30]. Common tests include the Balance Error Scoring System (BESS [17]) or the Sensory Organization Test (SOT [33]). There is limited data on the reliability and validity of the SOT to determine postural instability following a concussion [33]; however, both the SOT and BESS have been reported to be sensitive to postural deficits during the first 3–5 days post-injury [5, 16, 17, 28, 33, 36, 37]. The BESS has been shown to return to normal or baseline scores within 5 days post-injury [16, 28]. However, a number of studies, suggest there are postural and motor symptoms that last well beyond the initial 7–10 day recovery period [2, 23, 43]. The ability of these postural assessments to identify deficits in later stages of recovery is limited, but it may be augmented by the inclusion of vestibular and oculomotor testing.
Currently, there is no agreed upon standard by which to assess individuals following a concussion [18, 50]. There are many balance, vestibular, and oculomotor tests that an athletic trainer could use for the assessment of a concussion, but this can be time-consuming for both the clinician and the athlete. The purpose of this study was to investigate the usefulness of 10 assessments for detecting symptoms following a concussion, which were specifically selected because they depend on vestibular, oculomotor, or sensorimotor processing.

Materials and Methods

Study design

A cross-sectional research design with a known-groups approach (i.e., concussion vs. healthy) was implemented to determine the best balance, vestibular, and oculomotor assessment model to assess the presence of concussion symptoms.

Subjects

72 active college student athletes participating in either a Division I NCAA sport or college intramural team were recruited to participate in this study (42 males; 30 females) aged 21.5 ± 3.4 years. There were 60 healthy participants (21.7 ± 3.6 years; 68.3 ± 3.7 in; 71.4 ± 12.2 kg) and 12 concussed (20.5 ± 1.8 years; 69.4 ± 4.2 in; 72.8 ± 8.4 kg). All participants had been active in competitive sports (17 different sports; **Table 1**) for at least one year and the concussed athletes had experienced symptoms for 4–90 days, with 6 participants being acutely concussed (2–10 days). All participants self-reported having no recent orthopedic impairments that would negatively affect balance. The healthy athletes self-reported having no ear infection or vestibular, oculomotor or balance issues for the past month. Concussion in this study was defined as sustaining a pathomechanical event that induced one or more concussion S/S [18, 30]. All participants in the concussion group were evaluated by a certified athletic trainer (JM, RT) and during the initial evaluation verbally reported that they experienced a recent pathomechanical event followed by one or more concussion S/S.
All participants signed the Temple University Institutional review board approved consent form in accordance with the guidelines of the Helsinki Accords. All subjects received monetary compensation for participation in the study [19]. Participants completed the concussion questionnaire, which included background information such as history of concussion and general medical history including headache, vestibular and visual issues. If recently concussed, then a description of injury, location of impact, and immediate and current S/S were also collected.

Table 1 Sport participation data by group.

Sport n (%)	Concussed *n* = 12	Control *n* = 60
Australian Football	0 (0)	1 (1.7)
Baseball	0 (0)	1 (1.7)
Basketball	1 (8.3)	11 (18.3)
Fencing	1 (8.3)	0 (0)
Field Hockey	1 (8.3)	1 (1.7)
Figure Skating	0 (0)	1 (1.7)
Flag Football	3 (25)	3 (5)
Football	0 (0)	1 (1.7)
Gymnastics	1 (8.3)	2 (3.3)
Ice Hockey	1 (8.3)	3 (5)
Lacrosse	0 (0)	3 (5)
Mixed Martial Arts	0 (0)	1 (1.7)
Rugby	1 (8.3)	3 (5)
Soccer	1 (8.3)	21 (35)
Ultimate Frisbee	0 (0)	2 (3.3)
Volleyball	0 (0)	6 (10)
Not Reported	2 (17)	0 (0)

Instrumentation

Sensory organization test (SOT)

All SOT testing was performed using the Neurocom (Natus Medical Inc., Pleasanton, CA). The SOT was designed to objectively identify abnormalities in the participant's ability to use the 3 sensory systems that contribute to postural control: somatosensory (proprioception), visual and vestibular. The SOT measures the vertical ground reaction and shear forces produced from the body's center of gravity moving around a fixed base of support. The test systematically disrupts the sensory selection process by altering available somatosensory and/or visual information while measuring the ability to minimize postural sway in the anterior-posterior direction [34].
The SOT protocol requires participants to stand upright as stably as possible for 20 s under 6 different testing conditions each repeated 3 times: (1) eyes open with stable support surface and visual surround, (2) eyes closed with stable support surface, (3) eyes open with sway-referenced visual input with stable support surface, (4) eyes open with unstable, sway-referenced support surface, (5) eyes closed with unstable, sway-referenced support surface, and (6) eyes open with both a sway-referenced support surface and a sway-referenced visual surround.
The participants were tested barefoot with feet placed in a standardized position, as suggested by the manufacturer's testing guidelines (i.e., the medial malleolus was lined up with the anterior-posterior rotational axes of the support surface and visual surround, and the lateral calcaneus was positioned in accordance with the guidelines prescribed by the participants' height). The standard testing conditions were run in order (i.e., 1, 2, …, 6) with each condition repeated 3 times before proceeding to the next one. During all trials participants were asked to rest their arms by their sides and maintain a stable, upright position being as still as possible for the duration of the 20 s trial. The

participant wore a safety harness, which was secured to the frame of the Neurocom device.

The Neurocom device calculates the SOT composite score as a weighted average of all 6 conditions to determine the overall level of performance as a percentage from 0–100, with better performance represented as a higher score and a fall scored as 0. The Neurocom software also calculates the sensory ratios, which estimate the participants' ability to utilize each type of sensory input to maintain balance. The somatosensory ratio is the quotient of condition 2 over condition 1. The visual ratio is the quotient of condition 4 over condition 1. The vestibular ratio is the quotient of condition 5 over condition 1. The visual preference ratio is the sum of conditions 3 and 6 divided by the sum of conditions 2 and 5. This ratio represents the degree to which a participant relies on visual input to maintain balance even if the visual input is unreliable.

Balance error scoring system (BESS)

The BESS test provides an objective measure of postural stability by testing balance in a series of 6 stances. The 6 conditions, always tested in the same order, are 3 stances (double-leg, single-leg, and tandem) on a firm surface followed by the same 3 stances in the same order executed on the foam pad (Alcan Airex, Sins, Switzerland). All stances are performed barefoot, each lasting 20 s with the participants' eyes closed and hands on hips. A trained rater counted the number of performance errors. Errors included lifting the hands off of the iliac crest; opening the eyes during the test; stepping, stumbling, or falling; moving the hip into more than 30° of flexion or abduction; lifting the forefoot or heel; or remaining out of the testing position for more than 5 s. The total numbers of errors were summed to determine the participant's score, with a higher score demonstrating poorer performance. The maximum number of errors for any single condition is capped at 10, or in total 60 maximum possible errors. An escalation from baseline in the number of errors greater than 3 within the 6 conditions indicated a possible concussion [16, 17]. Intra-class correlation coefficients (ICCs) were used to establish reliability metrics. Three testers in a 3-day pilot study of healthy individuals (n = 8) established intra-rater (ICC = 0.93,0.98, 0.93) and inter-rater reliability (ICC = 0.74) for the total BESS. Test-retest reliability ICC was 0.96.

Near point convergence (NPC)

NPC measures the ability to view a target without double vision as it approaches one's nose. NPC was measured using the standardized push-up method [7, 47]. Briefly, the participant was seated (wearing corrected lenses, if necessary), and the accommodation convergence ruler (Bernell Incorp. Mishawaka, IN) was placed underneath the nose. The participant fixated on a card with a line of 4 letters and was instructed to focus on the letter "F" on the top line (font 14 point) of the card as the experimenter moved the card towards the participant's face, only stopping once the participant reported that the letter appeared double. The measurement started from 25 cm away with the examiner moving the card 1.5–2.0 cm per second. The test concluded when the participant stated that the target appeared double, and that measurement was recorded from the ruler in centimeters. The previously reported cut-points for the NPC range from 5 cm to 17.5 cm; therefore, due to this variable range of cut points, the NPC cut point for the athletic population has yet to be determined [39]. Three testers in a 3-day pilot study of healthy individuals (n = 8) established intra-rater (ICC = 0.92, 0.89, 0.91) and inter-rater reliability (ICC = 0.96) for the near point convergence measures. Test-retest reliability ICC was 0.82.

Horizontal eye saccades (HES)

HES measures the participant's ability to quickly move the eyes back and forth between targets. To measure HES the participant was seated in front of a white sheet with 2 stationary targets (i. e., 2 x's in 48 bold, Arial font 25 cm apart at eye level and arm's length distance away). The participant was instructed to quickly look back and forth from one target to the next using only eye movements (without moving the head) synchronized with the sound of a metronome (Metronome, ONYX iPad App) beeping at 120 beats for 1 min (1 Hz = full cycle back and forth). The examiner watched the eyes for quickness, smoothness, and accurate fixation of the target. The dependent variables were three 7-point verbal rating scales (VRS) used to subjectively report dizziness, headache, and nausea ("No symptoms" = 0, the highest level of symptoms = 6). The within-subject change from baseline level was used for outcome measure analysis. Before and after the test, the participant was asked the level of each symptom separately (i. e., headache, dizziness, nausea) using the VRS. A previous report determined that the cutoff score for a positive test occurs when the patient reports an increase of 2 or more on the VRS [32]. Normal or abnormal (disconjugate eye movement, or over/undershooting the target) saccadic eye movement was visually observed by the examiner and recorded as either positive or negative (i. e., present or absent). There were no eye movements rated abnormal during pilot testing of healthy individuals; therefore, this ceiling effect resulted in all HES ICCs being equal to 1.0 during pilot testing.

Slow and fast smooth pursuit

Smooth pursuits were used to test the participant's ability to follow a slow- or fast-moving target with their eyes. The seated participant was instructed to focus on the tip of a pen held at eye level by the experimenter. The examiner stood approximately 1 m away and moved the pen horizontally 0.5 m to the left and right (~30° in each direction) to the beat of a metronome for 30 s. The participant was instructed to follow the target with their eyes only. The slow condition required participants to make a 30° smooth pursuit movement at 60 beats per minute for 30 s, which was followed by the fast pace condition at 100 beats per min for 30 s. The participant was asked their baseline level of dizziness, headache, and nausea using the VRS before testing, then again after both slow and fast smooth pursuit tests. A previous report determined that the cutoff score for a positive test occurs when the patient reports an increase of 2 or more on the VRS [32]. Normal or abnormal (disconjugate eye movement, or over/undershooting the target) saccadic eye movement was visually observed by the examiner and recorded as either positive or negative (i. e., present or absent). There were no eye movements rated abnormal during pilot testing of healthy individuals; therefore, this ceiling effect resulted in all smooth pursuit ICCs being equal to 1.0 during pilot testing.

Optokinetic stimulation (OKS)

OKS measures whether a normal reflexive optokinetic nystagmus (OKN) response is elicited when viewing a moving striped visual stimulus with whole or part of the visual field [8, 48]. This test was performed using an OKN drum iPad app, which displays a high contrast grating passing horizontally across the visual field (OKN Stripes, downloadable app; Settings: red and white drum, 0.5 cm line width, 8.6 cm/s), which when held 15–20 cm from the eyes covers approximately a 60° diagonal field of view (FOV). Although both smooth pursuit and OKN will be activated by the stimulus used in this part of the study [22] our goal was to expose the participants to a fast moving optic flow field to elicit nystagmus, in general, and potentially induce S/S. To distinguish it from smooth pursuit test mentioned above, we refer to it nominally as OKS. The participant reported a baseline level of dizziness, headache, and nausea using the VRS. The seated participant was asked to maintain focus on the center of the iPad while the stripes were moving horizontally to the right for 30 s. This was immediately followed by a 30-s period of viewing the stripes moving horizontally to the left. After the full minute of OKS stimulation, the participant was asked to report levels of dizziness, headache, and nausea on the VRS before and after the test. Normal or abnormal (absence of normal fast phase nystagmus) optokinetic reflex was also assessed by observation. There were no eye movements rated abnormal during pilot testing of healthy individuals; therefore, this ceiling effect resulted in all OKS ICCs being equal to 1.0 during pilot testing.

Horizontal gaze stabilization test (GST)

The GST assesses the ability to stabilize vision as the head moves, which evaluates vestibular ocular reflex (VOR) function. The participant stood fixating a single visual target (i. e., an "X" on a piece of paper with Arial, bold, 48 font) at eye level, arm's length away. The participant was asked their level of dizziness, headache, and nausea using the VRS. They were instructed to turn their head horizontally approximately 30° in each direction to the beat of the metronome (240 beat per min) for 1 min. The participant was instructed to fixate their eyes on the target, and report if the target became blurry, or started to bounce around (i. e., oscillopsia). The participant was asked their baseline level of dizziness, headache, and nausea using the VRS before testing, then again after testing. A previous report determined that the cutoff score for a positive test occurs when the patient reports an increase of 2 or more on the VRS [32]. The quality of the VOR was also recorded as abnormal if the participant reported that the visual target was bouncing/blurry, or the experimenter noted excessive saccades in directions misaligned with the stimulus. There were no abnormal reflexes observed during pilot testing of healthy individuals; therefore, this ceiling effect resulted in all GST ICCs being equal to 1.0 during pilot testing.

Head thrust (VOR test)

The head thrust test evaluates the ability to stabilize vision as the head moves (i. e., VOR). The participant was seated and asked to fixate on the examiner's nose and to relax his or her head and neck as the examiner moved the participant's head quickly to the left or right. The examiner's hands were placed on the subject's occiput with thumbs on the temples rather than the temporomandibular joint. The examiner tilted the participant's head slightly down in order to provoke the horizontal semicircular canals (down about 30°). The head was first gently rotated to left and right ±45° to assess the participant's range of motion of neck and extra-ocular muscles. Then the head thrust was performed in the horizontal plane randomly to the right and left 3–4 times ±30°. The participant was asked their baseline level of dizziness, headache, and nausea using the VRS before and then again after VOR testing. Normal or abnormal VOR was also recorded. Abnormal VOR was recorded if the participant was unable to keep focused on the examiner's nose or the experimenter noted excessive saccades in directions misaligned with the stimulus. There were no abnormal reflexes detected during pilot testing of healthy individuals; therefore, this ceiling effect resulted in all VOR ICCs being equal to 1.0 during pilot testing.

Dynamic visual acuity (DVA)

The DVA test compares visual acuity when the head is static compared to when the head is moving to assess VOR function. A tumbling E visual chart was used to document visual acuity when the head was not moving. The participant stood 2.0 m from the chart per standard protocol and was asked to read the orientation of the E (i. e., left, right, up, or down) starting from the top until they could no longer read the chart clearly (i. e., no errors when reading the entire line). This was repeated while the participant actively moved his or her head 30° to left and right in the horizontal plane to the beat of the metronome (180 beats per min). The dependent variable is the line difference between the lowest line read with the head static and the head dynamic. Previous authors reported the cut-off points to be a loss of 3 or more lines during dynamic testing conditions is suggestive of potential vestibular dysfunction [20]. Three testers in a 3-day pilot study (n = 8) established intra-rater (0.71, 0.84, 0.70) and inter-rater reliability (0.86) ICCs for the DVA test. Test-retest reliability ICC was 0.53. Due to these lower ICC values we re-examined the protocol and determined that the errors occurred in maintaining speed of the athlete's head as well as in what constitutes an incorrect line. After this re-examination this improved the raters' ability to use this test.

King-Devick (KD) tool

The KD tool is a test that requires control of oculomotor, attentional, and language processes. Suboptimal performance on this test has been shown to be a sensitive indicator for detecting injury due to concussion [12, 13]. The KD utilizes 3 test cards with a series of a single-digit numbers that are read aloud from left to right as quickly as possible without making any errors. [12, 13]. The test includes one demonstration card and 3 tests cards. The 3 tests cards were repeated a second time in the same order. The cumulative time taken for reading the 3 cards twice through was recorded for the KD score. The participants were instructed beforehand to correct any errors as quickly as possible. Errors were also summed together to arrive at a KD error score. The KD test has been found to have moderate test-retest reliability (ICC = 0.70–0.78) [12, 13]. In our pilot tests (n = 8) with 3 testers across 3 days, ICCs for intra-rater (0.97,0.97, 0.96), inter-rater reliability (0.99), and test-retest (0.96) reliability were established.

Procedures

All participants performed the BESS and SOT protocols, in random counterbalanced order, and then proceeded to the vestibular and oculomotor assessment portion. Pilot testing of healthy individuals (n = 8) prior to this experiment found no statistically significant order effects ($p = 0.37$); however, some participants reported feeling less stable in the balance tests if the vestibular/oculomotor tests were performed first. Therefore, all participants in this experiment were tested on balance assessments first. The order of the vestibular and oculomotor assessments were NPC, HES, smooth pursuit tests, OKS, GST, head thrusts, DVAT, and KD test. All protocols were administered individually in a laboratory setting. The entire testing protocol took approximately 45 min to complete.

Statistical methods

Group differences in demographics, SOT composite and BESS total scores were analyzed using independent sample 2-tailed t-tests. The SOT conditions and BESS test stances were each analyzed using a 2 (group)×6 (condition) repeated measures ANOVA. Violations of sphericity were checked by Mauchly's test, and in cases where a large violation of sphericity occurred a MANOVA was used [10]. Between-group differences in reporting a history of previous concussion were calculated with a chi-square test. Pearson's correlations between balance, vestibular, and oculomotor assessments were examined within healthy participants to determine concurrent validity. A logistic regression for binary outcomes ("Enter Method" and "Forward Conditional") was performed to examine predictive validity of the balance, vestibular, and oculomotor assessments. From the logistic regression classification table, "accuracy" was calculated as the sum of the true positives and true negatives divided by the total sample size. Positive predictive value (PPV) was calculated using the sum of the true positives divided by the total number of concussed individuals in the sample (n=12). Logistic regression provided weighted coefficients (beta weights) for defining a regression model. The regression model was tested using receiver operating characteristic (ROC) curves. Then, area under the curve (AUC) for these ROC curves was calculated and a cutoff score was determined by choosing the value that maximized sensitivity and specificity. All statistical analyses were conducted using SPSS software (version 22.0; IBM Corporation, Armonk, NY) and significance was set at alpha equal to 0.05. Bonferroni correction was used to adjust *p*-values for multiple comparisons.

Results

▼

Demographic data

Means and standard deviations between groups are reported in ▶ **Table 2**. There were no differences in sex, height, weight, or years of experience within their main sport between groups. The concussed and healthy groups differed in age by 1.5 years on average, which was statistically different ($p=0.039$), but not clinically meaningful. The concussed participants performed the initial testing session on average 28 days post-injury (range 2–96 days). The concussed participants had significantly more previous concussions (2.6 concussions) compared to the controls (0.4 concussions; $p=0.024$), where the concussed cohort in this study was 20 times more likely to report a history of concussion ($p \leq 0.001$). Raw data from the 12 concussed participants are reported in ▶ **Table 3**. Following the SOT and BESS tests, 2 of the participants with a concussion reported headaches, one reported just feeling dizzy, one reported both headache and dizziness, and one reported feeling headache, dizzy, and nauseated. All reported a 1–2 out of 6 (very mild S/S). 8 of the participants with a concussion reported no S/S at the start of the vestibular and oculomotor assessment.

Table 2 Descriptive characteristics of participants enrolled in study.

Variables	Concussed Participant n=12 M±SD	Healthy Participants n=60 M±SD	*p*
Age	21.7±3.6	20.3±1.8	0.039 *
Height	68.3±3.7	69.4±4.2	0.399
Weight	157.5±26.8	160.6±18.6	0.722
Years Experience	8.0±5.7	10.5±5.4	0.189
No. of Previous Concussions	2.6±2.9	0.4±0.8	0.024 *
Sex n (%)			0.629
Male	7 (58.3%)	35 (58.3%)	
Female	5 (41.7%)	25 (41.7%)	

M (mean), SD (standard deviation), n (number). * significance at p<0.05

Balance assessments

The BESS test showed that the concussed group performed at or above the healthy group but there were no statistically significant differences between groups in the total score or in any individual stance conditions after correcting for multiple comparisons ($F_{5,66}=1.82$, p=0.12; ▶ **Table 4**). Logistic regression revealed that the BESS did not improve accuracy, moreover the sensitivity of the test was 8.3%, meaning only one in 12 of the individuals with concussion was correctly identified.

The SOT showed that the concussed group scored significantly lower on the SOT in the individual conditions ($F_{5,65}=3.26$, p=0.011), which were found to be due to differences in condition 3 (p=0.044) and condition 4 (p=0.033). The SOT visual ratio revealed that these difficulties were visually related (p=0.032). Logistic regression revealed that the SOT had a sensitivity of 33.3% and a PPV of 66.7%.

Vestibular and oculomotor assessments

The mean NPC distance was trending toward statistical significance with the concussed group showing larger NPC measures compared to the control group ($p=0.069$). The mean NPC distances in the concussed group (6.0±4.1 cm) and the healthy control group (3.6±2.2 cm; ▶ **Table 4**) correlated significantly with health status (r=0.337, p=0.004; ▶ **Table 5**). The DVAT test showed no significant differences between groups ($p=0.592$; ▶ **Table 4**) and no correlation with health status (r=0.06, p=0.592; ▶ **Table 5**). The KD test completion time did not show a significant difference between the concussed and healthy groups ($p=0.40$; ▶ **Table 5**) and did not correlate with health status (r=0.18, p=0.129; ▶ **Table 5**). The mean cumulative time for the concussed group was 90.0±34.9 s, and the mean time for the healthy control group was 81.1±13.1 s (▶ **Table 4**).

Symptom provocation after vestibular and oculomotor assessments

There was a significant difference in OKS ($p=0.033$) and GST ($p=0.022$) S/S provocation reported between groups. The mean S/S reported for OKS and GST within the concussed group was 2 on average, whereas the healthy control group reported no S/S 94.6% of the time (▶ **Table 4**). HES also had a mean S/S of 2 reported with a between-group difference trending towards significance ($p=0.061$). Each of these assessments correlated significantly with health status ($p<0.001$, ▶ **Table 5**).

Predicting concussed and healthy controls

A logistic regression model was found by testing the assessments, which were significantly correlated with concussion health status (▶ **Table 5**). Those significantly correlated with health status were SOT condition 2 ($p=0.036$), condition 3 ($p=0.001$), condition 4 ($p=0.033$), SOT visual ratio ($p=0.032$) and visual preference ratio scores ($p=0.028$), NPC ($p=0.004$), OKS S/S score ($p<0.001$), HES S/S score ($p<0.001$), GST S/S score ($p<0.001$). Using these assessments, we performed multivariate

Table 3 Individual assessment scores, concussion group.

Subject	Days since injury	BESS	SOT	NPC	HES S/S				OKN S/S				GST S/S				DVA	KD
					Head-ache	Dizz	Nausea	Total	Head-ache	Dizz	Nausea	Total	Head-ache	Dizz	Nausea	Total		
1	2	17	83	6	0	0	0	0	0	0	0	0	0	0	0	0	1	33.3
2	4	14	78	3	1	0	0	1	1	0	0	1	1	0	0	1	1	42.5
3	8	2	87	1.5	1	1	0	2	1	0	0	2	2	1	0	3	1	43.2
4	8	3	84	9	0	0	0	0	0	0	0	0	0	0	0	0	1	42.4
5	9	18	81	4	0	0	0	0	0	0	0	0	0	0	0	0	1	43.9
6	10	17	86	3	0	0	0	0	0	0	0	1	0	0	0	0	2	37.1
7	11	10	82	12	0	0	0	0	0	0	0	0	0	0	0	0	1	34.5
8	16	8	76	12	3	3	3	9	4	4	2	10	4	4	2	10	5	47.1
9	37	9	79	9	3	0	0	3	3	0	0	3	3	0	0	3	1	40
10	58	16	63	0	0	2	0	2	0	2	0	2	2	3	0	5	1	48.8
11	77	9	67	3.5	0	0	0	0	0	0	1	1	0	0	1	1	4	30.1
12	96	13	60	9	2	3.5	2	7.5	2	1	1	4	0	5	0	5	2	97.5

BESS (Balance Error Scoring System, total score), DVA (dynamic visual acuity, line difference), GST (gaze stabilization test), HES (horizontal eye saccades), KD (King-Devick, average of 2 trials), NPC (near point convergence), OKN (optokinetic reflex), SOT (sensory organization test, composite score), S/S (signs and symptoms)

Table 4 Means and standard deviations of concussion assessment scores.

Variables	Concussed Participant n = 12 M ± SD	Healthy Participants n = 60 M ± SD	*p*
BESS			
Total	11.8 ± 4.8	13.4 ± 4.5	0.230
Double Leg Firm	0.0 ± 0.0	0.0 ± 0.0	n/a
Single Leg Firm	1.7 ± 1.4	2.4 ± 1.9	0.172
Tandem Leg Firm	0.8 ± 1.0	1.1 ± 1.4	0.503
Double Leg Foam	0.1 ± 0.3	0.0 ± 0.1	0.448
Single Leg Foam	4.9 ± 1.6	6.2 ± 1.8	0.031
Tandem Leg Foam	4.2 ± 2.6	3.2 ± 1.5	0.570
SOT			
Composite	76.1 ± 8.5	79.6 ± 5.5	0.187
Condition 1	95.0 ± 1.3	95.3 ± 1.6	0.498
Condition 2	90.6 ± 5.5	92.8 ± 2.5	0.206
Condition 3	87.8 ± 5.9	91.7 ± 3.0	0.044 *
Condition 4	80.0 ± 10.1	86.0 ± 8.4	0.033 *
Condition 5	66.0 ± 10.2	68.0 ± 8.4	0.457
Condition 6	62.9 ± 15.6	67.0 ± 10.1	0.257
SOM Ratio	0.95 ± 0.5	0.97 ± 0.2	0.209
VIS Ratio	0.84 ± 0.1	0.90 ± 0.1	0.032 *
VEST Ratio	0.69 ± 0.1	0.71 ± 0.8	0.485
PREF Ratio	0.94 ± 0.7	0.97 ± 0.3	0.207
Vestibular and Oculomotor Assessments			
NPC	6.0 ± 4.1	3.6 ± 2.2	0.069
HES S/S score	2.0 ± 3.11	0.1 ± 0.3	0.061
Smooth Pursuit S/S	0.0 ± 0.0	0.0 ± 0.0	n/a
OKS S/S score	2.0 ± 2.8	0.0 ± 0.1	0.033 *
GST S/S score	1.9 ± 2.2	0.3 ± 0.7	0.022 *
DVA line difference	1.8 ± 1.4	1.5 ± 1.5	0.592
KD Score	90.0 ± 34.9	81.1 ± 13.1	0.400

M (mean), SD (standard deviation), n (number). BESS (Balance Error Scoring System), SOT (sensory organization test), SOM (somatosensory), VIS (visual), VEST (vestibular), PREF (visual preference), NPC (near point convergence), HES (horizontal eye saccades), OKS (optokinetic stimulation), GST (gaze stabilization test), DVA (dynamic visual acuity), KD (King-Devick), S/S (signs and symptoms). * BESS exam significance at $p < 0.025$ (0.05/2), * SOT exam significance at $p < 0.05$, * Vestibular and Ocular Motor exam significance at $p < 0.05$

Table 5 Correlation of concussion assessments with health status.

Variables	*r*	*p*
SOT		
Composite	−0.22	0.067
Condition 1	−0.08	0.498
Condition 2	−0.25	0.036 *
Condition 3	−0.38	0.001 *
Condition 4	−0.25	0.033 *
Condition 5	−0.09	0.457
Condition 6	−0.14	0.257
SOM Ratio	−0.26	0.028 *
VIS Ratio	−0.26	0.032 *
VEST Ratio	−0.08	0.485
PREF Ratio	−0.15	0.206
BESS		
Total BESS Test	−0.13	0.264
Double Leg Firm	n/a	n/a
Single Leg Firm	−0.16	0.172
Tandem Leg Firm	−0.08	0.503
Double Leg Foam	0.15	0.205
Single Leg Foam	−0.26	0.031 *
Tandem Leg Foam	0.10	0.409
Vestibular and Oculomotor Assessments		
NPC	0.34	0.004 *
HES S/S Score	0.49	< 0.001 *
OKS S/S Score	0.55	< 0.001 *
GST S/S Score	0.51	< 0.001 *
DVA Line Difference	0.06	0.592
KD Score	0.18	0.129

M (mean), SD (standard deviation), n (number). BESS (balance error scoring system), SOT (sensory organization test), SOM (somatosensory), VIS (visual), VEST (vestibular), PREF (visual preference), NPC (near point convergence), HES (horizontal eye saccades), OKS (optokinetic stimulation), GST (gaze stabilization test), DVA (dynamic visual acuity), KD (King-Devick), S/S (signs and symptoms). * significance at $p < 0.05$

logistic regression for binary outcomes using the "Enter" method (▶ Table 6,7), which provided the beta weights used to perform an ROC curve analysis. The regression equation with the greatest discriminant accuracy was

$$y_i = \beta_0 + \beta_{NPC} * (NPC)_i + \beta_{OKS} * (OKS)_i + \beta_{Som} * (Som)_i + \beta_{Vis} * (Vis)_i + \beta_{Vest} * (Vest)_i + \beta_{Pref} * (Pref)_i$$

This analysis identified the best subset of independent predictors of concussion as the 4 SOT sensory ratio scores (*SS* – somatosensory ratio, *Vis* – visual ratio, *Vest* – vestibular ratio, *Pref* – visual preference ratio), NPC, and OKS S/S score (accuracy = 98.6 %, AUC = 0.983, $p \le 0.001$). Although a similar model using the individual SOT conditions 2, 3, and 4 together with vestibular and oculomotor assessments was also highly accurate, these tended to result in over-fitting when applied all together. SOT visual preference ratio score, GST and HES could also be left out of the best model with little or no loss to accuracy. ROC curve analyses of each SOT sensory ratio individually revealed that only the visual ratio was a significant discriminator (AUC = 0.71, $p = 0.025$) with a sensitivity of 83 % and specificity of 56 % (▶ Table 8). A second model without any SOT variables included using only OKS, GST, and NPC was still able to discriminate between groups accurately (accuracy = 94.4 %, AUC = 0.951, $p \le 0.001$). Individual evaluation of the vestibular and oculomotor assessments showed that the GST S/S score alone (accuracy = 87.5 %, AUC = 0.74, $p = 0.008$) and OKS S/S alone (accuracy = 93.0 %, AUC = 0.83, $p \le 0.001$) were significant, but the NPC distance when used alone was not ($p = 0.125$). However, when NPC was combined with the other 3 assessments it significantly improved discrimination. In fact, when performing a forward, conditional logistic regression on all variables, the top 2 models were OKS S/S alone and OKS S/S plus NPC (accuracy = 93.0 %) with the latter having a better ROC outcome (AUC = 0.94, $p \le 0.001$).

Table 6 Concussion assessment model – binary logistic regression results.

Variables	ß	SE	Wald X^2	*p*
SOT ratios/OKS/NPC Model				
SOM Ratio	40.8	48.0	0.7	0.395
VIS Ratio	−25.0	11.2	5.0	0.026 *
VEST Ratio	47.4	22.7	4.4	0.037 *
PREF Ratio	12.7	18.6	0.5	0.495
NPC	1.1	0.5	5.4	0.020 *
OKS S/S Score	11.9	4.6	6.7	0.010 *
Constant	−76.9	56.4	1.9	0.173
Vestibular/Oculomotor Model				
NPC	0.6	0.3 6.2	0.013 *	
OKS S/S Score	120.4	10 339.0	0.0	0.991
GST S/S Score	−43.9	3 909.8	0.0	0.991
Constant	−5.9	1.7	12.0	0.001 *
OKS + NPC Model				
NPC	0.6	0.2	6.4	0.012 *
OKS S/S Score	5.0	1.4	12.1	0.001 *
Constant	−5.8	1.6	13.1	0.001 *

SE (standard error), CI (confidence interval), SOT (sensory organization test), SOM (somatosensory), VIS (visual), VEST (vestibular), PREF (visual preference), NPC (near point convergence), OKS (optokinetic stimulation), GST (gaze stabilization test), S/S (sign and symptom). * significance at p < 0.05

Discussion

The findings of this study demonstrate that using a condensed set of balance, and vestibular and oculomotor tests results in a model with the greatest accuracy for detecting concussion within the cohort tested. From the full battery of assessments that were tested in this study, the evidence supports using the SOT's ratio scores together with the NPC and the OKS S/S score to

Table 7 Logistic regression classification tables.

		SOT ratios/OKS/NPC Model Prediction		
		Health Status		Percentage Correct
Actual State		Healthy	Concussed	
Health Status	Healthy	59	0	100.0
	Concussed	1	11	91.7
Overall Percentage (Accuracy)				98.6
		OKS/NPC/GST Model Prediction		
		Health Status		Percentage Correct
Actual State		Healthy	Concussed	
Health Status	Healthy	58	1	98.3
	Concussed	3	9	75.0
Overall Percentage (Accuracy)				94.4
		OKS/NPC Model Prediction		
		Health Status		Percentage Correct
Actual State		Healthy	Concussed	
Health Status	Healthy	57	2	96.6
	Concussed	3	9	75.0
Overall Percentage (Accuracy)				93.0
		OKS Model Prediction		
		Health Status		Percentage Correct
Actual State		Healthy	Concussed	
Health Status	Healthy	58	1	98.3
	Concussed	4	8	66.7
Overall Percentage (Accuracy)				93.0

get the highest sensitivity and specificity for discriminating individuals with concussion (subacute to chronic) from healthy controls. Even without the SOT ratio our preliminary results show that a brief 3-min test using only the NPC, OKS S/S, and GST S/S were able to discriminate health status with a sensitivity of 91.7 % and specificity of 81.7 %. Not only did sensitivity/specificity decrease when the BESS, SOT, and all of the vestibular and oculomotor measurements were included in the assessment model, but the full exam took approximately 45 min, which can be cumbersome to an athletic trainer as well as overwhelming to an athlete who has just sustained an injury.

Previous researchers have reported the SOT and BESS tests as reliable measures of postural control during concussion assessment. While some studies have found the SOT to have moderate reliability (ICC = 0.64–0.66) [16, 51] another study looking individually at each condition found low to moderate reliability (ICC = 0.26–0.68, respectively) [11]. Very little research has been done to validate the SOT sensory ratios as a clinical marker for concussion [33]. The BESS test has been shown to have moderate to good reliability (ICC < 0.75) with moderate to high criterion-related validity depending on the stance assessed (r = 0.79 single foam, r = 0.64 tandem foam, r = 0.42 single leg firm, r = 0.31 double leg foam) [3]. Our findings indicate that the BESS test was unable to distinguish concussed from healthy athletes (r = − 0.13), which may be due, in part, to our concussion population, since less than half were in the acute stage and none were within 48 h of injury. This is consistent with previous research, where the BESS test has been found to be the most sensitive when the athletes are tested during the acute stage [16, 17].

Unlike the BESS, the SOT did show good sensitivity and specificity for detecting concussion in our sample. Previous research demonstrates that the Neurocom's SOT can be a good tool to assess deficiencies in the visual, vestibular, and somatosensory systems that may exist following a concussion even during the subacute stage [42]. There are subtle deficits to postural stability in participants with a history of concussion compared to those with no history of concussion, but others have found that these changes were not clinically significant [42]. Our results are in agreement with this, in that concussed athletes even in the subacute concussion stage score worse on the SOT; however, the differences in the SOT individual conditions and composite scores between groups were not large enough to establish a clinical cut point. Moreover, our results demonstrate that the SOT sensory ratios may be more clinically relevant than the composite and individual condition scores on the SOT.

Oculomotor assessments that have previously been found to be sensitive to concussion include static and dynamic vergence [44]. A recent study found that measuring NPC increased the probability of accurately diagnosing a concussion by at least 34 % [32]. In the current study, we also found that measuring NPC adds to the sensitivity and specificity when using a cut point of 4 cm. Our NPC mean is within the range of what other studies report [7, 32, 47]; however, more research is necessary for determining a cut-point for a concussed athlete. Another oculomotor assessment relied on assessing the optokinetic reflex and measuring S/S following OKS. There is only sparse literature showing the use of OKS on concussed athletes; however, a recent case study on one patient with PCS showed that gradual habituation to OKS together with balance training helped significantly reduce chronic symptoms [35]. Our study found OKS to be the most sensitive measure for discriminating concussed from healthy individuals. By itself, it was found to have a highly significant AUC (▸ **Table 8**), and when combined with other assessments, concussion detection was nearly perfect. This is encouraging evidence since this simple yet sensitive test can easily be added to a multifaceted battery of concussion assessments. One caveat that should be noted is that we used an optic flow field that covered only a 60 ° diagonal FOV, which may have elicited a combination of OKS and smooth pursuit [22]. Though dissociating these 2 oculomotor processes may be important for uncovering the underlying etiology of post-concussive symptoms, for the purposes of clinical assessment using less than a full FOV visual stimulus still proved to be a very sensitive tool. In future investigations, a full FOV stimulus may demonstrate even greater sensitivity and allow us to further describe the root of the oculomotor deficits associated with concussion.

Other oculomotor assessments that have been found to be reliable measures for assessing concussion in athletes were not found to be good discriminators in the current study. For example, the KD test has also been shown to correlate with post-concussion signs and symptoms score [45], but in a heterogeneous subacute cohort of individuals with concussion as was tested in this study, it was neither sensitive nor specific, and did not contribute significantly to our concussion detection model. Similarly, the DVAT, which has been shown to have moderate reliability using a computerized version of the test [24, 38, 49], did not discriminate between groups in the cohort we tested. A contributing factor to this lack of sensitivity may be due to great variation in how this test is applied across research studies, which reveal that no consensus in protocol has been reached (e.g., with or without computerized head tracking, velocity of head movements, angle of head movement, active vs. passive head movement) [24, 38, 49].

There has been a paucity of research examining VOR assessments in concussed athletes, however there is evidence that VOR abnormalities are prevalent following mild head trauma [2, 21]. The GST, which is a valid measure of VOR dysfunction [15], has been found to have moderate reliability to identify vestibular ocular deficits in individuals with concussion-like injury due to whiplash [46]. In a study that specifically focused on concussed athletes [32], GST together with oculomotor assessment of repetitive volitional eye saccades (i.e., HES) were tested, revealing that eye and head movements in the horizontal plane were the most sensitive [32]. Additionally, if the athlete reported at least 2 or more S/S on one of these tests, this increased the probability that the individual has suffered a concussion by at least 46 % [32]. Our results were similar in that our concussed athletes on average reported 2 or more S/S following the GST, OKS, and HES; however, only the GST and OKS were significant predictors

Table 8 ROC scores for SOT ratios, OKS S/S, and NPC individually.

Test	AUC	Cut-Point	p
SOM Ratio	0.611	0.97	0.228
VIS Ratio	0.707	0.91	0.025 *
VEST Ratio	0.538	0.09	0.095
PREF Ratio	0.578	0.71	0.339
NPC	0.641	3.95	0.125
OKS S/S score	0.828	0.50	0.000 *
GST S/S score	0.743	0.50	0.008 *

AUC (area under the curve), SOT (sensory organization test), SOM (somatosensory), VIS (visual), VEST (vestibular), PREF (visual preference), NPC (near point convergence), OKS (optokinetic stimulation), GST (gaze stabilization test), S/S (signs and symptoms). * significance at $p < 0.05$

of concussion. Our ROC curve analysis suggests that any increase in GST beyond baseline scores could be indicative of a concussion. However, the vestibular assessment was much stronger when combined with an oculomotor assessment (e.g., OKS or NPC).

Finally, several variables have been identified as risk factors for prolonged concussion recovery in other studies. For example, previous history and number of concussions, as well as specific S/S at the time of injury (e.g., headaches, dizziness) [6,25,26,37] predispose an athlete to prolonged recovery following concussive injuries. Out of all the risk factors, history of concussive injuries has the longest known association with increased concussion susceptibility [40]. One study found that football athletes with a history of concussions are more likely to take greater than 7 days to recover [29] and there is a 2.0–5.8 times greater risk of sustaining another concussion [37]. Despite this evidence, an association between concussion history and rate of recovery is still debatable. Lau et al. reported no difference in history of concussions and time of recovery [26], while others have identified significant differences between recovery rates of neurological function after a second concussion [41]. Another study found that only post-concussion S/S scores predicted recovery, whereas concussion history and loss of consciousness were not predictors for recovery duration [31]. Although our study was not designed at the outset to systematically investigate the role of concussion history, a cursory analysis that grouped all participants with a history of previous concussions ($n=17$) and compared them to those with no history of concussion ($n=55$) showed that SOT, NPC, OKS S/S, GST S/S were all sensitive to this group variable ($p<0.05$, Student's t-tests). Further investigation is required, however these results support the notion that concussion history may contribute to risk of future injury. Athletes may have lingering subacute symptoms affecting balance and sensorimotor control, which degrade performance and could expose a player to new injury after returning to play.

There were several limitations that should be noted. First, although our normative baseline for the healthy controls is a moderately large sample at $n=60$, our sample of concussed individuals includes only 12 participants. Despite the fact that the concussed sample size is small, we were still able to detect differences in many of the SOT and vestibular and oculomotor assessments. Another limitation of this study is that we do not have a homogenous concussed population. Only half of the subjects fell within the acute period (<2 weeks), while the rest were greater than 3 weeks post-injury and were possibly suffering from post-concussive syndrome. Interestingly though, despite the chronic state of many of our concussed participants, our assessment approach was still highly accurate. Future research will need to validate these findings in a larger cohort with a clearly defined concussed group, which can be stratified into acute vs. chronic groups or analyzed with time since injury as a covariate. Lastly, the vestibular oculomotor assessments are still based largely on participant reports of signs and symptoms provocation, which relies on the accuracy and integrity of subjective report. Therefore, ensuring subjective measures are supplemented by objective measures, which may include a neurocognitive exam, would all serve to provide a more comprehensive multi-faceted approach to concussion assessment.

Conclusion

These preliminary findings suggest that using this condensed exam consisting of the OKS S/S, NPC, and GST S/S is a valid measure for discriminating athletes impaired by concussion in the subacute stage from healthy controls, and eliminates the time-consuming burden of performing all of the balance, vestibular, and oculomotor tests available to athletic trainers.

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